An Integrated Extreme Rainfall Modeling Tool (SDExtreme) for Climate Change Impacts and Adaptation

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**An Integrated Extreme Rainfall Modeling Tool (SDExtreme) for Climate
Change Impacts and Adaptation**

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Abstract

The estimation of the Intensity-Duration-Frequency (IDF) relations is often necessary for the planning and design of various hydraulic structures and design storms. It has been an increasingly greater challenge due to climate change condition. This paper therefore proposes an integrated extreme rainfall modeling software package (SDExtreme) for constructing the IDF relations at a local site in the context of climate change. The proposed tool is based on a temporal downscaling method to describe the relationships between daily and sub-daily extreme precipitation using the scale-invariance General Extreme Value (GEV) distribution. In addition, SDExtreme provides a modified bootstrap technique to determine confidence intervals (CIs) of the estimated IDF curves for the current and the future climate conditions. The feasibility and accuracy of SDExtreme were assessed using rainfall data available from the selected rain gauge stations in Quebec and Ontario provinces (Canada) and climate simulations under three different climate change scenarios provided by the Canadian Earth System Model (CanESM2) and the Canadian Regional Climate Model (CanRCM4).

Keywords: extreme rainfalls; intensity-duration-frequency relations; statistical downscaling; generalized extreme value distribution; confidence interval of IDF curves; climate change impacts

1. Introduction

In urban hydrology and drainage applications, the rainfall intensity-duration frequency (IDF) relation for a given site is always required for the design and management of stormwater works. For locations where observed annual maximum precipitations (AMPs) are available, frequency analysis is implemented to estimate design rainfall intensities for a specific duration and a given return period (Buishand, 1989, Wilks, 1993, Zalina et al., 2002). The computational procedure of constructing the IDF relation can be summarized as: *i*) select the appropriate distribution, *ii*) parameterize the selected distribution for each duration, and *iii*) estimate quantiles (or intensities) with respect to the desired return periods.

The traditional procedure, however, has inherent limitations: time scaling limitation, spatial scale limitation, and climate change condition. The inferences from this procedure are applicable only to the particular time scale associated with the data used and at a local site where data are available. Satellite, Weather Research and Forecasting (WRF) model, and some statistical techniques are proposed to overcome the spatial scale limitation (Pizarro et al., 2018, Liew et al., 2014, Ombadi et al., 2018, Ouali and Cannon, 2018). Efforts to describe the association of extreme rainfalls at different time scales have been proposed and tested (Gupta and Waymire, 1990, Nguyen et al., 2002, Nhat et al., 2007, Vu et al., 2018, Yeo et al., 2020), however, it is unable to investigate climate change impacts on extreme rainfalls in the future time. By coupling climate change scenarios and the described temporal association, the IDF curves have been updated to account for the climate change impacts on extreme rainfalls and flooding (Nguyen et al., 2008, Vu et al., 2018, Yeo, 2014).

More specifically, it has been recognized that society becomes more vulnerable to extreme weather and climate events. Continuing population growth, land use changes, and industrial

development will further increase vulnerability by creating more potential for catastrophic impacts from climate extremes such as severe flooding events with large loss of human life, excessive economic losses, and uncertain long-term consequences to ecosystems. Of particular interest for water management are the investigations of precipitation change that have revealed some empirical evidence of increasing trends in precipitation extremes over many regions of the world (IPCC, 2014). Hence, it is important to understand not only the current patterns of extreme rainfalls but also how they are likely to change in the future. General Circulation Models (GCMs) have been recognized to be able to represent the main features of the global distribution of some basic climate parameters. Outputs from these models, however, are not usually applicable for frequency analysis at a local site due to their coarse temporal resolutions. To incorporate the climate change conditions into frequency analyses, the scale invariance properties of AMPs are coupled to GCMs' outputs (Nguyen et al., 2008, Vu et al., 2018, Yeo et al., 2020).

Confidence intervals (CIs) have been used to indicate the uncertainty of quantiles in hydrological frequency analysis. The uncertainty in extreme rainfall event estimation is the result of insufficient data size, the procedure for selecting appropriate probability distribution, and the estimation of parameters of the selected distribution. The increasing trend in the maximum daily and sub-daily rainfalls intensities becomes a critical challenge in the construction of future IDF curves. The use of ensemble of multiple climate change models and the downscaling approaches have been suggested to represent the uncertainty. However, it also has the additional challenge to determine appropriate climate models for extreme rainfall events because the extreme values behave differently (Yeo et al., 2020).

This paper introduces a software package that enables the construction of IDF curves and their CIs for the present and the future if a user has the historical annual maximum precipitation

series and daily climate change scenarios' outputs. There are already well-known commercial/non-profit tools such as Hydrognomon (Kozanis et al., 2010), HydroCAD (HydroCAD Software Solutions, 2015), TechnoLogismiki Works, and IDF_CC tool (Simonovic et al., 2016). These tools, however, are unable to account for the temporal scale limitations and climate change issue except IDF_CC tool. Moreover, these tools do not provide the users with the CI for the future IDF curves. Hence, the proposed IDF estimation tool, whose name is Statistical Downscaling for Extreme Rainfall (SDExtreme) available at the Mendeley Dataset (<https://data.mendeley.com/datasets/kc9frpgfvs/1>), can be used to estimate the IDF curves and the CIs for current and future periods. The dataset includes an installation file for SDExtreme and two example files from the three selected rain gauge stations from Ontario and Quebec Provinces (Canada). Because the main source codes are compiled by MATLAB 2014a, the requirement for running this software is to install MATLAB Runtime version 8.3 (see the website: <https://www.mathworks.com/products/compiler/matlab-runtime.html>).

In this study, the proposed assessment tool is tested using a historical annual maximum precipitation series available for the period of 1961-1990 from sixteen rain gauge networks located in Southern Ontario and Quebec Provinces (Canada). As for the effects of climate change on extreme rainfall system, future weather conditions are projected using the same set of variables taken from three climate change scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) given by the second-generation Canadian Earth System Model (CanESM2) and two climate change scenarios (RCP 4.5 and RCP 8.5) by the Canadian Regional Climate Model (CanRCM4). The proposed tool is used to generate future IDF curves and CI associated with both CanESM2 and CanRCM4 climate change scenarios.

