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ORIGINAL PAPER

Deriving short-duration rainfall IDF curves from a regional climate model

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Abstract Climate change is expected to exacerbate the extremes in the climate variables. Being prone to harsh climate impacts, it is very crucial to study extreme rainfall-induced flooding for short durations over regions that are rapidly growing. One way to study the extremes is by the application of the Intensity-Duration-Frequency (IDF) curves. The annual maximum rainfall intensity (AMRI) characteristics are often used to construct these IDF curves that are being used in several infrastructure designs for urban areas. Thus, there is a need to obtain high temporal and spatial resolution rainfall information. Many urban areas of developing countries lack long records of short-duration rainfall. The shortest duration obtained is normally at a daily scale/24 h. Thus, it is very crucial to find a methodology to construct IDF curves for short-duration rainfall (sub-daily) for these urban areas. Vietnam is a developing country with rapidly increasing population as well as urbanization. The fast extension of urban area that does not have adequate preparedness to cope with climate change is certainly a big risk to life and economy. The limitation in studying impacts over many regions of Vietnam is the need for robust and sufficient data, both spatial and temporal. To overcome this limitation, this paper describes constructing IDF curves using 6 hourly rainfall AMRI output from a regional climate model (RCM) that downscaled a global climate model (GCM) output at high spatial and temporal resolutions. The study region is Hanoi, the capital city of Vietnam. The sub-daily IDF curves for current and future climate for Hanoi were constructed from 1 to 24 h based on the simple scaling approach. The findings indicate that it is likely that Hanoi might experience more flooding conditions in the future with the AMRI increasing between 34 and 48% for all return periods from 10 to 200 years. The methodology adopted in this paper is suitable for

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similar ungauged areas elsewhere and will provide useful information in devising adequate planning strategies for drainage designs.

Keywords Flooding · IDF · Simple scaling · RCM · Climate change

1 Introduction

Rainfall intensities of different frequencies and durations are the fundamental inputs in hydrologic risk analyses and design. These data are normally used when designing urban infrastructures such as culverts and storm water drainage systems. The establishment of IDF relationships began in the 1930s (Sherman 1931; Bernard 1932) and ever since different forms and methods of IDF relationships have been constructed and published.

Precipitation extremes are expected to increase in intensity and frequency over many regions in the world due to global warming (Kharin et al. 2007; Lenderink and Van Meijgaard 2008). In urban areas, which are typically characterized by significantly higher population density, climate change is likely to exacerbate and compound existing vulnerabilities, especially for the urban poor (UN Habitat 2014). Therefore, there is a need to know the extent of increasing extreme rainfall for combating climate change impacts and for strategic planning. This study is one of the few to assess climate change impacts on short-duration maximum rainfall over urbanized areas in a developing country as that of Vietnam.

The general circulation models (GCMs), which are primary physically based tools that give information on current and future climates, provide reasonable climate simulations (when compared to observations) only in a global or a continental scale, but at a regional/subregional/city scale, such climate simulations are rather not good enough due to their coarse spatial resolutions (Giorgi 1990; Giorgi and Marinucci 1996a, b). Thus, there is a need to 'downscale' the GCM information to regional/subregional/city (urban) scales for applications in impact studies. Such downscaling is usually done by empirical or physical/dynamical methods. This paper applies results from a dynamical downscaling that employs a regional climate model (RCM) at high spatial resolution. Such downscaled data find applications in varied impacts studies. A similar hydrologic study, as this paper, has been done by Raghavan et al. (2012, 2014, 2015) and Vo et al. (2015).

There are several studies about climate impacts to extreme rainfall in urban areas. Rodrıguez et al. (2014) applied a statistical (empirical) downscaling approach to downscale GCMs and to quantify the influence of climate changes to intensity–duration–frequency for the metropolitan area of Barcelona (Spain). The authors concluded that the increase in the expected hourly rainfall resulted slightly higher than the corresponding daily rainfall. Ali et al. (2014) examined changes in extreme rainfall indices over 57 major urban areas in India under current and projected future climates using three regional climate model (RCM) data from CORDEX South Asia program. They reported that rainfall maxima at 1- to 3-day duration and 100-year return period were projected to increase significantly under future climate over a majority of urban areas in India. Gregersen et al. (2013) applied two RCMs from ENSEMBLES project (van der Linden and Mitchell 2009) to create the IDF curves for Denmark at sub-daily scales. Arnbjerg-Nielsen et al. (2013) performed a comprehensive review about the impacts of climate change on rainfall extremes and urban drainage systems, in which different methodologies of transferring information from

GCMs to local scale were discussed. Their objective was to construct the IDF curves for drainage system designs. One of our previous studies also dealt with constructing IDF curves under a changing climate for sites with scarce rainfall, and however, the duration was only limited to 6 hourly time steps (Liew et al. 2014a, b) while in this paper, we apply the simple scaling approach to extend the IDF curves from daily duration up to 1-h duration (on sub-daily durations). Subsequently, this methodology can be extended to construct the sub-daily IDF curves for any ungauged area.

