MAUSAM, **68**, 4 (October 2017), 589-596

551.585.3 : 511.509.331 (540.51)

Future climate change scenario in hot semi-arid climate of Saurashtra, Gujarat by using statistical downscaling by LARS-WG model

JAYANTA SARKAR and J. R. CHICHOLIKAR

India Meteorological Department, Ahmedabad, Gujarat – 382 475, India

(*Received 17 January 2017, Accepted 12 June 2017*)

e mail : jayantasarkar2003@yahoo.co.in

सार - इक्कीसवीं सदी में मानवों के लिए जलवायु परिवर्तन सबसे बड़ी चुनौती मानी जा रही है जिससे विश्व के अलग अलग महत्वपूर्ण क्षेत्रों जैसे: जल संसाधन, कृषि, ऊर्जा तथा पर्यटन पर भयंकर प्रभाव पड़ेगा और उससे वर्षा एवं अन्य मौसमी घटनाओं की प्रवृति तथा समय में काफी बदलाव होने की संभावना है। वर्षा एवं तापमान जैसी संक्रमित जलवायविक भिन्नताओं से विश्लेषण और पूर्वानुमान में परिवर्तन होना भी काफी महत्वपूर्ण होगा। इस तथ्य को ध्यान में रखकर इस शोध पत्र में एल ए आर एस - डब्ल्यू जी (लॉग ऑस्टन रिसर्च - वेदर जेनरेटर) जो एक संख्यात्मक निचले स्तर का मॉडल है, की दक्षता को सत्यापित करने के उद्देश्य से सौराष्ट्र की उष्ण अर्द्ध-शुष्कीय जलवायु के अनुरूपी मौसम आँकड़ों और आगामी सात जी सी ए प्रोजेक्शन द्वारा तैयार की गई है जो निकटवर्ती वर्ष 2011-2030, मध्यम (2046-2065) तथा सुदूर (2080-2099) की भावी अवधि के लिए तापमान (अधिकतम एवं न्यूनतम) तथा वर्षा की मात्रा में होने वाले परिवर्तनों का आई पी सी सी एस आर ए-2 परिदृश्य के आधार पर LARS-WG द्वारा विश्लेषण करेगा। इस उद्देश्य के लिए भारत मौसम विज्ञान विभाग की राजकोट (22.3° उ., 70. 78° पू.) वेधशाला का चयन किया गया है जो गुजरात राज्य के सौराष्ट्र की उष्ण अर्द्ध शुष्कीय जलवायु को दर्शाती है। इसमें वर्ष 1969 से 2013 की अवधि के दैनिक वर्षा, अधिकतम और न्यूनतम तापमान के आँकड़ों का उपयोग किया गया है।

एल ए आर एस-डब्ल्यू जी मॉडल को कम मात्रा की दैनिक वर्षा को बताने में अपेक्षाकृत अच्छी निपुणता और अधिकतम तथा न्यूनतम तापमान की मात्रा को बताने में उत्कृष्ट दक्षता हासिल है। कम मात्रा की वर्षा का निकटवर्ती, मध्यम तथा सुदूर भावी अवधियों के दौरान वर्षा की विभिन्न जी सी एम प्रक्षेपों में कोई सुसंगत बदलाव की प्रवृतियों का पता नहीं चला है। वर्षा प्रक्षेपों के विपरीत सात जी सी एम से अनुरूपणों के अधिकतम तथा न्यूनतम दोनों तापमानों के लिए सुसंगत परिणाम प्राप्त हुए हैं। सात जी सी एम के सामूहिक औसत के आधार पर मॉनसून ऋतु (JJAS) में राजकोट में होने वाली वर्षा के अनुमान बताते हैं कि निकट भविष्य अर्थात् 2011-2030, मध्यम भविष्य (2046-2065) और सुदूर भविष्य (2080-2099) की अवधियों में बेसलाइन मानों की तुलना में क्रमश: 2, 11 एवं 14 प्रतिशत की वृद्धि होगी। मॉडल अध्ययनों से पता चला है कि इस वृद्धि की प्रवृति का कारण क्षोभमंडलीय उष्णन के कारण वायुमंडलीय नमी की मात्रा में वृद्धि होना है। इस अध्ययन में यह भी बताया गया है कि ग्रीष्म (MAM) ऋतु में वर्ष 2011-2030, 2046-2066 एवं 2080-2099 की अवधि में अधिकतम तापमान में क्रमश: 0.5, 1.7 एवं 3.3 डिग्री सेल्सियस और सर्दी (DJF) के समय वर्ष 2011-2030, 2046-2066 एवं 2080-2099 की अवधि में न्यूनतम तापमान में क्रमश: 0.8, 2.2 एवं 4.5 डिग्री सेल्सियस की वृद्धि होने की संभावना है।

