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Downscaling approach to develop future sub-daily IDF relations for Canberra Airport Region, Australia

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Abstract. Downscaling of climate projections is the most adopted method to assess the impacts of climate change at regional and local scale. In the last decade, downscaling techniques which provide reasonable improvement to resolution of General Circulation Models' (GCMs) output are developed in notable manner. Most of these techniques are limited to spatial downscaling of GCMs' output and still there is a high demand to develop temporal downscaling approaches. As the main objective of this study, combined approach of spatial and temporal downscaling is developed to improve the resolution of rainfall predicted by GCMs. Canberra airport region is subjected to this study and the applicability of proposed downscaling approach is evaluated for Sydney, Melbourne, Brisbane, Adelaide, Perth and Darwin regions. Statistical Downscaling Model (SDSM) is used to spatial downscaling and numerical model based on scaling invariant concept is used to temporal downscaling of rainfalls. National Centre of Environmental Prediction (NCEP) data is used in SDSM model calibration and validation. Regression based bias correction function is used to improve the accuracy of downscaled annual maximum rainfalls using HadCM3-A2. By analysing the non-central moments of observed rainfalls, single time regime (from 30 min to 24 h) is identified which exist scaling behaviour and it is used to estimate the sub daily extreme rainfall depths from daily downscaled rainfalls. Finally, as the major output of this study, Intensity Duration Frequency (IDF) relations are developed for the future periods of 2020s, 2050s and 2080s in the context of climate change.

1 Introduction

Quantifying of the design storm magnitude is one of challenging steps of urban hydrology study. Once the impact of climate change need to be considered for sensitive hydrological studies, it becomes very complicated more than previous. Intensity Duration Frequency (IDF) curve is one of popular methods among the water engineers/hydrologists in estimating the magnitude of design storms. However these IDF curves do not represent the impact of climate change as it has been developed decades ago using historical rainfall records. In Australia, existing IDF relations have been developed by the Australian Bureau of Meteorology (BoM) are also based on past rainfall records, and impacts of climate change has not been taken into account in the IDF development. However urban development in most of Australian states need to evaluate the impacts of climate change on urban hydrologic processes. Consequently, there is a great need to develop IDF curves under climate change scenarios to facilitate future catchment investigations.

GCMs can be recognized as the one of the best way to predict main features of basic climate parameters for future periods. However, GCMs are not capable to generate high resolution climate parameters, which are required for high sensitive urban hydrology studies. According to the recent literature, spatial and temporal scale ranges vary in a wide range in the present GCMs and Regional Climate Models (RCMs) (Willems and Vrac, 2011). Therefore GCMs' outputs should be downscaled in spatially and temporally relevance to urban hydrological studies (Nguyen et al., 2006). Downscaling methods, as reviewed by Wilby et al. (2004) could be divided into four general categories namely regression meth-

Table 1. Details of study location.

State	BoM Rain gauge station	Cordinates
New south wales	Sydney observatory hill (066062)	33.86° S, 151.21° E
Victoria	Melbourne airport (086282)	37.67° S, 144.83° E
Western Australia	Perth airport (009021)	31.94° S, 115.96° E
Northern Territory	Darwin airport (014015)	12.42° S, 130.89° E
South Australia	Adelaide airport (23034)	34.95° S, 138.52° E
Queensland	Brisbane regional (040214)	27.48° S, 153.03° E
Australian Capital territory	Canberra airport comparison (070014)	35.30° S, 149.20° E

ods, weather pattern approaches, stochastic weather generators (these three types come under statiscal downscaling) and limited-area Regional Climate Models (Dynamic downscaling). Statistical Downscaling Model (SDSM) proposed by Wilby et al. (2002) can be identified as regression and stochastic weather generator based statistical downscaling tool to downscale point rainfall using GCMs' variables. By considering high capability of SDSM, it has been used in this study to downscale daily rainfalls using HadCM3-A2 scenario for future periods.

Temporal downscaling of spatially downscaled rainfalls is equally important in hydrological assessments, especially for small urban watersheds. In particular, the development of the IDF relations for sub-daily extreme/Annual Maximum (AM) rainfalls is required for planning and design of urban drainage systems. In the existing literature there are only few approaches that have addressed the temporal downscaling of future rainfalls (Nguyen et al., 2009; Willems et al., 2012).

Therefore, the main objective of this study is to develop a combined approach of spatial and temporal downscaling to estimate the depth of sub daily extreme rainfalls for future periods. Further study aims to develop IDF curves to assist hydrologists in estimating design storms which are taking the potential future climate change into account. The results of the study will be helpful in the assessment of the climate change impacts on urban water resources which need fine spatial resolution and sub daily temporal rainfall data.

