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Downscaling of future rainfall extreme events: a weather generator based approach

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Abstract: Future climate projections of Global Climate Models (GCMs) under different scenarios are usually used to develop climate change mitigation and adaptation strategies. However, present GCMs have limited skills to simulate the complex and local climate features and to provide reliable information on precipitation which is a principal input to hydrologic impact assessment models. Furthermore, the outputs provided by GCMs are too coarse to be used by such hydrologic models, as they require information at much finer scales. Downscaling of GCM outputs is usually employed to provide fine-resolution or point-scale information required for impact models. The downscaling methodologies developed to date can be broadly categorized as statistical and dynamical. Statistical downscaling tools have three main classes: 1) regression based, 2) weather generators, and 3) weather typing. The weather generator is one of the popular downscaling techniques. It is based on statistical principles and considered to be computationally less demanding than other downscaling techniques. In the present study, LARS-WG (a weather generator) and the outputs from HadCM3 (a climate change model) for present climate as well as future time slice of 2070-2099 (2080s) based on A2 scenario of Special Report on Emission Scenarios (SRES) are used to evaluate LARS-WG as a tool for the assessment of climate change impacts on extreme characteristics of daily rainfall at Owairaka station located in the Auckland region in New Zealand. The results obtained in this study illustrate that LARS-WG has reasonable skill to simulate the extreme rainfall events and can be adopted as an effective tool for incorporating climate change impacts into sustainable development.

Keywords: Statistical downscaling, Global climate models, LARS-WG, Generalized extreme value distribution

1. INTRODUCTION

Climate change is considered to be the greatest challenge faced by mankind in the twenty first century. The change in the climate mean state within a certain time period is referred to as climate variability which can be more detrimental than the climate change. Both climate variability and change can lead to severe impacts on different major sectors of the world such as water resources, agriculture, energy and tourism.

Many countries around the world have significant water resources and they rely heavily on them for energy production, agriculture and drinking water which affect their economic development. To develop strategies and make informed decisions about the future water allocation for different sectors and management of available water resources, they need climate change information (usually in terms of watershed scale precipitation and temperature) that can directly be used by the hydrologic impact models. Atmosphere-ocean coupled Global Climate Models (GCMs) are the main source to simulate the present and project the future climate of the earth under different climate change scenarios (e.g. SRES, 2000). The computational grid of the GCMs is very coarse (a grid box covers more than 40000 km^2), and thus they are unable to skillfully model the sub-grid scale climate features like topography or clouds of the area in question (Wilby et al., 2002). Consequently, GCMs to date are unable to provide reliable information of rainfall for hydrological modeling. Thus, there is a need for downscaling, from coarse resolution of the GCM to a very fine resolution or even at a station scale. The downscaling methodologies developed to date can be broadly categorized as statistical and dynamical. Among the statistical downscaling methods, the use of stochastic weather generators is very popular. They are not computationally demanding, simple to apply and provide station scale climate change information (Dibike and Coulibaly, 2005; Kilsby et al., 2007).

The weather generators are statistical models used to generate a long synthetic series of data, fill in missing data and produce different realizations of the same data (Wilby, 1999). They employ random number generators and use the observed time series of a station/site as input. Stochastic weather simulation is not new and has a history starting from 1950s, as reported by Racsko et al. (1991). Among some researchers who contributed to its evolution are Bruhn (1980), Bruhn et al. (1980), Nicks and Harp (1980), Richardson (1981), Richardson and Wright (1984) and Schoof et al. (2005). Wilby (1999) has presented a comprehensive review of the its theory and evolution over time. Weather generators have been employed to get long time series of hydro-meteorological variables which can be used by crop growth model to forecast agricultural production (e.g. Riha et al., 1996; Hartkamp et al., 2003) and assessment of risk associated with climate variability (Bannayan and Hoogenboom, 2008). Further details on the use of weather generator in crop production studies can be found in Semenov (2006).