ABSTRACT. Climate change is considered to be the greatest challenge faced by mankind in the twenty first century which can lead to severe impacts on different major sectors of the world such as water resources, agriculture, energy and tourism and are likely to alter trends and timing of precipitation and other weather drivers. Analyses and prediction of change in critical climatic variables like rainfall and temperature are, therefore, extremely important. Keeping this in mind, this study aims to verify the skills of LARS-WG (Long Ashton Research - Weather Generator), a statistical downscaling model, in simulating weather data in hot semi-arid climate of Saurashtra and analyze the future changes of temperature (maximum and minimum) and precipitation downscaled by LARS-WG based on IPCC SRA2 scenario generated by seven GCMs' projections for the near (2011-2030), medium (2046-2065) and far (2080-2099) future periods. Rajkot (22.3° N, 70.78° E) observatory of IMD, representing hot semi-arid climate of Saurashtra, Gujarat state was chosen for this purpose. Daily rainfall, maximum and minimum temperature data for the period of 1969-2013 have been utilized.

LARS-WG is found to show reasonably good skill in downscaling daily rainfall and excellent skill in downscaling maximum and minimum temperature. The downscaled rainfall indicated no coherent change trends among various GCMs' projections of rainfall during near, medium and far future periods. Contrary to rainfall projections, simulations from the seven GCMs have coherent results for both the maximum and minimum temperatures. Based on the ensemble mean of seven GCMs, projected rainfall at Rajkot in monsoon season (JJAS) showed an increase in near future, *i.e.*, 2011-2030, medium future (2046-2065) and far future (2080-2099) periods to the tune of 2, 11 and 14% respectively compared to the baseline value. Model studies indicating tropospheric warming leading to enhancement of atmospheric moisture content could be the reason for this increasing trend. Further, at the study site summer (MAM) maximum temperature is projected to increase by 0.5, 1.7 and 3.3°C during 2011-2030, 2046-2065 and 2080-2099 respectively and winter (DJF) minimum temperature is projected to increase by 0.8, 2.2 and 4.5 °C during 2011-2030, 2046-2065 and 2080-2099 respectively.

Key words – Climate change, LARS-WG model, Weather data generation, GCMs, Semi-arid climate of Saurashtra.