In order to construct the IDF curve for short-duration rainfall in hourly scale, an hourly annual maximum rainfall intensity (AMRI) is required. However, as most of the GCM/RCM outputs are in daily or 6 hourly, the scaling invariance of rainfall is required to transfer daily rainfall to sub-daily/sub-6 hourly using simple scaling formulae. The concept of simple scaling was first initiated by Gupta and Waymire (1990) when they characterized the probabilistic structure of the precipitation process. Burlando and Rosso (1996) applied this simple scaling methodology for deriving depth–duration–frequency (DDF) curves for two stations in Italy using log-normal probability distribution functions. Nguyen et al. (1998, 2002, 2007) applied the generalized extreme value (GEV) parameters to estimate short-duration extreme rainfall distribution for partially gauged sites in Canada where data for longer time scales (1 day) were available. The authors noted that the rainfall statistical moments followed two different scaling regimes for duration of less than 1 h and duration from 1 h to 4 days. Menabde et al. (1999) applied a simple form of rainfall distribution called the extreme value type I (EVI—commonly called 'Gumbel' distribution) to derive the IDF relationship for short-duration maximum rainfall which was applied to 2 stations in Australia and South Africa. Since then, this simple scaling methodology using Gumbel distribution to derive sub-daily IDF curves has matured and has been applied widely (Yu et al. 2004; Nhat et al. 2007; Bara et al. 2009; Rodrıguez et al. 2014). It is to be noted that the any other extreme value distributions can be used instead of the Gumbel distribution to fit the maximum rainfall (for example, generalized extreme value distribution or log-Pearson type III), and however, comparisons of choosing different fitting functions is not within the scope of this study. We use the Gumbel distribution method in this paper.

This paper assesses the changes in extreme rainfall at sub-daily scales over Hanoi, the capital of Vietnam. We apply the 6 hourly rainfall results from a dynamical downscaling using the Weather Research and Forecasting (WRF) model and then extracting the data for Hanoi station. Two GCMs, CCSM3.0 and ECHAM5 T63 were downscaled for the baseline period 1961–1900 and a future climate period 2070–2099 using the A2 future climate emission scenario. Bias correction was applied to match the downscaled 24-h AMRI data to local station data at daily scales for the current climate period 1961–1990 using the quantile mapping approach (QMA) (Maurer and Hidalgo 2008; Cayan et al. 2008) fitted by Gumbel distribution functions. The future climate period 2070–2099 was bias corrected using the equidistance quantile mapping approach (E-QMA) as this method explicitly accounts for distribution changes for a given model between the future climate and its current climate. Detailed explanation can be found in Li et al. (2010). The sub-daily IDF curves from the downscaled rainfall information were constructed by using the simple scaling approach with Gumbel distribution, for duration of 24–1 h, for both current and future climates. The overall schematic diagram for the study is displayed in Fig. 1.

This study contributes significantly to areas where there is a limitation in obtaining short-duration rainfall information for any storm design project. Given the fact that AMRI follow Gumbel distribution—two parameters (location 'μ' and scale 'σ')—bias correction has been carried out using daily observation to match the RCMs output of 6, 12, 18 and 24 h using E-QMA with Gumbel distribution, similar method can be found in Srivastav

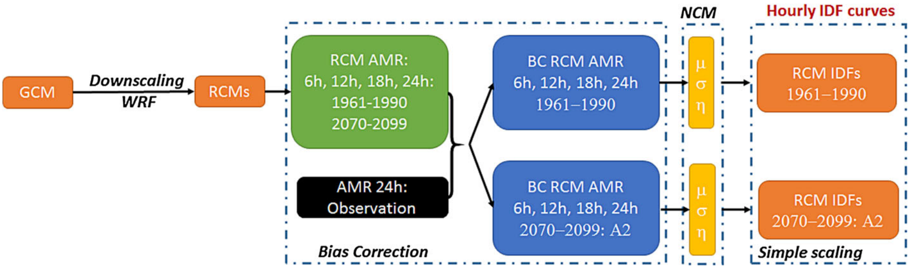

Fig. 1 Schematic diagram methodology

et al. (2014). As thus (μ and σ) have been generated at 24-h scale for different RCM outputs. The constant scaling exponent η which preserves the relationship between AMRI of 24-h data of up to 1-h data has been computed from bias-corrected RCM outputs. There have been several studies which applied the constant scaling exponent η from 48 h of up to 30 min (Bara et al. 2009; Menabde et al. 1999), and however, some recent studies suggested that the constant scaling exponent would change from 1-h duration to sub-hourly duration (Rodrıguez et al. 2014; Nhat et al. 2008). Therefore, in this study, we suggest to limit the constant scaling exponent η to 1-h duration. Consequently, this study is applicable to derive projection of sub-daily IDF curves based on available daily information data and global climate downscaled datasets.

2 Data and model

2.1 Station data

Hanoi is one of the two cities (Ho Chi Minh City, being the other) that have fastest population growth as well as urbanization in Vietnam. Industrialization is rapidly progressing in Hanoi and over the Red River Delta region due to its proximity to massive industrial bases in South China (Cities Alliance 2009). Therefore, the design structures for extended area and for industrial parks/zones surrounding this region require accurate information of future climate short-duration extreme rainfall. In addition, this design storm information is also useful for insurance/reinsurance companies such as Willis Re in the region in order to prepare for the factory insurance quotation. The daily data for Hanoi station were provided by the Vietnam Institute of Meteorology, Hydrology and Climate Change, Ministry of Natural Resources and Environment (MONRE), Vietnam, for the current climate period 1961–1990 to compute the AMRI at daily scales.