When the climate change research community started looking for low cost, computationally less expensive and quick methods for impact assessment, the weather generator emerged as a most suitable solution (e.g. Wilks, 1992, 1999). Long Ashton Research Station Weather Generator (LARS-WG) is a stochastic weather generator specially designed for climate change impact studies (Semenov and Barrow, 1997). It has been tested for diverse climates and found better than some other generators (Semenov et al., 1998). A recent study by Semenov (2008) has tested LARS-WG for different sites across the world, including one site in South Island of New Zealand, and has shown its ability to model rainfall extremes with reasonable skill.

The main focus of the present study is downscaling of rainfall using a weather generator. We make use of LARS-WG weather generator to assess the changes in extreme rainfall characteristics, at Auckland's Owairaka station in New Zealand, for 2080s according to the projections of a GCM (HadCM3). The results of this study would help in the evaluation of this weather generator as a simplified and low cost tool for climate change impact assessment in terms of rainfall extremes.

It has been reported (e.g. AR4, 2007) that climate change is likely to affect the mean as well as variability of rainfall across the world. Change in variability and rainfall extremes can seriously affect the sustainable management of urban water infrastructure in big cities, such as Auckland. If a weather generator is adequately skillful in simulating the mean as well as extreme properties of rainfall, such as wet/dry spell length and annual maximum (AM) rainfall, it can be adopted as a simplified, computationally inexpensive global solution for incorporating climate change information into decision making for planning sustainable infrastructure of a big city.

2. STUDY AREA AND DATA

In this study, data from the Owairaka rain gauge located in the Auckland region (shown in Figure 1, Lat: -36.893, Lon: 174.726) is selected, as it has sufficient record length as required by LARS-WG. The daily rainfall data is available for 1948 to 2007. But only data of 1961-2000 (40 years) is selected for analysis as required for the calibration of the weather generator. In climate change studies, this period is used to represent the current climate (cf. Wilby et al., 2002). The rainfall data used in this study was obtained from National Institute of Water and Atmospheric research, New Zealand (NIWA) (http://cliflo.niwa.co.nz/).

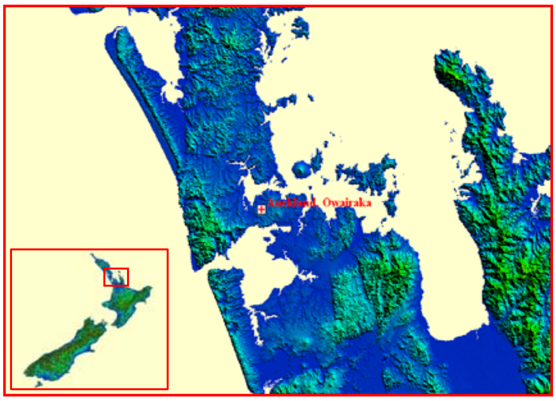

Figure 1. Location of the study site on map of North Island, New Zealand

In order to get a downscaled time series using a weather generator, the mean daily precipitation output of HadCM3 covering the whole globe is obtained from the Program for Climate Model Diagnosis and Inter-comparison (PCMDI) website (https://esg.llnl.gov:8443/) for the present period of 1960-89 (called 20th century run) and Special Report on Emission scenarios (SRES) A2 scenario run for 2080s. The selection of the HadCM3 output for A2 scenario is based on the fact that, among the four basic storylines of SRES (A1, A2, B1, B2), A2 stands among the worst case scenarios, as it sees the future world as heterogeneous and more concerned for economic growth than environmental aspects (SRES, 2000).

3. METHODOLOGY

Figure 2 illustrates the methodology adopted in LARS-WG for data generation and analysis of rainfall properties. As a first step, observed daily data is used as input to LARS-WG. It computes statistical properties of observed data, such as monthly totals, standard deviation and wet/dry spell lengths, in order to generate synthetic rainfall data with same properties. To check the ability of the weather generator in reproducing observed statistical properties, LARS-WG is made to generate 500 years of daily data which is subsequently analyzed in terms of the same parameters as were computed for the observed data. After obtaining satisfactory results, the weather generator is used to produce a 40-year daily data series without any perturbations to the rainfall properties, such as monthly amount and wet/dry spell length. From this 40-year synthetic time series, the AM rainfall are obtained for the purpose of comparison with the observed AM rainfall.