1. Introduction

A stochastic weather generator is a numerical model which produces synthetic daily time series of a suite of climate variables, such as precipitation, temperature and solar radiation, with certain statistical properties (Richardson 1981; Richardson and Wright 1984; Racsko *et al.*, 1991). There are several reasons for the development of stochastic weather generators and most important of them, in today's context, is their application in future climate change studies. Climate change is considered as the greatest challenge faced by mankind in the twenty first century. Analyses and prediction of change in critical climatic variables like rainfall and temperature are, therefore, extremely important to develop strategies and make informed decisions about the future water allocation for different sectors and management of available water resources. The output from Global Climate Models (GCMs), which are the main tools for predicting the evolution of climate on Earth, cannot be used directly at a site because some of them have coarse spatial resolution (Semenov *et al.*, 1998). Wilby and Wigley, 1997 and Xu *et al.*, 2005 also mentioned about this. Therefore, it is of vital importance to transform the changes of large-scale atmospheric predictions of GCMs to the changes of regional-scale climate variables, such as precipitation and temperature (Chen *et al.*, 2013). Through downscaling, GCM outputs are converted into local meteorological variables (Goyal and Ojha, 2012; Olsson *et al.*, 2012; Segui *et al.*, 2010). The basic assumption of downscaling is that the large scale atmospheric characteristics highly influence the local scale weather, but, in general, the reverse effects from local scales upon global scales are negligible and thus can be disregarded (Maraun *et al.*, 2010).The downscaling methodologies developed to date can broadly be 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 and Jones, 2007). Wilks (1992, 1999) also opined that 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 the most suitable solution. Out of the different weather generators Long Ashton Research Station Weather Generator (LARS-WG), a stochastic weather generator, found to be better than some other generators (Semenov *et al.*, 1998). It is specially designed for climate change impact studies (Semenov and Barrow, 1997) and has been tested successfully for diverse climates (Semenov *et el.* 1998; Reddy *et al.*, 2014; Hashmi *et al.*, 2012; Sarkar *et al.*, 2015) of the world. LARS-WG can be used for the simulation of weather data at a single site (Racsko *et al.*, 1991) under both current and future climate conditions. These data are in the form of daily time series for climate variables, namely, precipitation (mm), maximum and minimum temperature (°C) and solar radiation ($MJm^{-2}\cdot day^{-1}$). Another advantage of LARS-WG is that 15 GCMs' outputs with different scenarios have been incorporated into the model to better deal with the uncertainties of GCMs.

Keeping in mind the above fact the present study has been conducted with the following objectives:

(*i*) To verify the skills of LARS-WG in simulating weather data in hot semi-arid climate of Saurashtra by using long period observed metrological data and

(*ii*) To bring out to the fore the future climate scenario at the study site by analyzing precipitation and temperature data downscaled by LARS-WG model which can further be used as reference results for developing future sustainable water resources and heat action plan for Rajkot, Saurashtra.

2. Materials and method

2.1. *Study area and data*

For this study Rajkot (22.3° N, 70.78° E) observatory of IMD, representing hot semi-arid climate of Saurashtra, Gujarat state was chosen. Save the monsoon season, the climate here is very dry. The weather is hot through the months of March to June. The average summer maximum and winter minimum temperature is 40 °C and 11 °C respectively. Southwest monsoon (June-September) brings in humid climate from mid-June to mid-September. Sometimes heavy rains cause local rivers to flood; however, drought is not uncommon to this place when south west monsoon is below par. The data series

TABLE 1

Selected 7 global climate models from IPCC AR4 incorporated into the LARS-WG 5.0 in this study

No.	GCM	Research center	Grid
1.	CNCM3	Centre National de Recherches France	1.9 × 1.9°
2.	GFCM21	Geophysical Fluid Dynamics Lab USA	2.0 × 2.5°
3.	HADCM3	UK Meteorological Office UK	2.5 × 3.75°
4.	INCM3	Institute for Numerical Mathematics Russia	4 × 5°
5.	IPCM4	Institute Pierre Simon Laplace France	2.5 × 3.75°
6.	MPEH5	Max-Planck Institute for Meteorology Germany	1.9 × 1.9°
7.	NCCCS	National Centre for Atmospheric USA	1.4 × 1.4°

TABLE 2

Results of the statistical tests comparing the observed data for Rajkot site with synthetic data generated through LARS-WG for the seasonal distributions of wet and dry series (WDSeries), distributions of daily rainfall (RainD), monthly mean rainfall (RMM) and its variances (RMV) and distributions of daily maximum (TmaxD)and minimum (TminD) temperature and their monthly means (TmaxM and TminM). Distributions were compared using the *K-S* test and means and variances were compared using the *t*-test and *F*-test, respectively. The numbers in the table show how many tests gave significant results at the 5% significance level. A large number of significant results indicate a poor performance of the generator

Site	WDSeries	RainD	RMM	RMV	TminD	TminM	TmaxD	TmaxM
Rajkot	1	1	0	1	1	1	0	0
Total tests	8	12	12	12	12	12	12	12

used in this study is daily rainfall, maximum and minimum temperature from 1969 to 2013 and obtained from IMD, Ahmedabad.

