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A Decision Support Tool for Climate Change Adaptation and Mitigation

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Abstract*— This paper proposes an integrated modeling tool for assessing climate change impacts on extreme rainfalls and the consequent hydrologic responses. The supporting tool is based on the combination of a spatial downscaling method for describing the association between the large-scale atmospheric variables and daily precipitation series at a local site and a temporal downscaling method for linking daily annual maximum precipitations (AMPs) and sub-daily AMPs. The feasibility test is carried out using the historical AMP series available at Ottawa station (Canada) for cold region and Saipan International Airport (CNMI) for tropical region with three second-generation Canadian Earth System Model (CanESM2) and two scenarios of the Canadian Regional Climate Model (CanRCM4). In brief, the updated IDF curves provided by the proposed assessment tool can be used for various climate-related impact assessment studies for given regions.

***Index Terms*— climate change assessment, extreme rainfalls, intensity-duration-frequency curves, statistical downscaling**

I. 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 [1-3]. 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.

Recently, climate variability and change have been recognized to have important impacts on the hydrologic cycle at different temporal and spatial scales. The temporal scales could vary from a very short time interval of 5 minutes (for urban water cycle) to a yearly time scale (for annual water balance computation). The spatial resolutions could be from a few square kilometers (for urban watersheds) to several thousand square kilometers (for large river basins). General Circulation Models (GCMs) have been commonly used to assess these impacts since these models could describe reasonably well the main features of the distribution of basic climate parameters at global scale. However, the coarse-scale outputs from these GCMs are not suitable for hydrological impacts assessment at the regional or local scale. Therefore, several downscaling methods have been developed in order to link large-scale climate variables to local-scale hydrological variables such as precipitation.

In view of above-mentioned issues, the overall objective of this study is therefore to propose an integrated extreme rainfall modeling tool to assess the climate change impacts on the extreme rainfall and runoff processes. More specifically, the proposed modeling tool is based on a combination of a spatial downscaling method to link large-scale climate variables given by GCMs simulations with daily extreme precipitations at a site using the statistical downscaling method (SDRain) proposed by Yeo et al. [4] and a temporal downscaling procedure to describe the relationships between daily and sub-daily extreme precipitations based on the scaling General Extreme Value (GEV) distribution (hereafter called SDExtreme). The proposed decision-supporting tool was tested using observed AMP data at two raingauge stations (i.e. Ottawa International Airport station in Canada and Saipan International Airport station in the Commonwealth of the Northern Mariana Islands (CNMI)) for the periods of 1961-2000 and 1979-2020, respectively, and climate simulations under 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).

II. STATISTICAL DOWNSCALING METHODS

For the hazard mitigation studies induced by climate change, three steps are required to conduct the adaptation and mitigation studies: i) spatial downscaling modeling to describe the linkage of large-scale atmospheric variables to at-site weather conditions, ii) temporal downscaling modeling to estimate sub-daily/hourly AMPs from the downscaled daily AMPs with sub-daily extreme precipitations using the scaling GEV distribution, and iii) construction of design storms for the future and application to stormwater management models for calculating future peak discharge magnitudes.

A. A spatial downscaling method

To illustrate SDExtreme for future IDF curves, two different downscaling methods are used. For statistical downscaling, SDRain [5] is calibrated and used to generate a daily precipitation time series with the three climate change scenarios (RCP2.6, RCP4.5, and RCP8.5), where RCP denotes a representative concentration pathway provided by the second-generation Canadian Earth System Model (CanESM2). A secondary quantile mapping is implemented to adjust the dynamically downscaled Canadian Regional Climate Model (CanRCM4) with historical rainfall data series. Results of the numerical application of the SDRain downscaling and quantile mapping methods to different climatic regions have indicated that the method is adequately able to describe the local daily precipitation occurrences and amounts with large-scale climate predictors provided by GCMs for the assessment of climate change impacts [4].