The remainder of this paper is organized as follows: section 2 provides a brief overview of the theoretical approach, section 3 describes the design and application, and the last section presents our conclusion, respectively.

2. Model Developments

In this section, we review the three steps, which are described in more detail in Yeo et al. (2020) and Nguyen et al. (2008).

2.1. Temporal Downscaling using Scaling- General Extreme Value (GEV) distribution

The GEV distribution has been commonly used to describe the distribution of extreme rainfalls for different durations and to construct the IDF curves (Nguyen et al., 2008, Yeo et al., 2020). The cumulative distribution function, $F(x)$, for the GEV distribution is given as

$$F(x) = \exp \left[- \left(1 - \frac{\kappa(x - \xi)}{\alpha} \right)^{1/\kappa} \right] \quad (\kappa \neq 0) \quad (\text{Eq.1})$$

where ξ , α , and κ are the location, scale, and shape parameter, respectively. The k -th order of non-central moments (NCMs), μ_k , of the GEV distribution can be expressed as:

$$\mu_k = \left(\xi + \frac{\alpha}{\kappa} \right)^k + (-1)^k \left(\frac{\alpha}{\kappa} \right)^k \Gamma(1 + k\kappa) + k \sum_{i=1}^{k-1} (-1)^i \left(\frac{\alpha}{\kappa} \right)^i \left(\xi + \frac{\alpha}{\kappa} \right)^{k-i} \Gamma(1 + i\kappa) \quad (\text{Eq.2})$$

in which $\Gamma(\cdot)$ is the gamma function. Therefore, it is possible to estimate parameters (ξ , α , and κ) of GEV distribution by the method of moments (MOM) using the first three NCMs. The quantiles (X_τ) can be calculated by the inverse distribution function as follows:

$$X_\tau = \xi + \frac{\alpha}{\kappa} \{1 - [-\ln(p)]^k\} \quad (\text{Eq.3})$$

120 where p is the exceedance probability of interest and τ is the return period.

121 For a simple scaling process, the relationship between the NCMs of order k and the
122 variable t can be written in a general form as follows:

$$\mu_k = E\{f^k(t)\} = t^{\beta(k)} a(k) \quad (\text{Eq.4})$$

123 in which $\alpha(k) = \{f^k(1)\}$ and $\beta(k) = k\beta$ under simple scaling condition. Hence, the scaling
124 behavior of extreme rainfall can be examined by the power-form relationship between the k -order
125 NCMs and the t durations. If extreme rainfall data exhibit the scaling properties, the log-linearity
126 will be shown.

127 In addition to the scaling properties in NCMs, for a simple scaling process, it can be shown
128 that the statistical properties of the GEV distribution for two different time scales t and λt are
129 related as follows:

$$\kappa(\lambda t) = \kappa(t) \quad (\text{Eq.5})$$

$$\alpha(\lambda t) = \lambda^\beta \alpha(t) \quad (\text{Eq.6})$$

$$\xi(\lambda t) = \lambda^\beta \xi(t) \quad (\text{Eq.7})$$

$$X_T(\lambda t) = \lambda^\beta X_T(t) \quad (\text{Eq.8})$$

130 Based on these relationships, it is possible to derive the statistical properties of sub-daily AMPs
131 using the properties of daily AMPs. Therefore, the proposed GEV distribution based on the scaling

property of NCMs for different rainfall durations can be used to construct the IDF curves for a given site.

Yeo et al. (2020) addresses three possible parameter estimation methods (Scaling L-moment, Scaling One-NCM, and Scaling Three-NCM) from Equation 4~8. The comparison studies with observed AMPs from two stations indicate that the Scaling Three-NCM method estimating the parameters of GEV distributions for the specific durations (λt) provides the most accurate quantiles with the observed values. Therefore, this software package uses the Scaling Three-NCM method in order to estimate the parameters of GEV distributions for shorter durations.

2.2. Error Adjustment Function with Climate Change Scenario Outputs

For climate change impact studies or flood risk studies under climate change, the daily AMPs are extracted from the downscaled daily precipitation series given from different GCM-based climate change scenarios. However, it is usually expected that these downscaled AMPs are not comparable to the observed extreme values. A bias-correction procedure is, therefore, required to improve the accuracy of the downscaled AMPs at a given site. The proposed procedure is described in the following (Nguyen et al., 2007, Yeo, 2014):

$$e_{\tau} = y_{\tau}^o - \hat{y}_{\tau} \quad (\text{Eq.9})$$

in which y_{τ}^o is the observed daily AMP at a probability level τ , and $\hat{y}_{\tau}$ is the estimated daily AMP with each GCM scenario, and e_{τ} is the residual associated with $\hat{y}_{\tau}$. The residual (e_{τ}) is modelled by the second order polynomial regression.

$$e_{\tau} = m_0 + m_1 \hat{y}_{\tau} + m_2 \hat{y}_{\tau}^2 + \varepsilon \quad (\text{Eq.10})$$

where m_0 , m_1 , and m_2 are regression coefficients in the function, $\hat{y}_t$ is the estimated AMP, and ε is the modeling error term.

2.3. Modified Bootstrapping for CIs

This section reviews the modified bootstrap technique, which is introduced by Yeo et al. (2020), to determine CIs of the downscaled sub-daily extreme rainfall series. Given the simple scaling properties of annual extreme rainfalls, the proposed technique is conducted by the combination of bootstrapping technique and the Scaling Three-NCM estimation method. Once n sets of AMPs are generated for daily duration T from observed or projected AMP series by bootstrapping technique, the n sets of the first three NCMs can be estimated. For constructing CIs, first the upper and lower limits of the NCMs for duration T at a given significance level (e.g. 95%) are estimated from the n sets of the first three NCMs. The estimated first NCMs for duration T are used to calculate the NCMs for duration t , and then parameters (ξ , α , and κ) of the downscaled GEV distributions for each duration t are calculated by the Scaling Three-NCM estimation method. CIs at a given confidence level are constructed by computing rainfall quantiles from the estimated parameters and Equation 3.