LARS-WG is having the advantage that output from 15 GCMs with different scenarios have been incorporated into the model to better deal with the uncertainties of GCMs. Among the 15 GCMs used in the IPCC AR4 (regarding precipitation or temperature variability there are no considerable improvements or changes happened over the Indian region from AR4 to AR5), 7 GCMs (Table 1) had SRA2 emission scenario that stands among the worst case scenario, as it sees the future world as heterogeneous and more concerned for economic growth than environmental aspects (SRES, 2000). These 7 GCMs with SRA2 scenario were used to predict the future change of local-scale precipitation and temperature in three periods: 2011-2030, 2046-2065 and 2080-2099.

2.2. *Method*

The LARS-WG uses semi empirical distributions to simulate weather data based on the observed statistical characteristics of daily weather variables at a site both under current and future climatic conditions. There are two major stages in this method: the first is the site analysis (calibration) stage and the second is the scenario generation, which includes the downscaling processes. The inputs to the weather generator are the series of daily observed data (precipitation, minimum and maximum temperature) of the base period (1969-2013) and site information (latitude, longitude and altitude). In the LARS-WG, the quality check is performed on fly (for example, some stations show Tmin is greater than Tmax) and corrected through site analysis module (Fiseha *et al.*, 2012). After the input data preparation and quality control, the observed daily weather data at a given site were used to determine a set of parameters for probability distributions of weather variables. These parameters are used to generate a synthetic weather time series of arbitrary length by randomly selecting values from the appropriate distributions. The LARS-WG distinguishes wet days from dry days based on whether the precipitation is greater than zero. The occurrence of precipitation is modelled by alternating wet and dry series approximated by semi-empirical probability distributions. The detailed model setup and working principle are explained by Semenov and Barrow, 1997 and Semenov, 2007.

2.3. *Calibration and validation of LARS-WG*

The calibration of the LARS-WG model is based on the derivation of statistical parameters using the observed historical data. The data on daily precipitation as well as minimum and maximum temperatures for the period of 1969-2013 at the selected station Rajkot were used to perform the site analysis. LARS-WG produces monthly means and standard deviations of precipitation, minimum and maximum temperature using semi-empirical distributions of dry and wet series. The statistical significance of the result is analysed by forcing the model to generate synthetic series of data for 500 years. The resulting synthetic values are then compared with the observed records considering the *t*-test, *F*-test and *K-S* (Kolmogorov-Smirnov) tests.

2.4. *Climate scenarios*

In this study, the local-scale climate scenarios based on the SRA2 scenario simulated by the selected seven GCMs are generated by using LARS-WG (5.0) for the

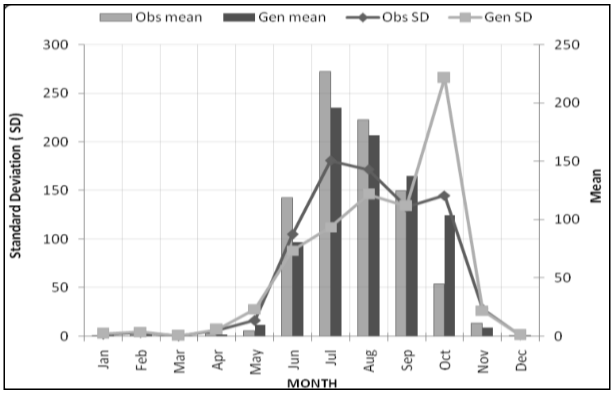


Fig. 1. Comparison of the mean monthly observed and LARS-WG simulated rainfall (mm) and standard deviation at Rajkot in the period 1969-2013

Fig. 2. Comparison of the mean monthly observed and LARS-WG simulated minimum and maximum temperature at Rajkot in the period 1969-2013

time periods of 2011-2030, 2046-2065 and 2080-2099 to know the future change of precipitation and temperature at Rajkot. Semenov and Stratonovitch, 2010 introduced and used the procedure to generate the local-scale climate scenarios.