2 Study area and data sets

Seven rain gauge stations in seven states in Australia are subjected to this study. By considering the urbanization of the area, availability and quality of observed rainfalls data; Melbourne, Adelaide, Canberra, Perth, Darwin airport rain gauge stations, Sydney observatory hill and Brisbane regional rain gauge station are selected for this study. Observed 6 min rainfall data for 1961–2000 period (full detail of seven stations are included in Table 1) are obtained from Bureau of Meteorology, Australia. In addition to observed data, normalized Hadley Centre's GCM (HadCM3) under A2 emission scenarios data for 1961–2099 period and NCEP reanalysed interpolated data corresponding to HadCM3 computational grid for

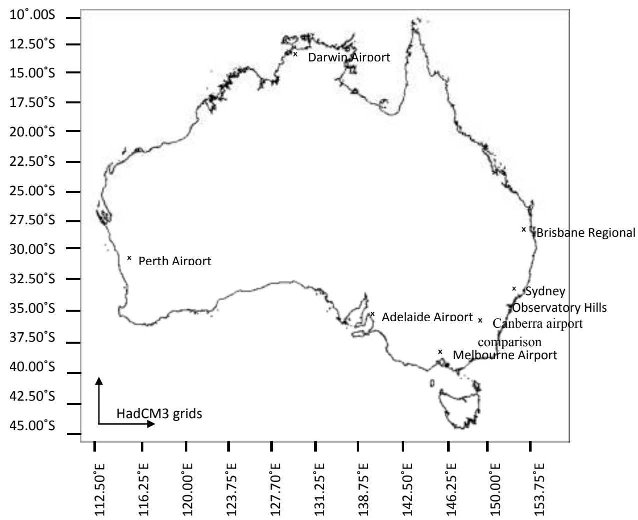


Figure 1. Location map of study area.

1961–2000 period are used in this study. Map of the study area including HadCM3 computational grid are presented in Fig. 1.

3 Methodology

The methodology of downscaling sub daily point rainfalls, based on GCM data, has been divided into two separate steps; spatial downscaling and temporal downscaling. By spatial downscaling process, it is possible to describe the linkage between the low resolute climate predictors given by GCMs and the rainfall characteristics at a given local site using the SDSM method. The temporal resolution of the SDSM model output is limited to one day. Hence, the SDSM outputs need to be subjected to a temporal downscaling to obtain the sub-daily rainfall extremes which are required for the development of the IDF relations. There are many evidences in literature to show the suitability of Generalized Extreme Value (GEV) distribution to model the extreme rainfall events (Nguyen et al., 1998; Overeem et al., 2006). In the present study the temporal downscaling approach developed by Nguyen et al. (2002) using the GEV distribution is employed to estimate the sub-daily rainfall extremes to develop IDF relations.

3.1 Spatial downscaling

SDSM tool is a combination of the stochastic weather generator approach and a transfer function model with high performance in capturing future inter-annual variability (Wilby et al., 2002). Data requirement for the SDSM tool includes two aspects; local predictands of interest, such as daily rainfall, daily minimum temperature, daily maximum temperature and the GCM/NCEP predictors with low resolution. To select the predictors, SDSM facilitates to screen the predictor – predictand correlation through linear correlation analysis by percentage of explained variance (E %), correlation matrix and scatter plots. Predictor – predictand correlations in rainfall downscaling show low values compare to the correlation in temperature downscaling (Wilby et al., 2002).

3.2 Bias correction of SDSM annual maximum rainfalls

In most of the rainfall modelling in the context of climate change, bias corrections are required to obtain accurate results. In this study regression based bias correction technique is used to improve the accuracy of annual maximum rainfall of spatially downscaled SDSM rainfall data series. Equations (1) and (2) describe the bias correction approach which is employed in this study.

$$P_\tau = P_{o\tau} + e_\tau \tag{1}$$

in which P_τ denotes the adjusted daily annual maximum rainfall at a probability level T, $P_{0\tau}$ denotes the corresponding GCM–SDSM estimated annual maximum daily rainfall and e_τ denotes the residual associated with $P_{0\tau}$. Then, e_τ is estimated using the second order regression function as follows.

$$e_\tau = a \cdot P_{0\tau}^2 + b \cdot P_{0\tau} + c + e \tag{2}$$

in which a, b, and c are the parameters of the regression function, and e is the resulting error term.