B. Temporal downscaling method using SDExtreme

The application of GEV distribution has been dealt with to model properties of AM precipitation series and to construct IDF curves. The cumulative distribution function, F(x), for the GEV distribution is

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

in which α, κ, and ξ are the location, scale, and shape parameter, respectively. For linking GEV parameters and quantiles with scaling property, the *k*-th order of non-central moment (NCM), μ_k, of the GEV distribution can be expressed as

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

in which $\Gamma(\bullet)$ is the gamma function. Therefore, it is possible to estimate parameters of GEV distribution using first three NCMs. The quantiles (X_τ) corresponding to a return period can be calculated by the inverse distribution function as follows

$$X_\tau = \xi + \frac{\alpha}{\kappa}\left\{1-\left[1-\ln(p)\right]^\kappa\right\} \quad (3)$$

Where, p is the exceedance probability of interest.

The proposed temporal downscaling method is based on the concept of scale-invariance (or scaling). According to the definition, if a function *f(x)* has a proportional relationship with respect to scaled λx, the *f(x)* follows scaling behaviour for all positive values of the scale factor λ. With scaling property, the relationship between *C(λ)* and *f(x)* can be expressed such that

$$f(x) = C(\lambda) f(\lambda x) \quad (4)$$

C(λ) can be readily derived as

$$C(\lambda) = \lambda^{-\beta} \quad (5)$$

in which β, called a scaling exponent, is a constant for a local site.

Consequently, since *k*-th order NCMs (μ_k) are proportionally associated with each other, the μ_k can be expressed in the same form of Eq. (6) as

$$\mu_k(x) = E\left\{f^k(x)\right\} = \alpha(k)x^{\beta(k)} \quad (6)$$

Further, for a simple scaling process, it can be shown that the statistical properties of the GEV distribution for two different time scales *t* and λt are related as follows:

$$\kappa(\lambda t) = \kappa(t) \quad (7)$$

$$\alpha(\lambda t) = \lambda^\beta \alpha(t) \quad (8)$$

$$\xi(\lambda t) = \lambda^\beta \xi(t) \quad (9)$$

$$X_T(\lambda t) = \lambda^\beta X_T(t) \quad (10)$$

Hence, based on these relationships it is possible to derive the statistical properties of sub-daily AM precipitations using the properties of daily AM precipitations. Then, the derived NCMs are used to estimate three parameters of GEV distribution for sub-daily extreme rainfalls. Therefore, the proposed scaling GEV method can be used to construct IDF curves taking account of climate-related impacts on extreme rainfalls.

The daily AMPs are extracted from the downscaled daily precipitation series given by the SDRain and the quantile mapping method for different GCM-based climate scenarios. A bias-correction procedure is, hence, required to improve the accuracy of the downscaled AMPs at a given site. The SDExtreme applies the second order polynomial regression for modeling the residual (e_τ).

III. APPLICATION

Fig. 1 shows the main menu of the proposed extreme rainfall modeling software package (SDExtreme) (i) for constructing IDF relations for the current climate; (ii) for performing the temporal downscaling of AMPs and for estimating the scaling GEV distribution; (iii) for making bias error correction of downscaled AMPs; and (iv) for establishing IDF relations under different climate change scenarios.

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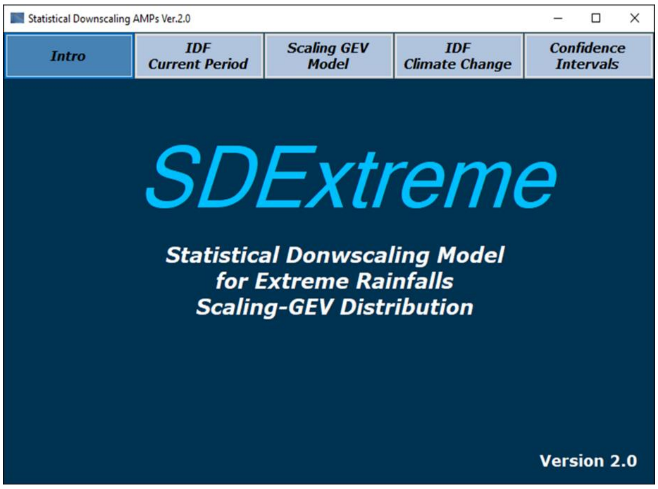

Figure 1. SDExtreme

To assess the feasibility and accuracy of the proposed integrated extreme rainfall modeling tool, an illustrative application was carried out using global GCM climate simulation outputs and at-site AMP data available at two raingage stations located in two completely different climate regions: Ottawa station in Ontario (Canada) for cold region and Saipan Int'l Airport in the CNMI for tropical region, respectively.