3. Design and Application

Figures 1 and 2 show the main menu of SDExtreme and four main modeling processes: (i) IDF Current Period; (ii) Scaling GEV Model; (iii) IDF Climate Change; and (iv) Confidence Intervals. Full technical details for this software package are described by Yeo et al. (2020).

Figure 1. Main menu of SDExtreme.

Figure 2. SDExtreme computational steps.

176

177 **3.1. IDF Current Period**

178 The ‘IDF Current Period’ operation generates current IDF curves given historical AMPs
179 records. Because both the L-moment and Three-NCM parameter estimation methods are used here,
180 the procedure enables the verification of the quantiles estimated by Three-NCM methods. The user
181 must specify the duration for observed data and the return period to ‘SDExtreme.ini’ file. After
182 reading the historical records and specified information file, the tool automatically shows the
183 information on data length, the number of intervals, duration, and return period. Finally, this tool
184 provides both graphical and numerical IDF curves so that the user can easily compare the quantiles.

185 **3.2. Scaling GEV Model**

186 Given the historical AMP series, the ‘Scaling GEV Model’ operation conducts the simple
187 scaling properties for them. The log-linearity is observed worldwide for duration between 1-hour
188 up to 24-hours. Regarding the scale-invariance properties for the sub-hourly, a breakpoint at 1-
189 hour (or 30-min) duration has been observed through various regions by the number of studies.
190 For instances, Nhat et al. (2007) investigates the two scaling regimes at Nagoya (Japan), South
191 Korea, Geraldton (Australia), and Malaysia. Breakpoints through many Provinces of Canada are
192 also observed (Bougadis and Adamowski, 2006, Nguyen et al., 2008, Yeo, 2014). Rodríguez et al.
193 (2014) and Chang and Hiong (2013) find breakpoints of scaling properties between sub-hourly
194 and sub-daily duration for Spain and Singapore, respectively. The presence of the breakpoint
195 would imply the transition of extreme rainfall systems (Vu et al., 2018). Therefore, this operation
196 allows the user to find the breakpoint in the first three NCMs in order to avoid the overestimation
197 of NCMs.

Once the breakpoint is identified, the operation generates a directory, named ‘Scaling Exponent,’ and saves the estimated scaling exponents (β) for both short-/long-durations. The user can examine the linearity of the scaling exponents for both short-/long-durations for the simple properties. The parameters of the downscaled GEV distributions for the duration of sub-hourly and sub-daily can be estimated by the function of ‘Estimating Parameters and Quantiles’ and saved in the directory of ‘Scaling-GEV’ with the name of ‘Scaled-GEV_Param_Obs.txt.’ Finally, the user can compare the estimated quantiles by the scaling-GEV models to the observed values graphically.

3.3. IDF Climate Change

SDExtreme version 2.0 uses the second-degree polynomial equation to improve the accuracy of the downscaled AMPs at a given site. Before the error-adjustment, the ‘IDF Climate Change’ divides GCMs’ output series (1961-2100) into four time periods: 1961-1990, 2020s, 2050s, and 2080s. The length of each time period is identical as 30 years. After making the bias-correction adjustment using Equation 10, SDExtreme provides relative root mean square of errors (RMSE) so that the user can identify the improved agreement between the adjusted downscaled AMPs and the observed values as compared to the unadjusted downscaled AMP amounts for the calibration period. The adjusted NCMs are saved in the ‘Adjusted-NCM’ directory. Finally, this software allows the user to compare the IDF curves with respect to time periods (e.g. calibration period, 2020s, 2050s, and 2080s) after estimating parameters of the downscaled GEV distributions for sub-daily and sub-hourly durations. All parameters, quantiles, and IDF curves for each time period are saved in the ‘Scaling-GEV’ directory.

3.4. Confidence Intervals

The main purpose of the ‘Confidence Intervals’ operation is to quantify the uncertainties of IDF curves. As a combination of bootstrapping technique and scale-invariance properties of AMPs are used, the user must specify the number of resampling and the significant level. Procedure for calculating CIs for the present is conducted using the historical record, while those for the future are done with climate change scenario outputs. The estimated upper and lower limits of the IDF curves are saved in the ‘Confidence-Interval’ directory.

4. Applications of SDExtreme

4.1. Study area and data

The feasibility of the proposed SDExtreme was demonstrated with at-site AMP data available at 16 rain gauge stations in the southern Quebec and Ontario provinces (Canada) as shown in Figure 3. Table 1 provides the geographical information on the rain gauge stations used in this study. Historical at-site AMP series were obtained from Canadian Weather Energy and Engineering Datasets (CWEEDS). They were made up of 9 durations (5-min, 10-min, 15-min, 30-min, 1-hr, 2-hr, 6-hr, 12-hr, and 1-day).

Table 1. Geographical information of the selected 16 rain gauges.

Station Name	Province	Latitude	Longitude	Station Name	Province	Latitude	Longitude
Delhi	Ontario	42.87	-80.55	Toronto	Ontario	43.68	-79.63
Hamilton	Ontario	43.29	-79.91	Windsor	Ontario	42.28	-82.96
Kingston	Ontario	44.24	-76.48	Bagotville	Quebec	48.33	-71.00
London	Ontario	43.03	-81.15	Drummondville	Quebec	45.88	-72.48
Ottawa	Ontario	45.38	-75.72	Mont Joli	Quebec	48.60	68.22
Sault Ste Marie	Ontario	46.48	-84.51	Montreal	Quebec	45.47	-73.75
St Thomas	Ontario	42.77	-81.21	St-Hubert	Quebec	45.52	-73.42
Thunder Bay	Ontario	48.38	-89.25	Val-D'Or	Quebec	48.06	-77.79

Figure 3. The study area encompasses the southern Quebec and Ontario Provinces (Canada). Red points denote the rain-gauge stations in Quebec Province, and blue circles do the rain-gauge stations in Ontario Province.

4.2. Verification of the Three-NCM parameter estimation method

In the 'IDF Current Period' procedure, SDExtreme provides numerical and graphical results (e.g. quantile plots and IDF curves) in order to evaluate the Three-NCM parameter estimation method using the observed and estimated quantiles by L-moment method. Figure 4 shows the quantile plots for duration 5-min and 30-min for the selected representative stations (Toronto International Airport for Ontario province and St. Hubert for Quebec province). Black,

blue, and red dots represent observed, estimated quantiles by L-moments and the Three-NCMs methods, respectively. Good agreement between the estimated by two estimation methods was observed for both stations. Numerical IDF curves were obtained using the conventional parameter estimation method and the Three-NCMs method for both Toronto and St. Hubert stations in Tables 2 and 3, respectively.