3. Results and discussion

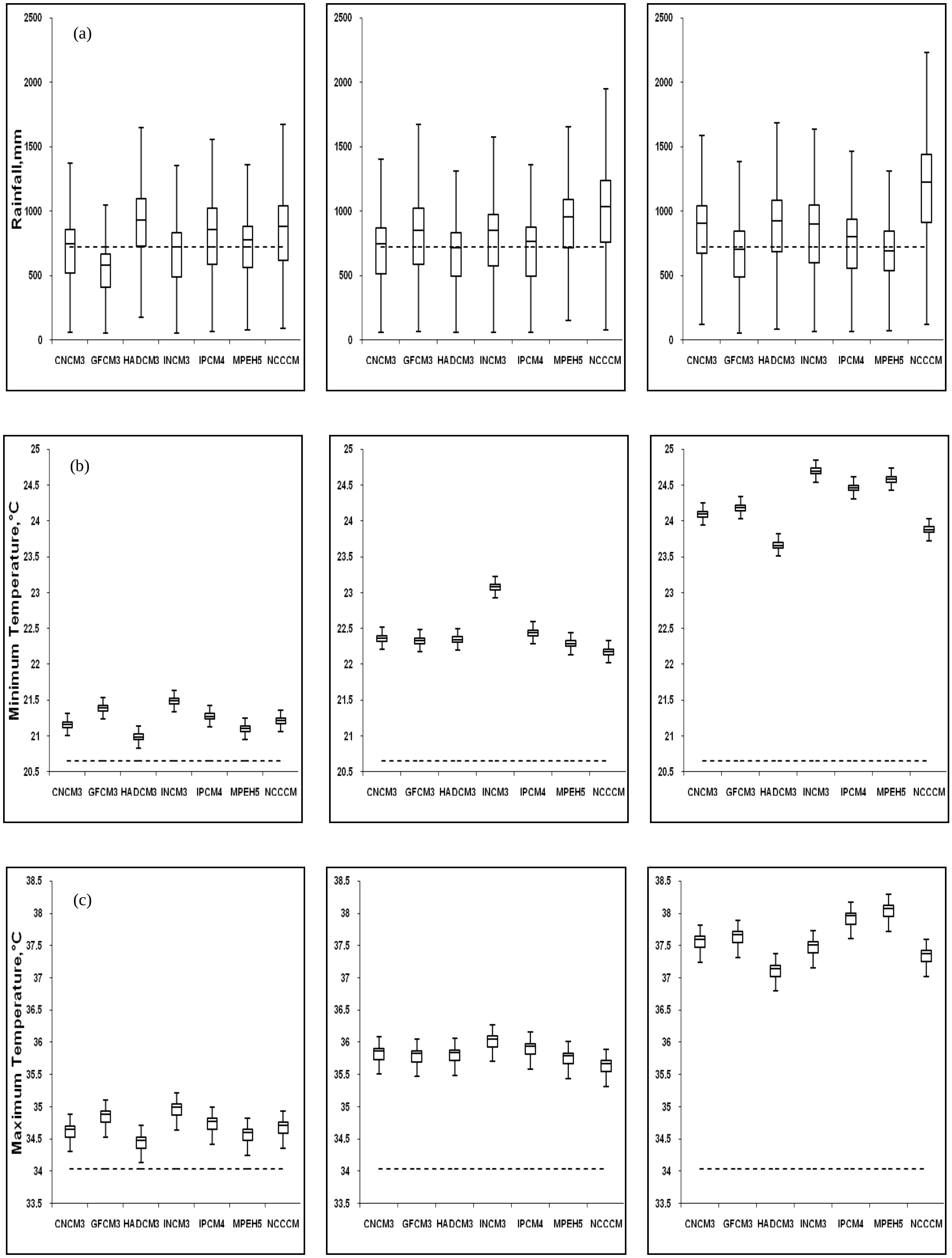
3.1. *Results of calibration and validation of LARS-WG model*