To verify the Three-NCM parameter estimation method, the 'IDF Current Period' was implemented to evaluate the Three-NCM parameter estimation method using the observed and estimated quantiles by L-moment method. Fig. 2 shows the quantile plots for comparing the observed to the estimated values by L-moments and the Three-NCM methods for Ottawa (a) and Saipan Int'l Airport (b). Good agreement between the estimated by two estimation methods was observed for both stations.

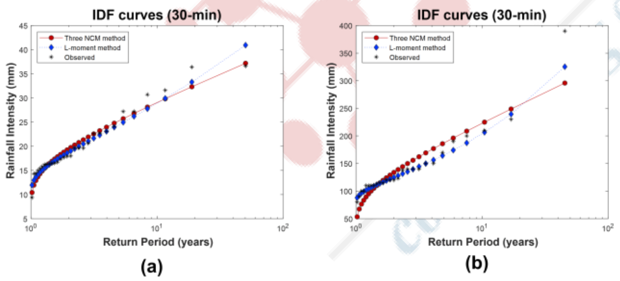

Figure 2. Quantile plots comparing the observed to the estimated values by L-moments method and Three-NCM method for 30-minute duration. (a) Ottawa and (b) Saipan Int'l Airport.

To examine the temporal scaling properties of the AMP series, SDExtreme provides graphical analyses using the first three NCMs.

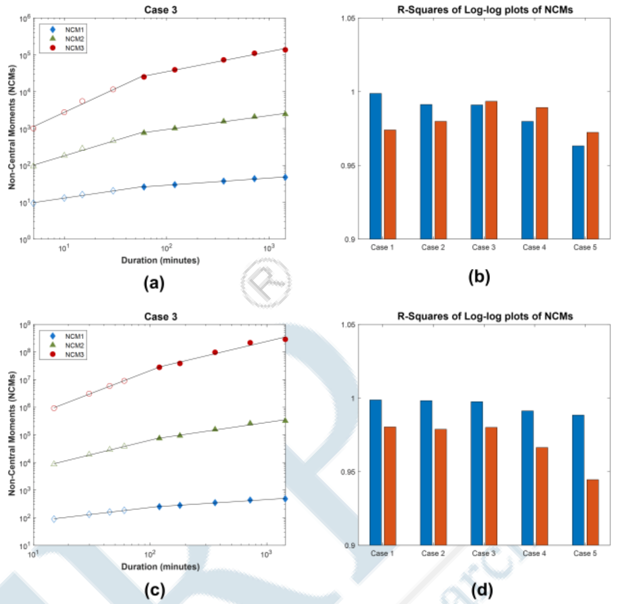

Figure 3. Log-log plots of the first three NCMs and r-square values for (a) & (b) Ottawa and (c) & (d) Saipan Int'l Airport.

Fig. 3 shows the scaling relationships between NCMs and rainfall durations for Ottawa and Saipan Int'l Airport stations. The log-linearity of NCMs shows two distinct scaling regimes: from 5 minutes to 1 hour and from 1 hour to 1 day for Ottawa station; and from 15 minutes to 2 hours and from 2 hours to 1 day for Saipan Int'l Airport station. In addition, the linearity of the scaling exponents β(k) against the order of NCMs of AMPs for both stations as shown in Fig. 4 has indicated the simple scaling behavior of the AMPs at these two stations. The graphical comparison is carried out to figure out the temporal downscaling method.