3.3 Temporal downscaling

GEV distribution is used to model annual maximum rainfall in this study and cumulative distribution function $F(x)$ for the GEV distribution is given as

$$F(x) = \exp\left[-\{1-\{\kappa(x-\xi)/\alpha\}\}^{\frac{1}{\kappa}}\right]. \tag{3}$$

For $\kappa \neq 0$, where ξ, α and κ are known as the GEV parameters for location, scale and shape, respectively. The Non Central Moment (NCM) method is used in this study as it is the most appropriate method to use with the scale invariance concept (Nguyen et al., 1998, 2002, 2009) to estimate the GEV parameters in scaling studies. More specifically, the kth order NCM, (μ_k) of the GEV distribution (for $\kappa \neq 0$) has been readily shown that

$$\mu_k = \left(\xi + \frac{\alpha}{\kappa}\right)^k + (-1)^k \left(\frac{\alpha}{\kappa}\right)^k \Gamma(1+\kappa k) + k\sum_{i=1}^{k-1}(-1)^i \left(\frac{\alpha}{\kappa}\right)^i \left(\xi + \frac{\alpha}{\kappa}\right)^{k-1} \Gamma(1+i\kappa) \tag{4}$$

where $\Gamma(.)$ is the gamma function. Using Eq. (4), it is possible to derive three equations for first three NCM to estimate the parameters of GEV distribution. Further, the quantiles, X_t has been readily defined as the

$$X_t = \xi + \frac{\alpha}{\kappa}\{1-[-\ln(p)]^\kappa\} \tag{5}$$

where, $p = 1/T$ is the exceedance probability of interest.

Further, it has been shown (Nguyen et al., 1998, 2002, 2009) that the statistical properties of the GEV distributions for two different time scales of "t" and "λt" according to simple scaling process as,

$$\kappa(\lambda t) = \kappa(t) \tag{6}$$

$$\alpha(\lambda t) = \lambda^\beta \alpha(t) \tag{7}$$

$$\xi(\lambda t) = \lambda^\beta \xi(t) \tag{8}$$

$$X_\tau(\lambda t) = \lambda^\beta X_\tau(t) \tag{9}$$

$$\lambda^\beta = \mu_1/\mu_2 \tag{10}$$

where $\mu_1$and μ_2 are the first NCMs of annual maximum rainfall for λt and t periods respectively. Based on these relationships, statistical properties of shorter period (sub daily) of rainfall are derived. Then, statistical properties of sub daily rainfalls are utilized to develop IDF curves for sub daily events in this study.

4 Numerical application

Herein after, proposed methodology is illustrated by worked example of Canberra Airport Comparison rain gauge station. In Sect. 4.5, it proves the applicability of proposed methodology for all other main cities as well.

4.1 Calibration and validation of the SDSM model

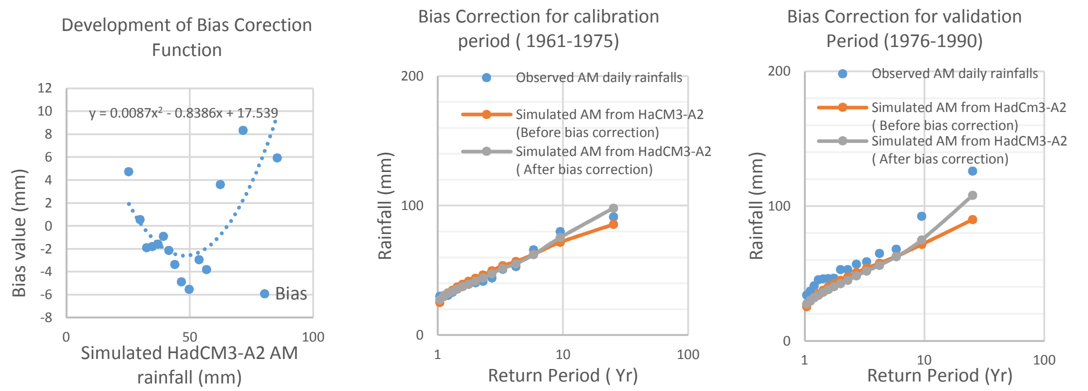
Interpolated NCEP reanalysis data on HadCM3 grids is used to downscaling SDSM model calibration and validation. NCEP data consist with 26 climate variables as presented in Table 2.

SDSM daily rainfall spatial downscaling using HadCM3-A2 can be demonstrated by following basic steps.

- Step 1: screening the NCEP climate variables to identify most potential climate variables in daily rainfall generating. Scatter plot, correlation matrix and explained

Table 2. NCEP reanalysis climate variable for HadCM3.