Figure 4. Quantile plots comparing the observed to the estimated values by L-moments method and Three-NCM method for the selected durations (e.g. 5-min and 30-min) at Toronto (Ontario) and St. Hubert (Quebec), respectively. (A) 5-min quantile plot for Dorval, (B) 30-min quantile plot for Toronto, (C) 5-min quantile plot for St. Hubert, and (D) 30-min quantile plot for St. Hubert. The black asterisk represents the observed values, the red line does the quantiles estimated by Three-NCM method, and blue line denotes those by L-moment method.

Table 2. Numerical IDF curves (the current period) using the L-moment method and the Three-NCMs method for Toronto station (Ontario): (A) numerical IDF curves by L-moments method and (B) those by Three-NCMs method.

(A) IDF Curves estimated by L-moments									
Return Period	Duration (minutes)								
	5	10	15	30	60	120	360	720	1440
2	107.98	79.6	65.27	42.79	23.8	13.85	5.85	3.3	1.92
5	144.22	105.86	87.46	57.56	31.84	18.59	7.97	4.44	2.49
20	186.71	135.04	112.55	74.53	42.41	25.62	11.27	6.46	3.54
50	211.21	151.06	126.53	84.13	49.19	30.66	13.75	8.17	4.45
100	228.45	161.96	136.15	90.79	54.31	34.76	15.83	9.72	5.3

(B) IDF Curves estimated by Three-NCMs									
Return Period	Duration (minutes)								
	5	10	15	30	60	120	360	720	1440
2	108.44	80.26	66.07	43.31	24.3	14.17	6.04	3.47	2.01
5	143.59	105.56	87.34	57.52	32.08	18.92	8.23	4.7	2.66
20	184.06	132.45	109.85	72.82	41.17	25.08	11.06	6.28	3.5
50	207.01	146.59	121.64	80.96	46.39	28.97	12.86	7.29	4.03
100	222.96	155.94	129.42	86.39	50.05	31.89	14.2	8.04	4.42

Table 3. Numerical IDF curves (the current period) using the L-moment estimation method and the Three-NCMs method for St. Hubert station (Quebec): (A) numerical IDF curves by L-moments method and (B) those by Three-NCMs method.

(A) IDF Curves estimated by L-moments									
Return Period	Duration (minutes)								
	5	10	15	30	60	120	360	720	1440
2	90.51	66.35	54.53	35.91	21.21	12.26	5.7	3.57	2.11
5	120.23	87.78	73	48.22	29.29	16.65	7.4	4.52	2.57
20	152.01	110.52	94.75	62.3	39.7	23.09	9.81	5.68	3.03
50	168.83	122.47	107.37	70.23	46.27	27.64	11.46	6.36	3.25
100	179.99	130.36	116.26	75.73	51.18	31.33	12.76	6.85	3.4

(B) IDF Curves estimated by Three-NCMs									
Return Period	Duration (minutes)								
	5	10	15	30	60	120	360	720	1440
2	91.72	66.36	55.11	36.48	21.67	12.54	5.78	3.62	2.11
5	120.11	87.15	72.97	48.13	29.38	16.88	7.46	4.52	2.55
20	148.17	109.29	92.87	60.37	38.33	22.51	9.63	5.53	2.98
50	161.96	120.96	103.83	66.74	43.45	26.07	11.01	6.09	3.19
100	170.66	128.69	111.29	70.91	47.03	28.73	12.04	6.47	3.32

4.3. Investigation of scale-invariant properties

Figure 5 shows the scaling relationships with respect to all duration. SDExtreme provides the R-square plot for determining the breakpoint to identify scaling properties at two different regimes of durations. From Figure 4-(B) and (D), case 2 (30-min) are determined for both Toronto and St. Huber stations. Table 4 shows scaling exponents (i.e. slopes of the NCMs) and the duration when breakpoints are observed. The breakpoints at thirteen stations are located at 30-min. While the points at Ottawa and Hamilton are of 60-min, the point at Kingston is located at 360-min. The spatial distributions of exponents are shown in Figure 6. Figure 6-(A) is for the scaling exponents for the duration before breakpoints and Figure 6-(B) for the duration after breakpoints. Because the scaling exponent is a ratio of extreme precipitation intensities to duration, a station with a bigger value of the scaling exponent would have more intensive extreme rainfall than a station with a lower value of the scaling exponent. In general, rain gauge stations in the southern portion have more intensive rainfall during short periods.

To examine the simple scaling properties of the AMP series, SDExtreme carries out the simple scale test with graphically and numerically. As shown in Figure 7, the linearity of the scaling exponents with the moment order supports the assumption that the extreme rainfall series can be described by a simple scaling model for both stations.

(A)

(B)

(C)

(D)

Figure 5. Log-log plots of non-central moments (NCMs) of the first three orders against several durations for (A) Toronto and (C) St. Hubert. Blue diamonds denote the first order NCMs, green triangles do the second order NCMs, and red dots represent the third order NCMs. R-square plots are provided for detecting the best case to demonstrate two scaling regimes.

Table 4. Scaling exponents of the third NCMs for the shorter and longer durations, and the durations for the break-points.

Station Name	Scaling Exponents of the third NCMs (short duration)	Scaling Exponents of the third NCMs (long duration)	Breakpoint Duration (min)
Delhi	1.467	0.911	30
Hamilton	1.376	0.591	60
Kingston	1.179	0.955	360
London	1.371	0.661	30
Ottawa	1.287	0.544	60
Sault Ste Marie	1.397	0.818	30
St Thomas	1.261	0.759	30

Thunder Bay	1.548	0.821	30
Toronto	1.477	0.632	30
Windsor	1.552	0.598	30
Bagotville	1.612	0.629	30
Drummondville	1.401	0.77	30
Mont Joli	1.356	1.041	30
Montreal	1.54	0.562	30
St-Hubert	1.491	0.741	30
Val-D'Or	1.353	0.69	30

290

(A)

(B)

Figure 6. Spatial distributions of scaling exponents for the third NCMs. (A) scaling exponents for the shorter durations and (B) for the longer durations.