2.2 Weather Research and Forecasting model (WRF)

Developed at the National Center for Atmospheric Research (NCAR) in the USA, the WRF model is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. The model incorporates advanced numeric and data assimilation techniques, a multiple nesting capability and numerous state-of-the-art physics options and is a widely used regional climate model by the climate research community around the globe. Additional information can be obtained from http://www.wrf-model.org.

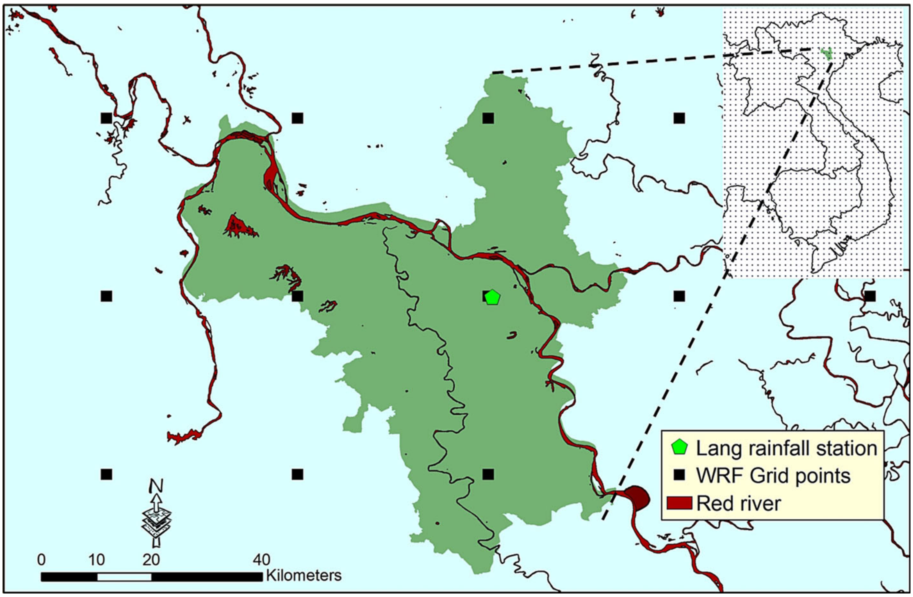

Fig. 2 Hanoi region and WRF grid points

The WRF model has been used in our previous studies: Raghavan et al. (2012, 2014, 2015), Liew et al. (2014a, b) and Vu et al. (2015a, b).

In this study, the WRF model (at a spatial resolution of 30 × 30 km) was initially driven by the reanalysis data ERA40 for the baseline (current climate) period 1961–1990 and subsequently driven by the GCMs CCSM3.0 and ECHAM5 T63 for both the baseline (1961–1990) and future climate (2070–2099), forced under the IPCC A2 future greenhouse gas emission scenario. For simplicity in reading, the simulations of the WRF model driven by the GCM CCSM3 and GCM ECHAM5 are referred to, in this paper, as WRF/CCSM and WRF/ECHAM, respectively. The 6 hourly rainfall output from the WRF model was bilinearly interpolated to Hanoi station point and was then used to calculate the AMRI for 6, 12, 18 and 24 h, for current and future climates. These AMRI were bias corrected (methods mentioned earlier) using daily station data from Hanoi. Figure 2 shows the map of Hanoi and the distribution of the climate model grid points over the study domain Indochina. As this paper does not deal with WRF model simulations exclusively and IDF curves being the focus, we suggest that Raghavan et al. (2015) be referred to, for details on WRF methods and other simulation details.

3 Methodology

3.1 Bias correction

Bias correction is usually undertaken using parametric and nonparametric approaches (Johnson and Sharma 2011). The former approach adjusts the mean and standard deviation of the model rainfall to match with observations (with the assumption that the distribution of the model rainfall is similar to the observations) while the latter matches the distribution of the model to the station data. The latter is preferred in many bias correction comparison studies (Teutschbein and Seibert 2012). Bias correction is normally applied for monthly data. However, this study applies the bias correction to the AMRI data using the Gumbel distribution function. Many previous studies have dealt with bias corrections for AMRI data using sub-daily or sub-hourly station data as a benchmark for temporal downscaling the RCMs (Mirhosseini et al. 2013; Srivastav et al. 2014; Rodrıguez et al. 2014). However, in this case, with station data available at daily scales, the RCMs with temporal resolution of 6 hourly is still useful to construct the IDF curves of up to 1 h with the assumption that the durations from 1 to 24 h belong to the same scale regime (Rodrıguez et al. 2014). Therefore, we propose the following nonparametric bias correction methodology for this study:

(1) Bias correction of daily data from RCM current climate to daily station data using QMA
(2) Bias correction of daily data from RCM future climate by E-QMA.

3.1.1 Bias correction of daily current climate using quantile mapping approach

The QMA has already been used for bias removal in climate models (Maurer and Hidalgo 2008; Cayan et al. 2008). This method maps the distribution of the climate data to the station data. This is simple, reliable and has been effectively used in hydrologic and other climate impact studies (Panofsky and Brier 1968; Ines and Hansen 2006; Maurer and Hidalgo 2008; Teutschbein and Seibert 2012). We apply this approach to bias correct the current (baseline) climate precipitation.