No	Predictor name	Notation	No	Predictor name	Notation
1	Surface airflow strength	p_f	14	850 hPa zonal velocity	p8_u
2	Surface zonal velocity	p_u	15	850 hPa meridional velocity	p8_v
3	Surface meridional velocity	p_v	16	850 hPa velocity	p8_z
4	Surface velocity	p_z	17	850h Pa wind direction	p8th
5	Surface wind direction	p_th	18	850 hPa divergence	p8zh
6	Surface divergence	p_zh	19	500 hPa relative humidity	r500
7	500 hPa airflow strength	p5-f	20	850 hPa relative humidity	r850
8	500 hPa zonal velocity	p5_u	21	500 hPa geopotential height	P500
9	500 hPa meridional velocity	p5_v	22	850 hPa geopotential height	P850
10	500 hPa velocity	p5_z	23	Surface relative humidity	rhum
11	500 hPa wind direction	p5th	24	Surface specific humidity	shum
12	500 hPa divergence	p5zh	25	Mean temperature at 2 m height	temp
13	850 hPa airflow strength	p8-f	26	Mean sea level pressure	mslp



(a) (b) (c)

Figure 2. Illustration of proposed bias correction by applying to Canberra airport comparison rain gauge station. **(a)** Development of bias correction for calibration period of 1961–1975, **(b)** assessing of proposed bias correction for calibration period (1961–1975) and **(c)** assessing of proposed bias correction for validation period (1976–1990).

variance calculations are available in SDSM to assess this predictor (NCEP climate variables) predictand (daily observed rainfall) correlations.

– Step 2: SDSM model calibration is carried out under this step using selected predictors in Step 1. In this study SDSM model is calibrated in monthly basis for the rain gauge station. (It provides individual correlation index for each month.) By considering the skewness of daily rainfall, SDSM model is calibrated as forth root conditional model (Wilby et al., 2002). Further threshold value of wet day is taken as 0.3 mm day^{-1}.

– Step 3: calibrated and validated model is used to simulate daily rainfall using GCM scenarios. In this step, NCEP predictors which are used to SDSM calibration and validation are replaced by HadCM3-A2 climate predictors for 1961–2099 period. Here, model regenerate point daily rainfall (100 ensembles) based on the correlation of daily rainfall and climate variables established in calibration steps.

4.2 Bias correction

Even though the SDSM model is capable in simulating spatially downscaled daily rainfalls, these simulated rainfalls should be subjected to a bias correction. According to proposed bias correction procedure, regression relationship has been developed between simulated annual maximum daily rainfalls by HadCM3-A2 and their bias with observed annual maximum daily rainfall for the calibration period (Fig. 2a). Figure 2a describes the second order regression function which is fitted to bias which are associated with HadCM3-A2 simulated values. According to Fig. 2b, observed annual maximum daily rainfalls at T_r return periods show good agreement with bias corrected downscaled annual maximum rainfalls. Therefore Fig. 2b verifies the suitability of second

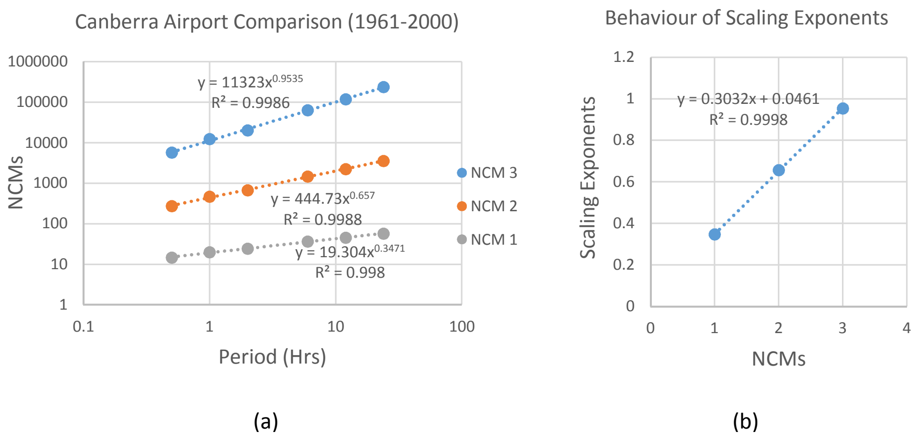


Figure 3. Assessing of behaviour of Non Central Moments of Canberra airport comparison rain gauge stations. **(a)** Log-Log plot of observed rainfalls and **(b)** behaviour of scaling exponent of first three NCMs.

order regression function for bias correction of SDSM simulated annual maximum rainfalls of calibration period. To verify the accuracy of proposed bias correction approach, same bias correction function that is developed for the calibration period is applied to the validation period data. Figure 2c presents the probability plot of annual maximum daily observed rainfalls and simulated from HadCM3-A2 for the validation (1976–1990) period. Moreover, Fig. 2 confirms the suitability of proposed second order bias correction functions in rectifying the associated bias with SDSM's estimations for the validation period. Therefore developed bias correction function is utilized to improve the accuracy of simulated annual maximum daily rainfall by HadCM3-A2 for the future periods as well.