(A)

(B)

Figure 7. Plots of the scaling exponents against the order of NCMs of AMP for (A) Toronto and (B) St. Hubert stations. Blue-diamonds represent the scaling exponents for the shorter duration and red-dots denote those for longer duration.

On the basis of the simple scaling relationship, Figure 6 shows the comparison between the observed and estimated AMPs by L-moments and scaling GEV distributions for 5-min and 30-min durations for Toronto and St. Hubert stations. It can be seen that the quantiles derived from the daily AMPs using the established scaling relationships agree very well with those values given by the conventional fitted GEV distribution as well as with the observed values. Similar results were found for other durations and stations.

Figure 8. IDF curves of AMPs for 5-min (or 10-min) and 30-min durations estimated by L-moments and the simple scaling models for Toronto (A, B) and St. Hubert (C, D), respectively. Blue dots represent the observed rainfall intensities, green diamonds do the estimated

4.4. Update IDF curve for the future period

To illustrate SDExtreme for future IDF curves, two different downscaling methods were used. As a statistical downscaling, SDRain proposed by Yeo et al. (2019) was calibrated and used to generate daily precipitation time series for Dorval station. A set of significant global

atmospheric reanalysis variables of the NCEP/NCAR (Kalnay et al., 1996) given by the second-generation Canadian Earth System Model (CanESM2) was used to establish statistical downscaling models. Once the spatial downscaling model with SDRain was calibrated, future weather conditions were projected with the three climate change scenarios (RCP 2.6, RCP 4.5, and RCP 8.5), where RCP denotes a representative concentration pathway. As a dynamical downscaling method, the Canadian Regional Climate Model (CanRCM4) with 0.22° grid resolution was used. The downscaled daily precipitation series of climate variables for the grid point nearest to each rain gauge station were used. A secondary quantile mapping was implemented to account for uncertainty in the CanRCM4 coming from climate systems.

Tables 5~9 show the numerical IDF relations for Ottawa station given by SDExtreme based on the scaling GEV model for three time periods (2020s, 2050s, and 2080s) under three different climate change scenarios (RCP2.6, RCP4.5, and RCP8.5) provided by CanESM2 and two scenarios (RCP4.5 and RCP8.5) by CanRCM4. For the illustration purposes, Figure 9 shows the plot of daily AMPs corresponding to 100-year return period simulated by SDExtreme and the three greenhouse gas emission scenarios given by CanESM2 and CanRCM4. It is found that the estimated 100-year daily AMPs exhibit similarly continuous increasing trends from the current period to 2020s, 2050, and 2080s. With CanESM2, the intensity increases from about 3.6 mm/h (current) to 3.70 mm/h (RCP 2.6), to 3.74 mm/h (RCP 4.5), and to 3.79 mm/h (RCP 8.5), respectively. However, CanRCM4 shows different patterns from the estimated intensities by CanESM2.

Figure 9. Estimated daily AMPs corresponding to 100-year return period for the current and future periods (2020s, 2050s, and 2080s) for Ottawa station.

Table 5. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model under RCP 2.6 climate change scenario by CanESM2 for Ottawa rain gauge station.

(A) Period of 2020s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	114.96	75.56	59.14	39.08	25.82	14.82	6.14	3.53	2.03
5	144.62	96.89	76.63	51.53	34.62	19.65	8.01	4.55	2.59
20	180.73	124.01	99.29	67.68	46.03	25.93	10.42	5.85	3.28
50	202.31	140.89	113.65	77.91	53.27	29.91	11.95	6.67	3.71
100	217.84	153.38	124.4	85.58	58.69	32.89	13.1	7.28	4.02

(B) Period of 2050s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	120.09	78.8	61.65	40.59	26.82	15.39	6.4	3.68	2.12
5	148.68	99.65	78.83	52.83	35.52	20.16	8.23	4.68	2.66
20	181.76	125.30	100.51	68.71	46.81	26.34	10.56	5.92	3.31
50	200.61	140.78	113.91	78.78	53.96	30.26	12.02	6.67	3.69

100	213.76	152.00	123.77	86.32	59.32	33.20	13.10	7.23	3.97
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(C) Period of 2080s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	118.81	78.05	61.08	40.31	26.64	15.28	6.34	3.65	2.10
5	148.69	99.62	78.80	52.92	35.56	20.19	8.22	4.68	2.66
20	184.45	126.75	101.54	69.28	47.15	26.55	10.66	5.98	3.35
50	205.50	143.46	115.83	79.65	54.49	30.58	12.21	6.80	3.77
100	220.49	155.73	126.47	87.42	59.99	33.60	13.37	7.39	4.08

Table 6. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model under RCP 4.5 climate change scenario by CanESM2 for Ottawa rain gauge station.

(A) Period of 2020s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	111.69	73.43	57.53	38.01	25.12	14.41	5.98	3.43	1.98
5	140.80	94.33	74.68	50.22	33.74	19.15	7.80	4.43	2.52
20	176.61	121.10	96.92	66.04	44.91	25.30	10.17	5.72	3.21
50	198.21	137.87	111.01	76.07	52.00	29.20	11.67	6.53	3.63
100	213.87	150.34	121.58	83.59	57.30	32.120	12.8	7.13	3.94

(B) Period of 2050s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	117.74	77.29	60.48	39.85	26.33	15.11	6.28	3.61	2.08
5	146.55	98.20	77.67	52.09	35.01	19.87	8.11	4.61	2.62
20	180.32	124.12	99.51	67.97	46.28	26.05	10.45	5.86	3.28
50	199.79	139.88	113.07	78.03	53.41	29.96	11.93	6.63	3.67
100	213.47	151.36	123.10	85.57	58.76	32.90	13.02	7.19	3.96

(C) Period of 2080s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	122.89	80.67	63.11	41.58	27.47	15.77	6.55	3.77	2.17
5	153.19	102.63	81.17	54.42	36.58	20.76	8.47	4.82	2.74
20	188.63	129.82	104.07	71.07	48.38	27.24	10.93	6.13	3.43
50	209.02	146.32	118.27	81.62	55.86	31.34	12.47	6.93	3.84
100	223.34	158.32	128.76	89.53	61.47	34.42	13.62	7.52	4.14

Table 7. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model under RCP 8.5 climate change scenario by CanESM2 for Ottawa rain gauge station.