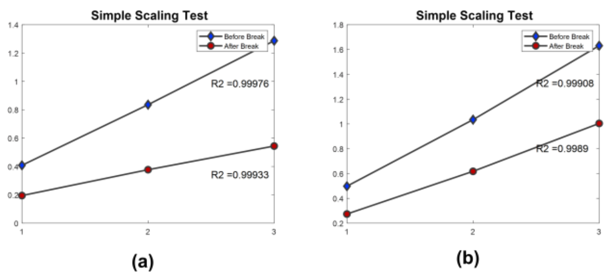

Figure 4. Plots of the scaling exponents against the order of NCMs of AMP for (a) Ottawa and (B) Saipan Int'l Airport stations.

To investigate the performance of the proposed temporal downscaling method, the quantiles estimated by L-moments based on the historical data and the scaling GEV method are compared. Fig. 5 indicates that the quantiles derived from the daily AMPs using the established scaling relationships agree very well with those values given by the traditional fitted GEV distribution as well as with the observed values.

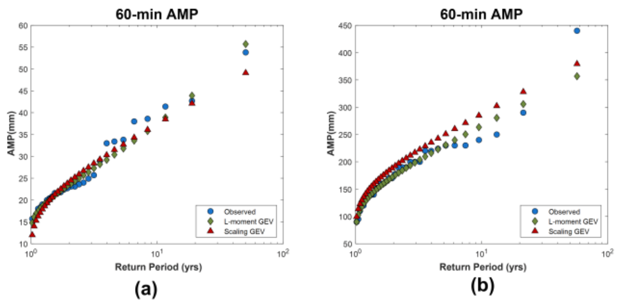

Figure 5. Probability plots of 1-hour observed and estimated AMPs using traditional and scaling GEV distributions for the 1961-1990 for Ottawa station (a) and Saipan Int'l Airport station (b).

SDExtreme was used to construct IDF curves for Ottawa station for future 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. Fig. 6 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.

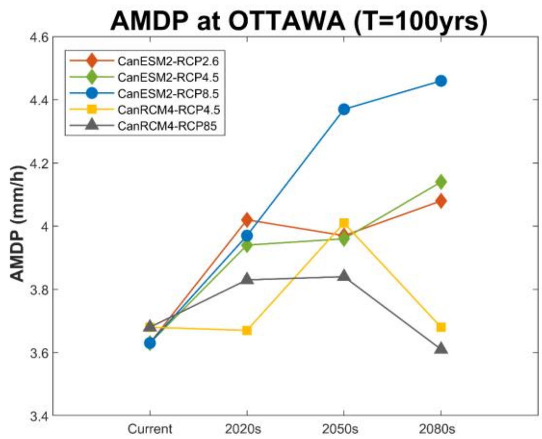

Figure 6. Estimated daily AMPs corresponding to 100-year return period for the current and future periods (2020s, 2050s, and 2080s) for Ottawa station

IV. CONCLUSIONS

An integrated extreme rainfall modeling tool was proposed in this study to describe the linkages between large-scale climate variables at the daily scale to AMPs at daily and sub-daily scales at a given local site. The feasibility and accuracy of this modeling tool has been tested using climate simulation outputs from two GCMs (CanESM2 and CanRCM4) under five different climate scenarios and using available AMP data for durations ranging from 5 minutes to 1 day at two stations located in completely different climatic regions: Ottawa airport station (Canada) for the 1961-2000 period and Saipan International Airport (CNMI) for the 1979-2020. Results of this numerical application have indicated the feasibility and accuracy of the proposed modeling tool. More specifically, it was found that the AMP series in these stations displayed a simple scaling behaviour. Based on this scaling property, the scaling GEV distribution has been shown to be able to provide accurate estimates of sub-daily AM precipitations from GCM-downscaled daily AMP amounts. Therefore, it can be concluded that it is feasible to use the proposed integrated spatial-temporal downscaling tool to describe the relationship between large-scale climate predictors for daily scale given by GCM simulation outputs and the daily and sub-daily AMPs at a local site.

Finally, the proposed modelling tool was used to construct the IDF relations for a given site for the 1961-1990 period and for future periods (2020s, 2050s, and 2080s) using climate predictors given by two GCM models' simulations. The different changing patterns of IDF relations have demonstrated the presence of high uncertainty in climate simulations provided by different GCMs.

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