4.3 Assessing the scaling behaviour of observed annual maximum rainfalls

As the compulsory requirement of the temporal downscaling approach which is based on scaling concept, scaling behaviour of the observed annual maximum rainfall series is assessed. Figure 3a presents the log–log plot of first three non-central moments of observed annual maximum rainfalls against rainfall durations of Canberra airport rain gauge station. According to Fig. 3a, power law dependency of rainfall statistical moments with duration is observed and it is identified in one time interval (30 min to 24 h). Furthermore, behaviour of scaling exponent (λ^{β}) of the first three non-central moments of observed annual maximum data is assessed and it is included in Fig. 3b. These figures depict the linearity of scaling exponent with the moment order. These linear relationships verify the applicability of the scaling model to describe extreme sub daily rainfall events using available daily extreme rainfall.

4.4 Assessing future rainfall trends and IDF relations

Then, above verified scaling concept is applied to obtain the statistical properties of GEV distributions which describe the sub-daily annual maximum rainfalls, using statistical properties of GEV distribution which is fitted to the observed daily annual maximum rainfalls. Figure 4a illustrates the capability of the proposed scaling model to reproduce sub daily annual maximum rainfall series. According to Fig. 4a, 30 min annual maximum rainfall estimated by scaling HadCM3-A2 estimation (bias corrected) and scaling by traditional fitted to observed series show the high accuracy of scaling method in sub daily rainfall estimation. Therefore it confirms the accuracy of proposed spatial and temporal downscaling approach to estimate the sub daily annual maximum extreme rainfalls. To evaluate the trend of daily and sub daily annual maximum rainfall for the future periods, same approach is applied to the bias corrected annual maximum future daily rainfall series which are simulated by HadCM3-A2. Figure 4b shows the probability plots of 1 h annual maximum rainfalls estimated from the bias corrected downscaled annual maximum daily rainfalls using the HadCM3-A2. By considering the 1961–1990 period as the standard reference period, 2050s intensities show significant high values. Further, even 2020s intensities up to 5 year return period shows higher values than 1961–1990 intensities. Therefore, it confirms the importance of assessing climate change impacts for future hydrological studies.

Finally, the IDF relations are developed for Canberra airport stations for current and future periods using the estimated sub-daily extreme rainfalls given by the proposed spatial-temporal downscaling approach. For the illustrating purposes, Fig. 5 represents the developed IDF curves for the future periods of 1961–1990, 2020s (2011–2040), 2050s (2041–2070) and 2080s (1971–2099) using downscaled rainfall HadCM3-A2 scenario. These results will be

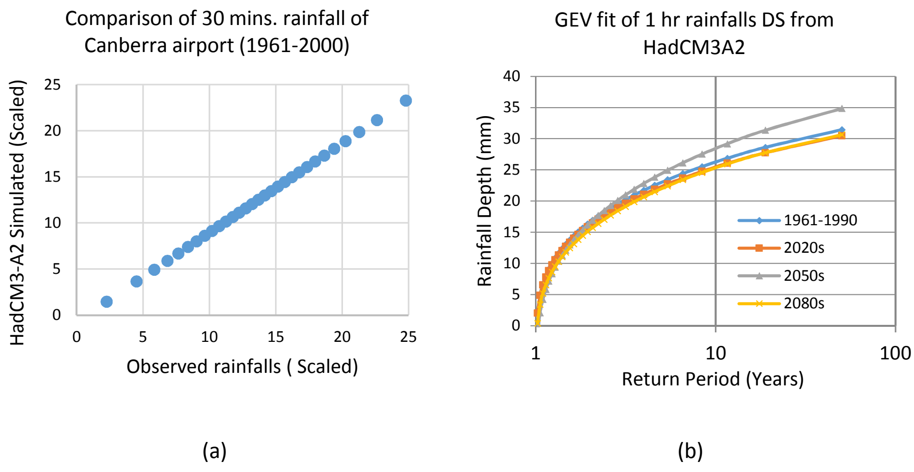


Figure 4. Evaluation of sub daily rainfalls. **(a)** Comparison 30 min AM rainfalls (scaling of observed AM daily rainfalls and scaling of AM daily rainfall by HadCM3-A2) and **(b)** probability plots of 1-hour annual maximum rainfalls estimated from scaling daily annual maximum rainfalls from HadCM3-A2 scenario.