Given a precipitation time series x, the method is formulated as:

$$\widetilde{x}_{\mathrm{mc}} = F_{\mathrm{oc}}^{-1}[F_{\mathrm{mc}}(x_{\mathrm{mc}})] \tag{1}$$

In which: $\widetilde{x}$ is the bias-corrected precipitation. F is the fitting function (in this case: Gumbel distribution) and F^{-1} is inverse of fitting function. 'o' and 'm' stand for 'observed' and 'modeled' with the 'c' is 'current' climate.

3.1.2 Bias correction of future climate using equidistance quantile mapping approach

Despite its usefulness, the QMA may not hold good for projecting future climate as it assumes stationarity and only to correct the CDF between model baseline and observation (Li et al. 2010). These authors proposed the equidistant cumulative distribution function (ECDF) matching method which took into account the difference between models and observations in current climate, hence incorporate and adjust the projection of climate models as compared to the baseline. Similar studies for IDF for future climate have also utilized this method (Srivastav et al. 2014; Mirhosseini et al. 2013).

The following formula, adapted from Li et al. (2010):

$$\widetilde{x}_{\mathrm{mp}} = x_{\mathrm{mp}} + F_{\mathrm{oc}}^{-1}\left[F_{\mathrm{mp}}\left(x_{\mathrm{mp}}\right)\right] - F_{\mathrm{mc}}^{-1}\left[F_{\mathrm{mp}}\left(x_{\mathrm{mp}}\right)\right] \tag{2}$$

in which 'p' stands for 'projected,' the rest, as explained before.

3.2 Simple scaling for deriving IDF curves

As described above, this study considers that the distribution of extreme value type I (Gumbel distribution) is suitable for the AMRI over Hanoi station. The scaling function of Gumbel distribution is:

$$F_d(i) = \exp\left[-\exp\left(-\frac{i-\mu_d}{\sigma_d}\right)\right] \tag{3}$$

With μ_d and σ_d are location and scale parameters of AMRI at sub-daily duration '*d*' (h) which can be scaled to daily (24 h) using equations:

$$\begin{aligned} \mu_d &= (d/24)^{-\eta}\mu_{24} \\ \sigma_d &= (d/24)^{-\eta}\sigma_{24} \end{aligned} \tag{4}$$

where η is the scaling exponent obtained from the linear slope of the non-center moment (NCM) of order q. Note that if η is not a linear function of NCM of order q then the process is called 'multi-scaling' (Gupta and Waymire 1990).

The final formula to calculate the intensity as a function of duration and return period derived from Gumbel distribution is shown in Eq. (5) (Menabde et al. 1999):

$$i(d,T) = \frac{\mu - \sigma\log\{-\log(1-1/T)\}}{d^{\eta}} \tag{5}$$

where i rainfall intensity (mm/h), d duration (h), T return period (year) which have three parameters μ, σ, η.

From Eq. (5), the short-duration (hourly) extreme rainfall intensity for a certain return period can be calculated from daily rainfall with known μ_d, σ_d and the scaling exponent, η. From previous studies (Menabde et al. 1999; Nguyen et al. 1998, 2002, 2007; Nhat et al. 2007; Bara et al. 2009; Rodrıguez et al. 2014), the constant scaling exponent η was determined for duration from 1 h to 4 days for different stations in different climate zones. Therefore, in this study, the exponent η and the statistic value of 24-h data (μ, σ) were used to construct the IDF curves of 24 h up to 1 h. η was calculated based on the NCM of order q of current climate RCM data from four sub-daily data (6, 12, 18 and 24 h). Arising from the limitation of available data only at daily value, no bias correction was performed for sub-daily data. Therefore, in this paper, we assume that the scaling exponent η derived from non-bias-corrected RCM data is similar to one with bias correction. The location and scale parameters μ_d and σ_d were calculated from the bias-corrected RCMs at daily scales, for current and future climates. Later, the IDF curves for current and future climates were constructed for hourly duration from 1 to 24 h using Gumbel distribution function.

The 1-h duration extreme rainfall intensity was calculated for different return periods. The relative anomaly Δ (climate change 'delta' factor for rainfall) was calculated from RCM projected future and RCM current climate, at 1-h duration using the following equation:

$$\Delta = \frac{I_{\mathrm{P}} - I_{\mathrm{C}}}{I_{\mathrm{C}}} \times 100\% \tag{6}$$

in which I is extreme rainfall intensity at 1-h duration (mm/h) and denote 'P,' 'C' are 'projection' and 'current' climate.

4 Results and discussions

4.1 Bias correction

The bias corrections at daily scale for both model realizations, WRF/ECHAM and WRF/CCSM, are shown in Fig. 3. The empirical points are displayed as markers while the fitting curves are drawn as lines: continuous (before bias correction) and dashed (after bias