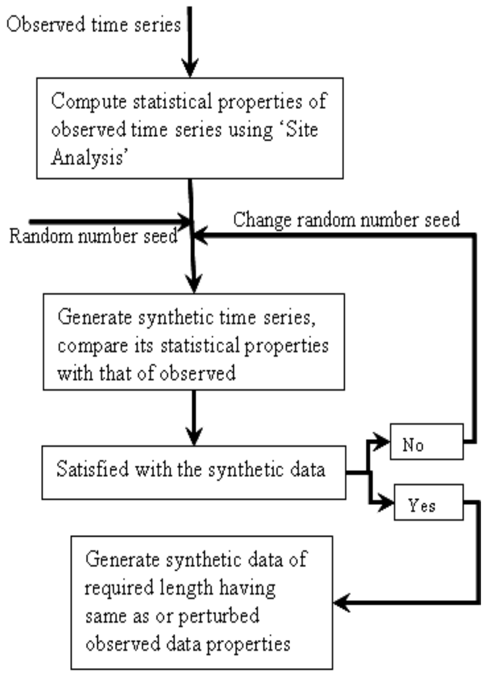

Figure 2. Flow diagram of the modeling process using a weather generator

For the downscaling of GCM daily data, HadCM3 precipitation data (for baseline and future period) is used by LARS-WG to compute statistical properties for each time series. On the basis of the relative difference between the two time series, the change factors for monthly rainfall amount and length of wet/dry spells are calculated (Relative change factor = 1 + [(Future value – Present value)/Present value] x 100). These change factors are used by LARS-WG to generate a 30-year daily time series, representing 2070-2099 period. The annual maximum values for this future 30-year record are then obtained.

The extreme properties of rainfall (e.g. lengths of wet and dry spells) are analyzed in LARS-WG. Rainfall frequency analysis is performed using the GenStat 10 software package (Payne et al., 2007) by fitting the Generalized Extreme Value (GEV) distribution to three sets of AM series obtained from observed, synthetic and downscaled data respectively. The 95% confidence interval (CI) of GEV estimate for the observed rainfall AM series of a selected return period are computed in GenStat 10 by using maximum likelihood estimation (MLE) for the three parameters of GEV distribution (i.e. location parameter ‘μ’, scale parameter ‘σ’ and shape parameter ‘ξ’) giving the standard error in the estimation of these parameters. The computations are done for 10, 20 and 40-year return periods. For mathematical details of GEV, readers are referred to Semenov (2008).

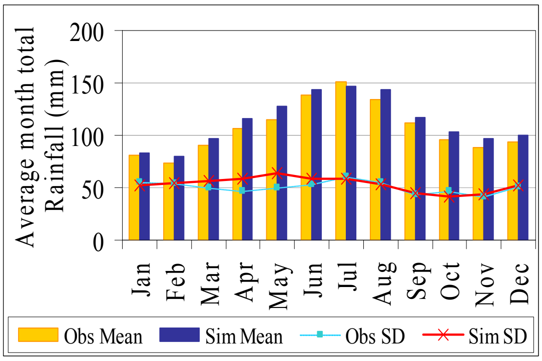

Figure 3. Comparison of observed and simulated rainfall amounts and standard deviation at study site

4. RESULTS AND DISCUSSION

A comparison of the statistical properties (mean and standard deviation) of generated and observed data, shown in Figure 3, reveals a very good performance of LARS-WG. Overall, mean monthly totals are very well modeled by LARS-WG but are a bit overestimated (by 5-10 mm). In terms of standard deviation, LARS-WG shows an excellent performance, except for March, April and May where LARS-WG overestimates the standard deviation. The simulation of wet/dry spell lengths is very important, as it can be used for the assessment of drought risk or drainage network efficiency of a big city. The simulation results of LARS-WG are shown in Figure 4 for wet and dry spell lengths. Examination of Figure 4 shows LARS-WG has a remarkable skill in simulating wet and dry spells’ lengths, as the lines representing observed and simulated values are almost overlapping throughout. Comparison of the observed and the LARS-WG simulated 40-year annual maximum series is shown in Figure 5. As explained earlier, LARS-WG generates random data which is comparable to the observed data in its statistical properties only. Examination of Figure 5 shows that both the observed and simulated values are of the same order which indicates good performance of LARS-WG simulation.