(A) Period of 2020s

Duration (min): mm/h									
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Return Period	5	10	15	30	60	120	360	720	1440
2	115.52	75.85	59.35	39.13	25.86	14.84	6.16	3.55	2.04
5	145.15	97.20	76.86	51.54	34.63	19.66	8.02	4.56	2.60
20	180.18	123.79	99.16	67.64	46.02	25.92	10.41	5.84	3.27
50	200.53	140.02	113.06	77.85	53.24	29.88	11.92	6.63	3.68
100	214.92	151.87	123.36	85.50	58.64	32.85	13.04	7.21	3.97

(B) Period of 2050s

Return Period	5	10	15	30	60	120	360	720	1440
2	124.20	81.64	63.93	42.24	27.92	16.02	6.64	3.82	2.20
5	156.58	104.89	82.98	55.80	37.49	21.28	8.67	4.93	2.80
20	196.20	134.56	107.71	73.39	49.91	28.12	11.30	6.35	3.56
50	219.98	153.08	123.37	84.54	57.78	32.45	12.97	7.25	4.03
100	237.17	166.81	135.11	92.90	63.68	35.69	14.22	7.92	4.37

(C) Period of 2080s

Return Period	5	10	15	30	60	120	360	720	1440
2	132.57	87.18	68.36	45.16	29.84	17.12	7.10	4.08	2.35
5	163.17	109.57	86.92	58.52	39.35	22.33	9.09	5.15	2.92
20	201.17	138.48	111.01	75.85	51.70	29.08	11.66	6.54	3.66
50	224.30	156.72	126.27	86.84	59.52	33.36	13.29	7.42	4.12
100	241.17	170.35	137.70	95.07	65.39	36.57	14.52	8.08	4.46

Table 8. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model under RCP 4.5 climate change scenario by CanRCM4 for Ottawa rain gauge station.

(A) Period of 2020s

Return Period	5	10	15	30	60	120	360	720	1440
2	126.79	83.17	65.08	42.93	28.35	16.28	6.76	3.89	2.24
5	147.2	99.4	78.93	53.29	35.93	20.35	8.25	4.68	2.65
20	171.13	119.86	96.78	66.72	45.77	25.64	10.2	5.68	3.15
50	184.94	132.5	108.03	75.23	52	29	11.43	6.3	3.45
100	194.64	141.8	116.43	81.6	56.67	31.51	12.36	6.76	3.67

(B) Period of 2050s

Return Period	5	10	15	30	60	120	360	720	1440
2	128.88	84.25	65.82	43.24	28.44	16.37	6.83	3.93	2.27
5	157.94	105.8	83.66	55.99	37.45	21.32	8.73	4.97	2.83

20	188.13	130.59	105	71.98	49.14	27.62	11.04	6.18	3.44
50	203.67	144.64	117.53	81.81	56.55	31.53	12.42	6.87	3.78
100	213.79	154.4	126.46	89.01	62.1	34.43	13.42	7.36	4.01

(C) Period of 2080s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	133.7	87.32	68.26	44.89	29.64	17.01	7.08	4.08	2.35
5	153.61	103.64	82.27	55.37	37.35	21.15	8.6	4.88	2.76
20	174.37	123.28	99.76	68.97	47.37	26.52	10.52	5.85	3.23
50	185.09	134.88	110.45	77.58	53.71	29.92	11.71	6.43	3.5
100	192.1	143.17	118.26	84.03	58.47	32.47	12.59	6.85	3.68

Table 9. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model under RCP 8.5 climate change scenario by CanRCM4 for Ottawa rain gauge station.

(A) Period of 2020s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	127.64	83.1	64.81	42.48	27.9	16.07	6.72	3.88	2.24
5	156.57	104.85	82.86	55.37	36.99	21.08	8.64	4.92	2.8
20	183.17	127.9	103.04	70.77	48.36	27.16	10.84	6.05	3.37
50	195.37	139.99	114.17	79.8	55.31	30.79	12.09	6.66	3.65
100	202.72	147.97	121.77	86.22	60.41	33.4	12.95	7.07	3.83

(B) Period of 2050s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	145.23	93.83	72.93	47.61	31.2	18	7.55	4.37	2.54
5	171.59	115.7	91.54	61.2	40.88	23.3	9.55	5.43	3.09
20	190.1	135.56	110.04	76.21	52.33	29.31	11.62	6.44	3.54
50	196.63	144.54	119.19	84.39	58.98	32.67	12.68	6.91	3.73
100	199.94	149.91	124.99	89.94	63.68	34.98	13.37	7.2	3.84

(C) Period of 2080s

Return Period	Duration (min): mm/h								
	5	10	15	30	60	120	360	720	1440
2	142.17	91.67	71.36	46.73	30.69	17.68	7.39	4.27	2.48
5	162.19	109.61	86.82	58.23	39.02	22.19	9.07	5.15	2.92
20	176.54	127.56	103.72	71.93	49.47	27.68	10.96	6.06	3.32
50	181.71	136.48	112.84	79.95	55.89	30.95	12.01	6.53	3.5
100	184.36	142.15	118.98	85.66	60.6	33.31	12.73	6.84	3.61

4.5. Construct confidence intervals

SDExtreme was used to construct CIs of AMPs for the present and the future periods. The modified bootstrap technique introduced by Yeo et al. (2020) was used to generate 1,000 sets of AMPs for a duration of 1-day using observed and synthesized daily AMPs by SDRain and quantile mapping with the three climate change scenarios by CanESM2 and CanRCM4. The significance level was set up as 0.05 for constructing the 95% CIs in this study. The Grey shade represents the range of CIs illustrating at the selected significance level and the black lines are the estimated IDF curves. CIs were constructed by not using historical records in order to evaluate the performance of SDExtreme CI methods. As shown in Figure 10, all observed values fall into the CI ranges for both durations of 5-min and 30-min. This implies that SDExtreme could provide robust CIs of extreme rainfall values without the observed sub-daily and sub-hourly AMPs. Once the CIs method with the historical records was verified, SDExtreme constructed CIs for IDF curves for the period of 2080s, estimated under four climate change scenarios (i.e. CanESM2 RCP 4.5 & 8.5 and CanRCM4 RCP 4.5 & 8.5), corresponding to the 50-year return period. As shown in Figure 11, it was found that the range of CIs for RCP 8.5 is quite thinner than those for other climate change scenarios. In addition, the ranges given by CanRCM4 are thinner than those by CanESM2 scenarios. Because the thin CIs implies low variability of the estimated AMPs, the result could imply that a significant increase in the extreme rainfall is highly likely under RCP 8.5 climate change scenario.