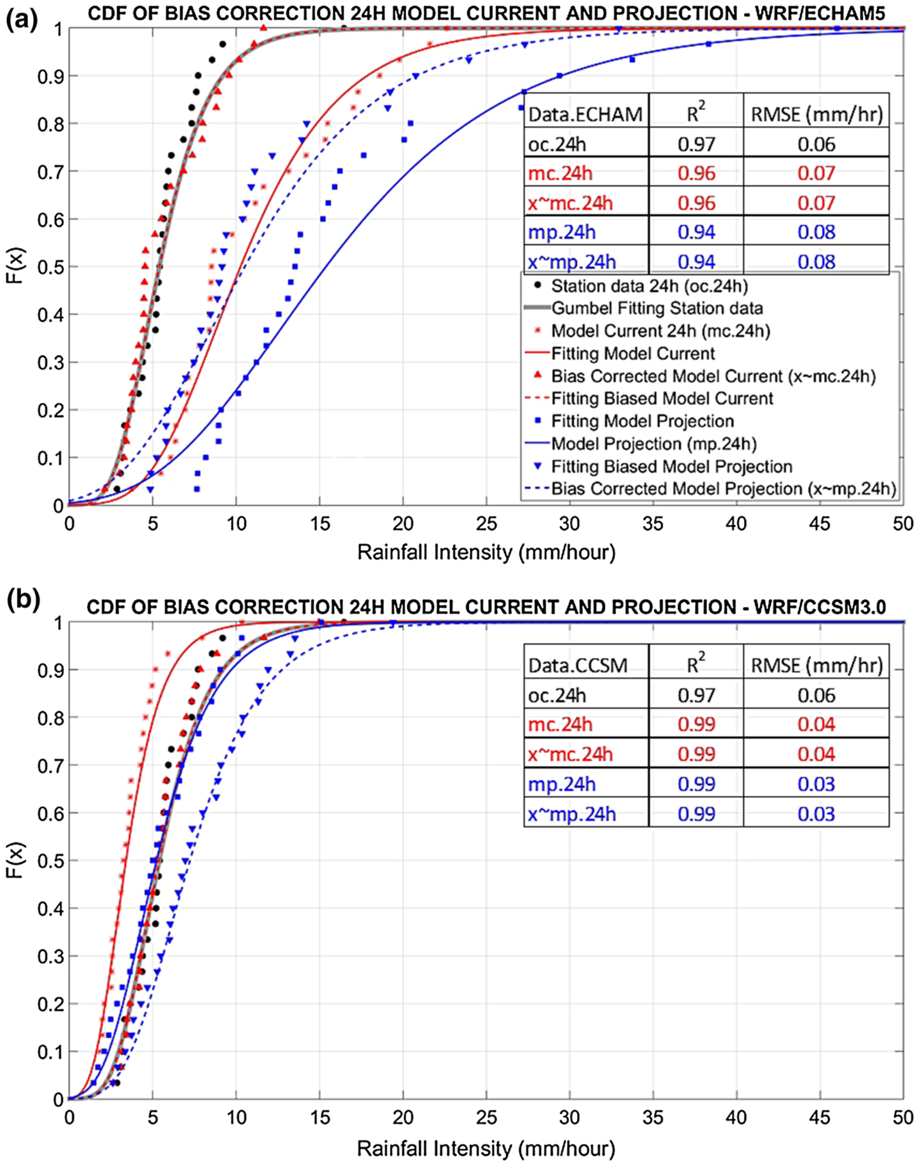

Fig. 3 Bias correction of daily AMRI for Hanoi station, current and future climate **a** WRF/ECHAM, **b** WRF/CCSM