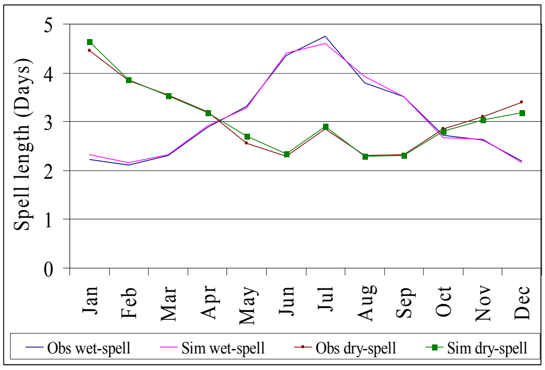

Figure 4. Comparison of observed and simulated wet/dry spell lengths at study site

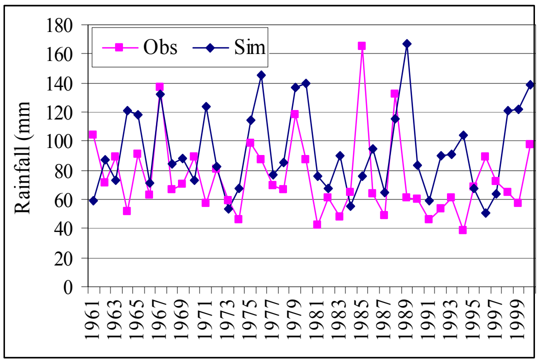

Figure 5. Comparison of observed and LARS-WG simulated annual maximum series

To generate a 30-year time series representing 2080s, month-wise change factors (given in Table 1) are used in conjunction with LARS-WG. Wet and dry spell lengths for the synthetic time series of 2080s are obtained and compared with that of observed current climate (as shown in Figure 6). The average monthly wet spell length is projected to be slightly decreasing, except in the months of Feb and Mar where it is increasing by almost a day. On the contrary, the average monthly dry spell lengths are increasing for most of the year with only few months (most clearly in Nov) showing a slight decrease and the months of Jan to Mar are likely to have an increase in dry spell length by one day or more. Overall, an increase in dry spell lengths and decrease in wet spell lengths are projected but only in a small magnitude.

In Figure 7, the AM rainfall frequency analysis results by fitting GEV distribution are presented. The topmost and bottommost thick lines represent the 95% CI of the GEV estimate derived from the observed data. Semenov (2008) has noted that, if N-year return period rainfall amount of synthetic data falls within the 95% CI for the same N-year return period, then one can consider it a successful simulation by LARS-WG. As values of 10-, 20- and 40-year return period rainfall amounts obtained by fitting GEV distribution to LARS-WG simulated AM series are within 95% CI of that obtained from observed AM, LARS-WG has successfully simulated the rainfall frequency for the study site. Assessment of the frequency of AM rainfall in 2080s (as projected by HadCM3 based on A2 scenario) is performed by fitting GEV to future AM series, obtained from the data generated by LARS-WG for 2080s. The GEV estimate of 10-, 20- and 40-year return period rainfalls for future AM series (given as broken line in Figure 6) are within the 95% CI of that of the observed AM values. This indicates that there is no significant change in AM rainfall frequency in 2080s for Auckland, Owairaka site.

Table1. Monthly change factors of rainfall properties derived from HadCM3 daily data

Month	**Mean monthly totals**	**Wet spell length**	**Dry spell length**
January	1.20	1.05	1.14
February	1.08	1.37	1.37
March	0.98	1.49	1.28
April	1.22	1.23	0.90
May	1.17	0.79	1.17
June	0.88	0.94	1.21
July	0.99	0.88	1.05
August	0.97	1.11	0.94
September	1.20	0.86	1.17
October	0.79	1.00	1.09
November	0.93	0.98	0.94
December	1.09	1.08	1.06