(A)

(B)

Figure 10. The 95% confidence intervals (CIs) of (A) IDF curves for the 5-min duration and (B) 30-min duration for Ottawa rain gauge station, respectively. Grey shade regions are the 90% CIs constructed by SDExtreme, black lines are the estimated IDF curves, and blue dots represent observed values.

Figure 11. The 95% confidence intervals (CIs) for IDF curves (for the period of 2080s) corresponding to 50-year return periods estimated under two greenhouse gases emission scenarios (RCP 4.5, and RCP 8.5) given by CanESM2 and two (RCP 4.5 and RCP 8.5) by CanRCM4, respectively. (A) under RCP 4.5 by CanESM2, (B) under RCP 5.5 by CanESM2, and (C) under RCP 4.5 by CanRCM4, and (D) under RCP 8.5 by CanRCM4. Grey shade regions are the 95% CIs and black lines are the estimated IDF curves by SDExtreme.

5. Conclusions

An integrated extreme rainfall modeling software package (SDExtreme Version 2.0) was proposed in this study to describe the linkage between different time durations and to construct the CIs for the estimated IDF curves. The feasibility and accuracy of this modeling tool have been tested using climate simulation outputs from CanESM2 and CanRCM4 under three different greenhouse gas emission scenarios and using available AMP series for durations ranging from 5 minutes to 1 day at 16 stations located in southern Quebec and Ontario provinces (Canada) over the period of 1961-1990. It is found that the AMP series at all stations displayed a simple scaling behavior within two different time intervals. Based on this scaling property, the scaling GEV distribution has been shown to be able to provide accurate estimates of sub-daily AMPs from observed and GCM-downscaled daily AMP amounts. Therefore, it can be concluded that it is feasible to use SDExtreme to describe the relationship between large-scale climate predictors for daily scale given by GCM and RCM simulation outputs and the daily and sub-daily AMPs at a local site.

Furthermore, the proposed assessment tool was implemented to construct the IDF relations for a given site for the 1961-1990 period and the future periods (2020s, 2050s, and 2080s) using climate predictors given by CanESM2 and CanRCM4 simulations. Results show the significant increasing trend in daily AMPs for the future periods. The highest increase in extreme rainfall was observed in the estimated by RCP 8.5 scenario given by CanESM2.

SDExtreme software package provides the CIs using only daily AMP series and simple scaling properties. The CI estimation method was implemented for the synthesized future daily AMPs as well as the observed value for the uncertainty study. It was found that the CIs vary with respect to climate change scenarios.

Declarations

Funding

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Conflicts of interest/Competing interests

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.

Code availability

SDExtreme, example annual maximum precipitation series, and statically/dynamically downscaled data sets are available at the Mendeley Dataset (<https://data.mendeley.com/datasets/kc9frpgfvs/1>). In addition, the main source are compiled by MATLAB 2014a. So, the requirement for running this software is to install MATLAB Runtime version 8.3 (see the website: <https://www.mathworks.com/products/compiler/matlab-runtime.html>).

Availability of data and material

The Mendeley Dataset (<https://data.mendeley.com/datasets/kc9frpgfvs/1>) contains several data sets: historical annual maximum precipitation series and downscaled daily precipitation series. More specifically, here is the detail information;

- Historical annual maximum precipitation series: the three rain gauge stations (Ottawa, St. Hubert, and Toronto) were downloaded from Canadian Weather Energy and Engineering Datasets (CWEEDS)

- Downscaled precipitation series: in this study two downscaling methods were implemented for the comparison purpose. For statistical downscaling model, SDRain (Yeo et al., 2019) was used for spatially downscaling CanESM2 model with three greenhouse gas emission scenarios (RCP2.6, RCP4.5, and RCP8.5). The file names are CanESM2_R**_Ottawa.OUT. For dynamical downscaling model, CanRCM4 is used. Because of low value events, an additional statistical procedure (quantile mapping) was used. The file names are CanRCM4_His_R**_Ottawa.OUT.

Ethics approval

Approved.

Consent to participate

Yeo, Myeong-Ho: Theoretical parts, Development of source codes and software, Methodology and Applications, Data analyses, Writing – Original draft

Van-Thanh-Van Nguyen: Writing – review & editing

Yong Sang Kim: Writing – review & editing

Theodore A. Kpodonu: Writing – review & editing.

Consent for publication

All authors are consent.

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525 **Table Caption List**

526 Table 10. Geographical information of the selected 16 rain gauges.

527 Table 11. Numerical IDF curves (the current period) using the L-moment method and the Three-
528 NCMs method for Toronto station (Ontario): (A) numerical IDF curves by L-moments
529 method and (B) those by Thee-NCMs method.

530 Table 12. Numerical IDF curves (the current period) using the L-moment estimation method and
531 the Three-NCMs method for St. Hubert station (Quebec): (A) numerical IDF curves by L-
532 moments method and (B) those by Thee-NCMs method.

533 Table 13. Scaling exponents of the third NCMs for the shorter and longer durations, and the
534 durations for the break-points.

535 Table 14. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model
536 under RCP 2.6 climate change scenario by CanESM2 for Ottawa rain gauge station.

537 Table 15. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model
538 under RCP 4.5 climate change scenario by CanESM2 for Ottawa rain gauge station.

539 Table 16. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model
540 under RCP 8.5 climate change scenario by CanESM2 for Ottawa rain gauge station.

541 Table 17. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model
542 under RCP 4.5 climate change scenario by CanRCM4 for Ottawa rain gauge station.