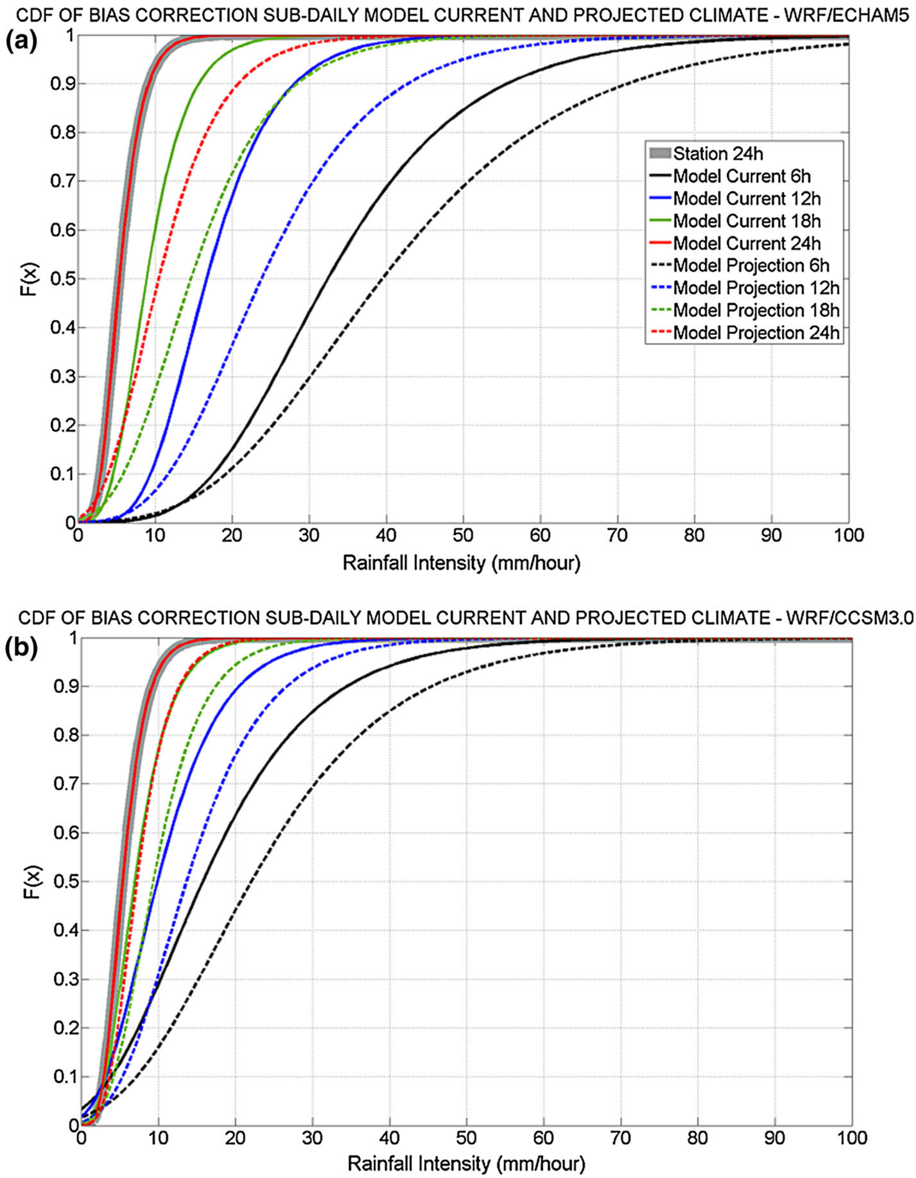

Fig. 4 Bias correction of short duration AMRI for Hanoi station, current and future climate **a** WRF/ECHAM, **b** WRF/CCSM

corrections); red (baseline/current climate) and blue (projection). The bias correction approach brings the RCM's current climate value (red dashed line) to the same distribution and location as that of the station data (thick gray line), as shown in both plots in Fig. 3. It can be seen that the WRF/ECHAM (Fig. 3a) overestimated the current climate rainfall while WRF/CCSM (Fig. 3b) underestimated it. The QMA shifted the current (red continuous line) WRF/ECHAM to the left and WRF/CCSM to the right of the distribution

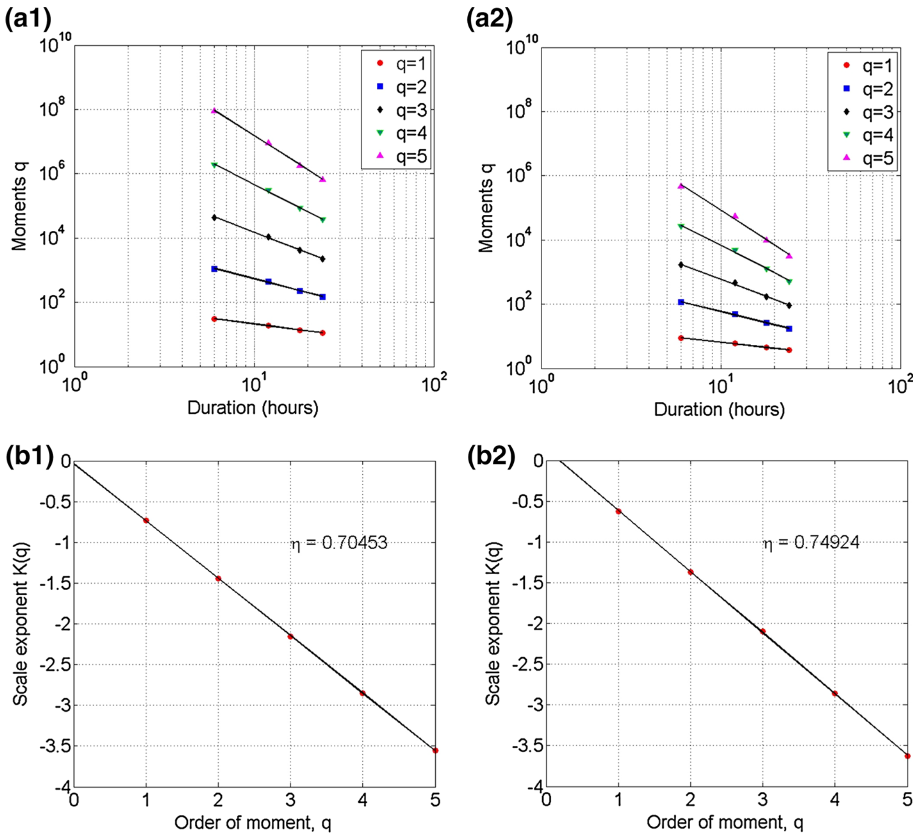

Fig. 5 **a** Statistical moments for different values of moment q of the AMRI Hanoi, **b** linear regression between order q of the moments and the scaling exponent η; (1) WRF/ECHAM; (2) WRF/CCSM—current climate

curves to match with the station data. The change in the distribution of the future rainfall (blue lines) can also be seen from these figures. The tables associated in Fig. 3a, b are the goodness of fits (R^2 and RMSE) between empirical points and model fitting using Gumbel distribution. These values show very good agreement between the fitted model and empirical points. From the distributions of the current and future climates, it is shown in Fig. 3 that the future climate is likely to witness a higher AMRI at daily scales than the baseline climate, for both model realizations.

The detailed bias-corrected AMRI for both downscaled models for other duration: 6, 12, 18 h are displayed in Fig. 4a, b for WRF/ECHAM and WRF/CCSM, respectively. Fitting curves represented as continuous lines denote current climate (1961–1990) and dashed lines, for projections, A2 scenario (2070–2099). Figure 4 clearly shows that the projected AMRI increases in rainfall intensity for all durations, for both downscaled climate models.