LARS-WG model was calibrated and validated at Rajkot using daily weather data for 1969-2013.To assess the ability of LARS-WG, besides the graphic comparison, some statistical tests are also performed. The Kolmogorov-Smirnov (*K-S*) test is performed on testing equality of the seasonal distributions of wet and dry series (WDSeries), distributions of daily rainfall (RainD) and distributions of daily maximum (TmaxD) and minimum (TminD) calculated from observed data and downscaled data. The *t*-test is performed on testing equality of monthly mean rainfall (RMM), monthly mean of daily maximum temperature (TmaxM) and monthly mean of daily minimum temperature (TminM). The *F*-test is performed on testing equality of monthly variances of precipitation (RMV) calculated from observed data and downscaled data. The test calculates a *p*-value, which is used to accept or reject the hypotheses that the two sets of data could have come from the same distribution (*i.e.*, when there is no difference between the observed and simulated climate for that variable). A very low *p*-value and a corresponding high *K- S* value means the simulated climate is unlikely to be the same as the observed climate; hence must be rejected. A *p*-value of 0.05 is the significance level used in this study. The test results have been presented in Table 2, where the numbers show how many tests give significantly different results at the 5% significance level out of the total number of tests of 8 or 12. A large number indicates a poor performance of the LARS-WG model. The data therein reveal that for RMV, TminM and TmaxM the number of significant results are 1, 1 and 0 respectively; for WDSeries, RainD, RMM, TmaxD and TminD the number of significant results are either 1 or 0. This indicates that at Rajkot LARS-WG model is quite capable of simulating seasonal distributions of wet and dry series (WDSeries), distributions of daily rainfall (RainD) and distributions of daily maximum (TmaxD) and minimum (TminD) temperature, as well as monthly mean rainfall (RMM), monthly mean of daily maximum (TmaxM) and minimum temperature (TminM) and monthly variances of precipitation (RMV).