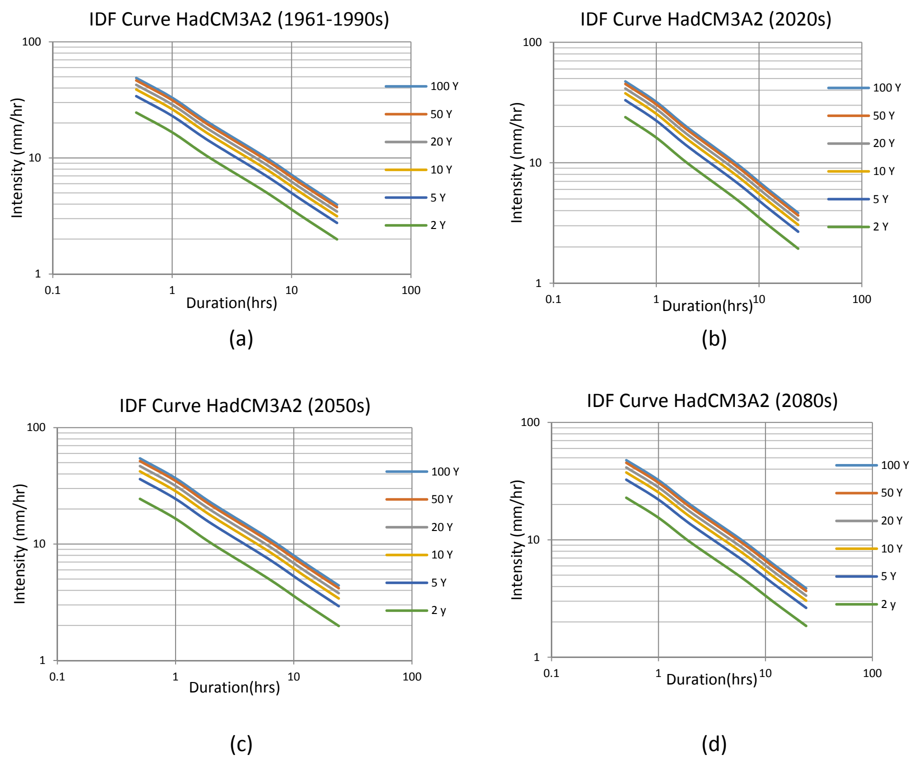


Figure 5. Developed IDF curves for Canberra Airport Comparison.

useful for water resources engineers in considering future climate change impact on future hydrological assessment.

4.5 Applicability of proposed downscaling approach for other locations

Numerical worked example of Canberra airport rain gauge station clearly confirms the accuracy of proposed downscaling approach in developing sub daily IDF relations for future periods. This section shows the applicability of proposed approach for all other locations included in this study. Following Fig. 6 illustrates the scaling behaviour first three NCMs of observed rainfalls at Adelaide airport, Brisbane regional, Sydney observatory hill, Perth airport, Melbourne airport and Darwin airport rain gauge stations. According to Fig. 6 it clearly depicts that all rain gauge stations shows