4.2 Simple scaling

As described in Sect. 3.1, once the 24-h location and scale (μ, σ) parameters with the scaling exponent η are known, the IDF curve can be constructed for a certain return period

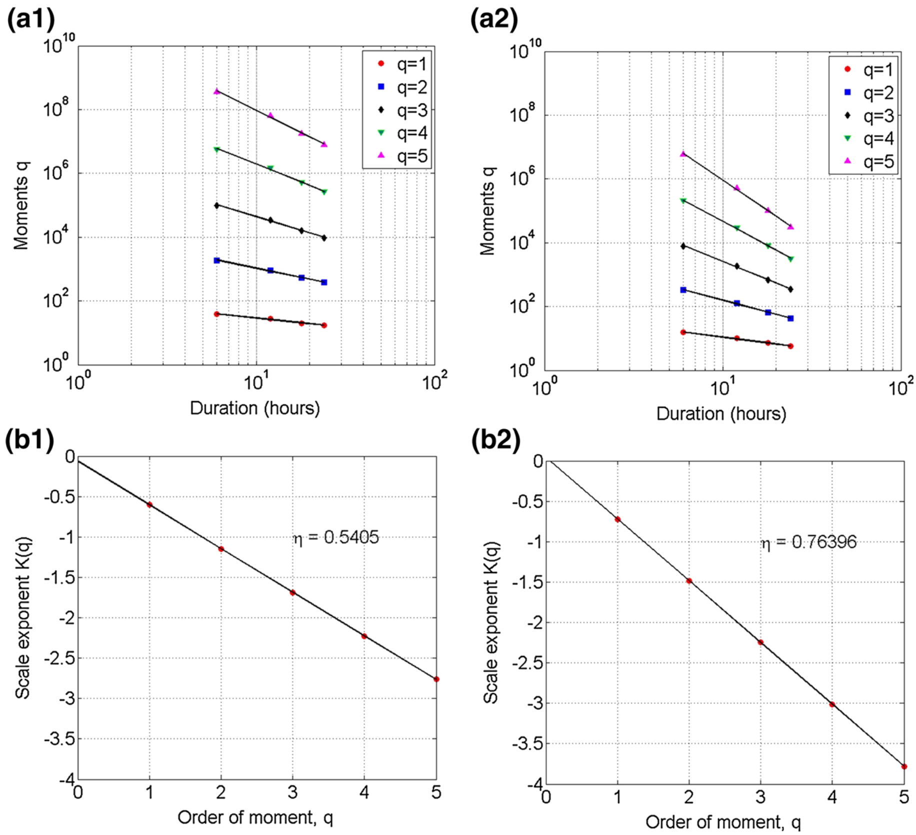

Fig. 6 **a** Statistical moments for different value of moment q of the AMRI Hanoi, **b** linear regression between order q of the moments and the scaling exponent η; (1) WRF/ECHAM; (2) WRF/CCSM—future climate

Table 1 Location, scaling parameters and scaling exponents of RCMs for different periods

Period	Datasets	μ	σ	η
1961–1990	WRF/ECHAM	4.65	2.02	0.70
	WRF/CCSM	4.65	2.02	0.75
2070–2099	WRF/ECHAM	8.51	5.48	0.54
	WRF/CCSM	6.15	2.94	0.76

for sub-daily durations. Therefore, the η was first calculated based on the NCM approach with order q using 6, 12, 18 and 24 h AMRI datasets from the WRF/ECHAM and WRF/CCSM outputs. Figure 5a1, b1 represent the statistical moments q of these two model realizations and it shows a good scaling for the 4 sub-daily durations. The corresponding scaling exponents η were then calculated based on the linear slope of the moments order q from Fig. 5a2, b2. The line that connects the order of moments q is linear as shown in Fig. 5a2, b2 that conforms to the simple scaling methodology by Gupta and Waymire (1990).