543 Table 18. Numerical IDF curves of AMP estimated by SDExtreme based on scaling GEV model
544 under RCP 8.5 climate change scenario by CanRCM4 for Ottawa rain gauge station.

545

546

547 **Figure Caption List**

548 Figure 12. Main menu of SDExtreme.

549 Figure 13. SDExtreme computational steps.

550 Figure 14. The study area encompasses the southern Quebec and Ontario Provinces (Canada). Red
551 points denote the rain-gauge stations in Quebec Province, and blue circles do the rain-
552 gauge stations in Ontario Province.

553 Figure 15. Quantile plots comparing the observed to the estimated values by L-moments method
554 and Three-NCM method for the selected durations (e.g. 5-min and 30-min) at Toronto
555 (Ontario) and St. Hubert (Quebec), respectively. (A) 5-min quantile plot for Dorval, (B)
556 30-min quantile plot for Toronto, (C) 5-min quantile plot for St. Hubert, and (D) 30-min
557 quantile plot for St. Hubert. The black asterisk represents the observed values, the red line
558 does the quantiles estimated by Three-NCM method, and blue line denotes those by L-
559 moment method.

560 Figure 16. Log-log plots of non-central moments (NCMs) of the first three orders against several
561 durations for (A) Toronto and (C) St. Hubert. Blue diamonds denote the first order NCMs,
562 green triangles do the second order NCMs, and red dots represent the third order NCMs.
563 R-square plots are provided for detecting the best case to demonstrate two scaling regimes.

564 Figure 17. Spatial distributions of scaling exponents for the third NCMs. (A) scaling exponents for
565 the shorter durations and (B) for the longer durations.

566 Figure 18. Plots of the scaling exponents against the order of NCMs of AMP for (A) Toronto and
567 (B) St. Hubert stations. Blue-diamonds represent the scaling exponents for the shorter
568 duration and red-dots denote those for longer duration.

569 Figure 19. IDF curves of AMPs for 5-min (or 10-min) and 30-min durations estimated by L-
570 moments and the simple scaling models for Toronto (A, B) and St. Hubert (C, D),
571 respectively. Blue dots represent the observed rainfall intensities, green diamonds do the
572 estimated

573 Figure 20. Estimated daily AMPs corresponding to 100-year return period for the current and
574 future periods (2020s, 2050s, and 2080s) for Ottawa station.

575 Figure 21. The 95% confidence intervals (CIs) of (A) IDF curves for the 5-min duration and (B)
576 30-min duration for Ottawa rain gauge station, respectively. Grey shade regions are the 90%
577 CIs constructed by SDExtreme, black lines are the estimated IDF curves, and blue dots
578 represent observed values.

579 Figure 22. The 95% confidence intervals (CIs) for IDF curves (for the period of 2080s)
580 corresponding to 50-year return periods estimated under two greenhouse gases emission
581 scenarios (RCP 4.5, and RCP 8.5) given by CanESM2 and two (RCP 4.5 and RCP 8.5) by
582 CanRCM4, respectively. (A) under RCP 4.5 by CanESM2, (B) under RCP 5.5 by
583 CanESM2, and (C) under RCP 4.5 by CanRCM4, and (D) under RCP 8.5 by CanRCM4.

584 Grey shade regions are the 95% CIs and black lines are the estimated IDF curves by
585 SDExtreme.

586

587

Figures

Figure 1

Main menu of SDExtreme.

Figure 2

SDExtreme computational steps.

Figure 3

The study area encompasses the southern Quebec and Ontario Provinces (Canada). Red points denote the rain-gauge stations in Quebec Province, and blue circles do the rain-gauge stations in Ontario Province. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors

Figure 4

Quantile plots comparing the observed to the estimated values by L-moments method and Three-NCM method for the selected durations (e.g. 5-min and 30-min) at Toronto (Ontario) and St. Hubert (Quebec), respectively. (A) 5-min quantile plot for Dorval, (B) 30-min quantile plot for Toronto, (C) 5-min quantile plot for St. Hubert, and (D) 30-min quantile plot for St. Hubert. The black asterisk represents the observed values, the red line does the quantiles estimated by Three-NCM method, and blue line denotes those by L-moment method.

(A)

(B)

(C)

(D)

Figure 5

Log-log plots of non-central moments (NCMs) of the first three orders against several durations for (A) Toronto and (C) St. Hubert. Blue diamonds denote the first order NCMs, green triangles do the second order NCMs, and red dots represent the third order NCMs. R-square plots are provided for detecting the best case to demonstrate two scaling regimes.

(A)

(B)

Figure 6

Spatial distributions of scaling exponents for the third NCMs. (A) scaling exponents for the shorter durations and (B) for the longer durations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(A)

(B)

Figure 7

Plots of the scaling exponents against the order of NCMs of AMP for (A) Toronto and (B) St. Hubert stations. Blue-diamonds represent the scaling exponents for the shorter duration and red-dots denote those for longer duration.

Figure 8

IDF curves of AMPs for 5-min (or 10-min) and 30-min durations estimated by L-moments and the simple scaling models for Toronto (A, B) and St. Hubert (C, D), respectively. Blue dots represent the observed rainfall intensities, green diamonds do the estimated

Figure 9

Estimated daily AMPs corresponding to 100-year return period for the current and future periods (2020s, 2050s, and 2080s) for Ottawa station.

(A)

(B)

Figure 10

The 95% confidence intervals (CIs) of (A) IDF curves for the 5-min duration and (B) 30-min duration for Ottawa rain gauge station, respectively. Grey shade regions are the 90% CIs constructed by SDExtreme, black lines are the estimated IDF curves, and blue dots represent observed values.

Figure 11

The 95% confidence intervals (CIs) for IDF curves (for the period of 2080s) corresponding to 50-year return periods estimated under two greenhouse gases emission scenarios (RCP 4.5, and RCP 8.5) given by CanESM2 and two (RCP 4.5 and RCP 8.5) by CanRCM4, respectively. (A) under RCP 4.5 by CanESM2, (B) under RCP 5.5 by CanESM2, and (C) under RCP 4.5 by CanRCM4, and (D) under RCP 8.5 by CanRCM4. Grey shade regions are the 95% CIs and black lines are the estimated IDF curves by SDExtreme.