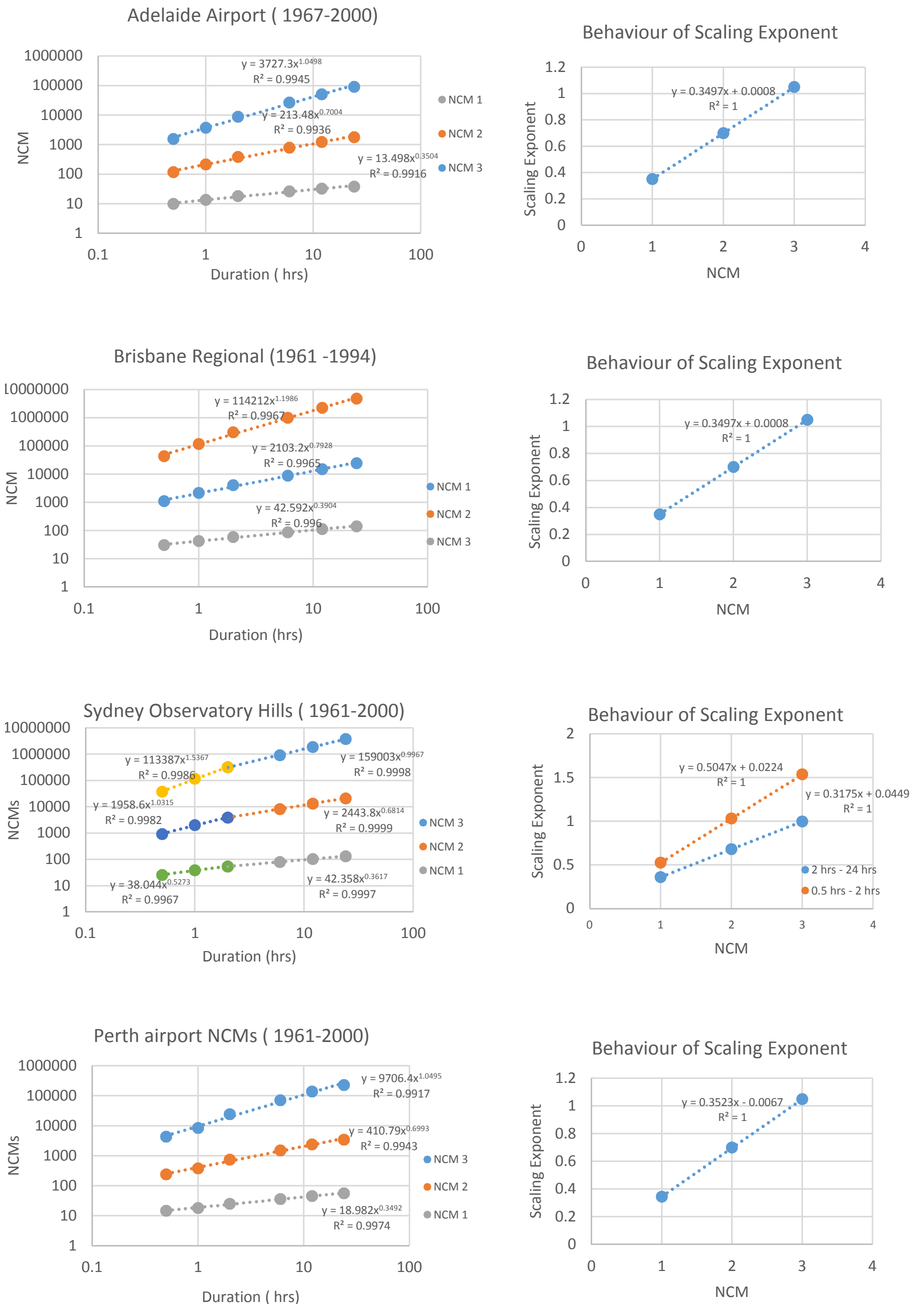


Figure 6.

scaling behaviour in their observed annual maximum rainfall series. Except Sydney observatory hill rain gauge station, other all stations show simple scaling regime of 24 to 0.5 h. It confirms the applicability of proposed temporal downscaling method in estimating subdaily IDF relations same as Canberra airport example. Sydney observatory hill rain gauge station shows two time regimes which exist power law dependency. It shows one time regime from 24 to 2 h and other regime for 2 to 0.5 h. Therefore, temporal downscaling of daily downscaled rainfall should be carried out by two steps. (i.e. (1) Estimating statistical properties up to 2 h rainfalls from statistical properties 24 h rainfalls. (2) Estimating statistical properties up to 0.5 h rainfalls from statistical properties 2 h rainfalls.)