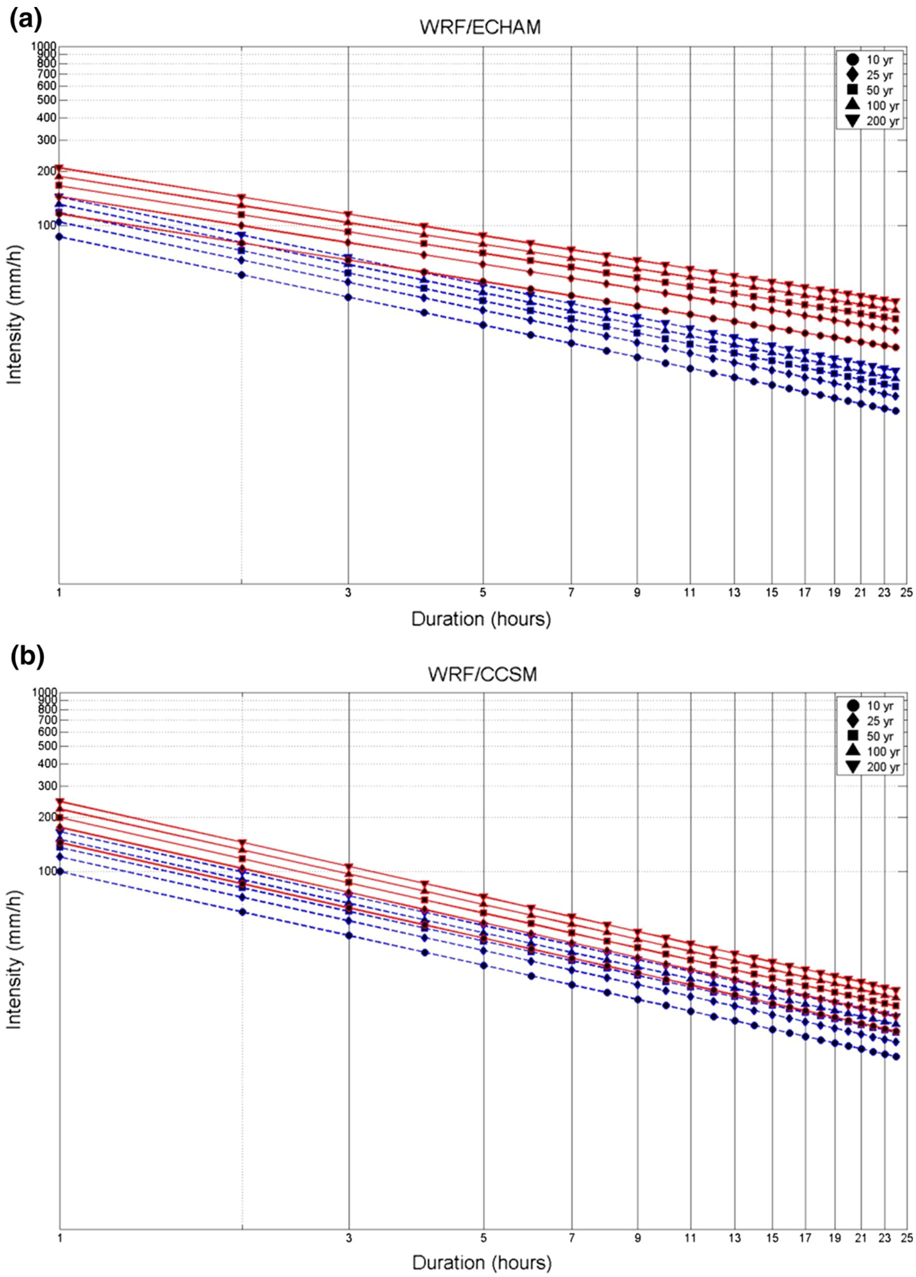

Fig. 7 IDF curves estimated for the period 1961–1990 (*blue dashed line*) and 2070–2099 scenario A2 (*red continuous line*) considering scaling invariance of rainfall **a** WRF/ECHAM, **b** WRF/CCSM

The scaling exponents η calculated for the future climate are shown in Fig. 6. The location, scale parameter and scaling exponent μ, σ, η for WRF/ECHAM and WRF/CCSM under current 1961–1990 and future climate 2070–2099, scenario A2 are tabulated in Table 1.

Table 2 One-hour duration extreme rainfall intensity for different return periods under current and future climate for Hanoi

Period	Datasets	Return period (years)				
		10	25	50	100	200
1961–1990	WRF/ECHAM	86.4	104.4	117.7	131.0	144.2
	WRF/CCSM	99.5	120.3	135.7	151.0	166.2
2070–2099 A2	WRF/ECHAM	116.1	145.0	166.5	187.8	209.0
	WRF/CCSM	144.5	176.1	199.5	222.7	245.9
Δ (%)	WRF/ECHAM	34.4	39.0	41.4	43.4	45.0
	WRF/CCSM	45.2	46.4	47.0	47.5	48.0

4.3 Construction of the IDF curves

Based on the data calculated in Table 1, the IDF curves for current and future climates were derived using Gumbel distribution functions for five return periods (10, 25, 50, 100 and 200 years), hourly duration from 1 to 24 h and is displayed in Fig. 7. The different markers represent different return periods. The dash lines display the current climate 1961–1990 and the continuous lines represent the future climate 2070–2099, scenario A2. From Fig. 7, the future climate shows increasing rainfall intensities at all durations and over all return periods, for both model realizations. The information from Fig. 7 has been translated to values in Table 2 for detailed analysis on 1-h duration extreme rainfall intensity with different return periods using Eq. (6).

From these results, it can be seen that it is likely that by the end of the 21st century, the extreme rainfall for 1-h duration would increase by 34% for the 10-year return period to 45% for the 200-year return period as simulated by WRF/ECHAM. A higher increasing rate for WRF/CCSM is likely at 45.2% for the 10-year return period and 48% for the 200-year return period.

5 Conclusions

A new methodology was proposed to construct the sub-daily rainfall IDF curves for current and future climate for data sparse area using daily station data and 6 hourly RCMs data. The methodology utilized the existing state-of-the-art simple scaling method, with Gumbel distribution functions. The bias correction was performed at daily scales using the QMA for the current climate and using the equidistance quantile mapping for the future climate. The sub-daily rainfall IDF curves were constructed based on the information from the location and scaling variables taken from the daily data and the scaling exponent from the RCM results. The constructed IDF curves for the current and future climates for Hanoi show that there is an increase in short-duration extreme rainfall in the future. The 1-h duration maximum rainfall intensity for future climate shows an increasing rate of 34–48% for all return periods (10, 25, 50, 100 and 200 year) using the two downscaled WRF model realizations, by the end of twenty-first century, scenario A2. This could be taken as initial studies in a cascade of more work to come in this topic. Possible use of a larger number of model realizations from the latest climate scenarios and using more models to this study would improve the confidence in the findings. As such, the findings could be of use to policy makers in their preliminary consideration of strategies for adaptation.

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