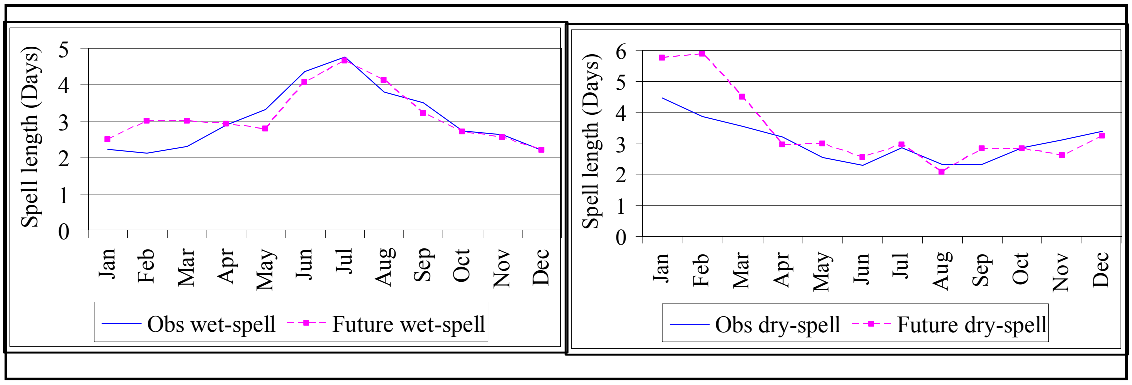

Figure 6. Month-wise comparison of the observed (1961-2000) and LARS-WG generated future (2080s) wet spell length (left) and dry spell length (right)

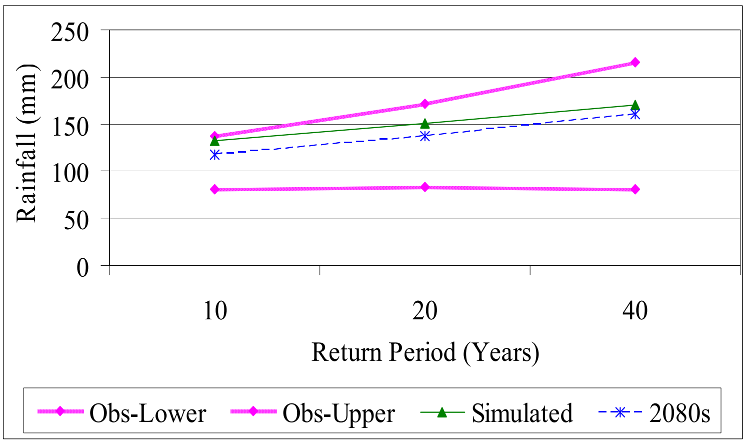

Figure 7. Rainfall frequency analysis using GEV distribution

5. CONCLUSIONS

In this study, evaluation of the performance of LARS-WG in simulating observed rainfall and downscaling future rainfall has been conducted. The evaluation was based on the extreme properties of rainfall namely, duration of wet/dry spells and frequency of extreme rainfall using data from the Owairaka, located in the Auckland region in New Zealand. For downscaling a GCM's future rainfall projection for 2080s (2070-2099), daily data of Hadley Center's GCM, HadCM3, has been used in conjunction with LARS-WG. LARS-WG has shown great skill in simulating the duration of wet/dry spell lengths when compared to the observed data and it has also successfully modeled the 10-, 20- and 40-year rainfall amounts as all are within 95% CI of that of observed. Based on the change factors obtained from GCM data, the wet spell length is likely to decrease slightly, while the dry spell length is projected to increase by 1-2 days for major part of summer season. AM rainfall frequency analysis shows that 10, 20 and 40-year return period rainfall amounts for 2080s are well within 95% CI of observed rainfall amounts for those return periods, at Auckland's Owairaka station. This leads to an obvious conclusion that, on the basis of HadCM3 future projection and methodology adopted for this specific study, there will be no significant change in rainfall. On the basis of results obtained in this study, LARS-WG has proved to be a very simple but efficient tool for simulating present climate and projecting its future state in terms of complex statistics, using the information from a GCM. In this way, it can facilitate the decision makers to incorporate climate change for devising sustainable local/regional strategies.

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