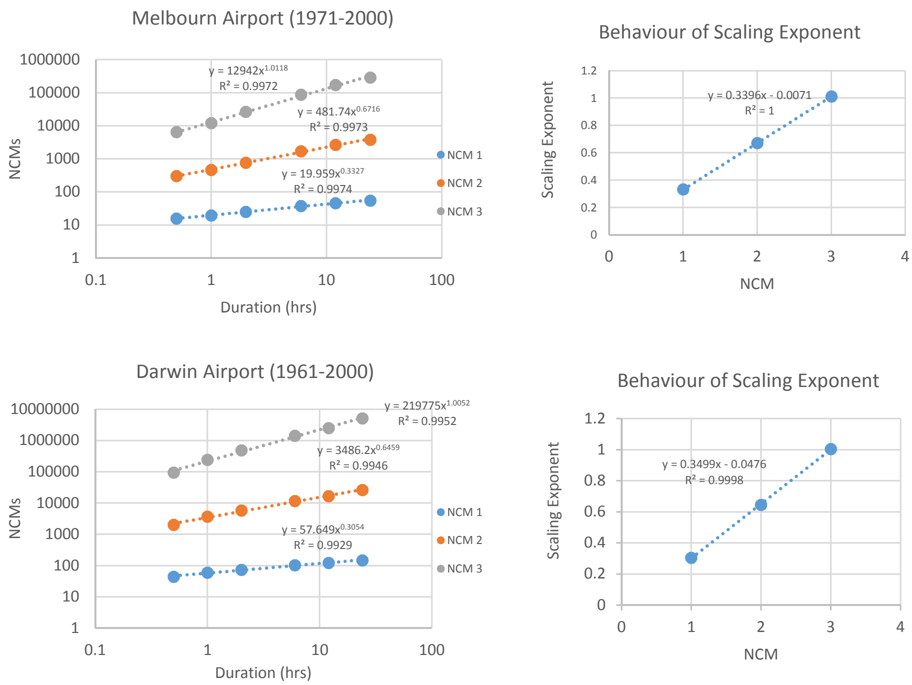


Figure 6. Assessing the behaviour of scaling exponents of observed rainfalls of Adelaide airport, Brisbane regional, Sydney observatory hill, Perth airport, Melbourne airport and Darwin airport rain gauge stations.

5 Conclusions

Spatial and temporal downscaling of climate change triggered rainfall data is prime important for hydrologists in estimating design storms in the context of climate change. This study develops an approach for spatial and temporal downscaling of regional rainfall data to develop IDF curves, which will assist hydrologists in estimating design storms in the future. Seven major cities in Australia are subjected to this study to this study. Daily and sub daily observed rainfall data by Australian Bureau of Meteorological, NCEP reanalysed data, and HadCM3-A2 climate predictor data are employed.

This study is conducted under two major steps; spatially downscale the future daily rainfall using a Statistical Downscaling Model (SDSM) and temporally downscale of spatially downscaled future rainfall using an approach based on scaling concept. SDSM model is successfully calibrated for the 1961–1975 period and validated for the 1976–1990 period. Results show that the SDSM model is feasible in simulating annual maximum daily rainfalls and simulated results should be subjected to a bias correction to improve the accuracy. In this study strong agreement is obtained between observed and simulated annual maximum daily rainfalls by applying second order bias correction functions. By applying GEV based scaling approach, statistical properties of sub daily annual maximum rainfalls are estimated. Estimated annual maximum sub daily rainfall are tested against observed annual maximum sub daily rainfalls. It proved the capability of proposed scaling approach in estimating annual maximum sub daily rainfalls and feasibility of establishing linkage between large-scale climate predictors with sub-daily rainfall characteristics.

The most remarkable outcome of this study is the development of IDF relationships for the future periods for HadCM3-A2 predictors. These IDF relations guide hydrologists in determination of design storms for the future periods. The results of the study will be helpful in the assessment of the climate change impacts on urban water resources which satisfies the demand of fine spatial resolution and sub daily temporal rainfall data.

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References

Nguyen, V. T. V., Nguyen, T. D., and Wang, H.: Regional estimation of short duration rainfall extremes, Water Sci. Technol., 37, 15–19, 1998.

Nguyen, V. T. V., Nguyen, T. D., and Ashkar, F.: Regional frequency analysis of extreme rainfalls, Water Sci. Technol., 45, 75–81, 2002.

Nguyen, V. T. V., Nguyen, T. D., and Gachon, P.: On the linkage of large-scale climate variability with local characteristics of daily precipitation and temperature extremes: an evaluation of statistical downscaling methods, in: Advances in Geosciences, edited by: Park, N., World Scientific, Singapore, 2006.

Nguyen, V. T. V., Desramaut, N., and Nguyen, T. D.: Estimation of urban design storms in consideration of GCM- based climate change scenarios, Taylor & Francis group, London, 2009.

Overeem, A., Buishand, A., and Holleman, I.: Rainfall depth duration frequency curves and their uncertainties, J. Hydrol., 348, 124–134, 2006.

Wilby, R. L., Dawson, C. W., and Barrow, E. M.: SDSM – a decision support tool for the assessment of regional climate change impact, Environ. Model. Softw., 17, 147–159, 2002.

Wilby, R. L., Charles, S. P., Zorita, E., Timbal, B., Whetton, P., and Mearns, L. O.: Guidelines for use of climate scenarios developed from statistical downscaling methods, available from the DDC of IPCC TGCIA, 27 pp., 2004.

Willems, P. and Vrac, M.: Statistical precipitation downscaling for small scale hydrological impact investigations of climate change, J. Hydrol., 402, 193–205, 2011.

Willems, P., Olsson, J., Arnbjerg-Nielsen, K., Beecham, S., Pathirana, A., Bulow Gregersen, I., Madsen, H., and Nguyen, V. T. V.: Impacts of Climate Change on Rainfall Extremes and Urban Drainage Systems, International Water Association Publishing, London, UK, 226 pp., 2012.