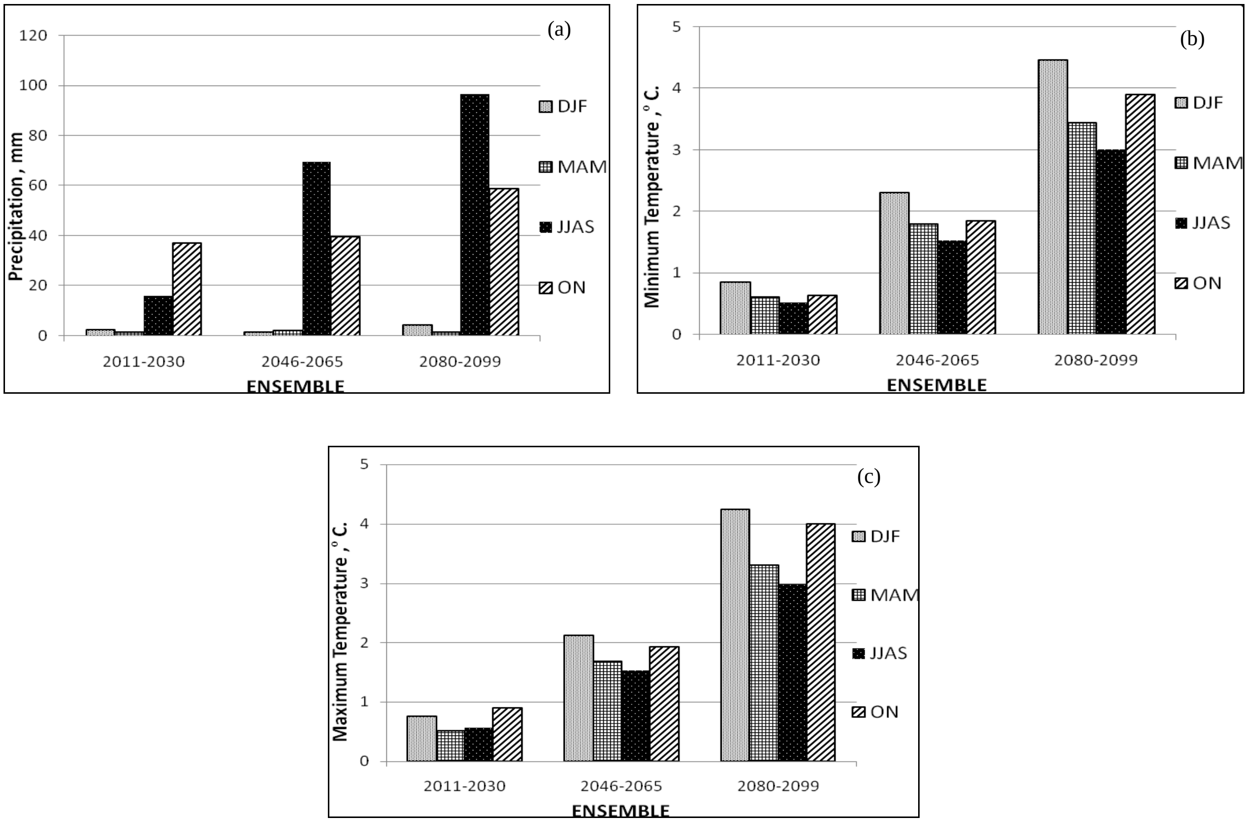
The comparisons of monthly mean and standard deviation of the simulated and observed rainfall at Rajkot (Fig. 1) reveals that there are good matches between the monthly mean of the simulated and observed precipitation; however, for standard deviation, the match is not as good as that of the mean, yet the results are reasonably good (Fig. 1), considering the fact that it is difficult to simulate well the standard deviations in most statistical downscaling studies. Fig. 2 shows that at Rajkot for all the months, LARS-WG simulated monthly mean daily Tmax and Tmin values match very well with the observed values as the lines representing the observed and simulated values are overlapping throughout which indicate that the new version of LARS-WG has great capacity in simulating temperature.

3.2. *Generation of future climate scenarios: downscaling with LARS-WG*

The results of the simulation of precipitation and temperature by using LARS-WG are presented in Figs. 3(a-c) as box plots which are considered to be favourable



Figs. 3(a-c). Box-whisker plots to show the distribution of (a) rainfall, (b) minimum and (c) maximum temperature for Rajkot downscaled from seven GCMs for the future [near (2011-2030), medium (2046-2065) and far (2080-2099)] periods compared to the current period (1969-2013). Dashed line is the value of observation in the baseline period



Figs. 4(a-c). The differences of (a) rainfall, (b) minimum temperature and (c) maximum temperature between the future [near (2011-2030), medium (2046-2065) and far (2080-2099)] periods and the current period (1969-2013) at Rajkot through calculating the mean ensemble of seven GCMs

methods of presenting data for analyses as they clearly display statistical information. The height of the box represents the inter-quartile range (distance between 25th and 75th percentiles), the horizontal line inside the box indicates the group median and the vertical lines (called whiskers) issuing from the box extends to the group minimum and maximum values. In Figs. 3(a-c) each box-whisker plot represents the prediction from one GCM. The plots in Fig. 3(a) reveal that at the study site (Rajkot), during 2011-2030, out of the 7 GCMs rainfall prediction from 4 GCMs (HADCM3, IPCM4, MPEH5 and NCCCM) are more than the values of the baseline period; that from the two GCMs (CNCM3 and INCM3) are close to the baseline period values; however, prediction from GFCM3 is less than the baseline period values. During 2046-2065, rainfall prediction of 5 GCMs (GFCM3, INCM3, IPCM4, MPEH5 and NCCCM) are more than the values of the baseline period and prediction from 2 GCMs (CNCM3 and HADCM3) are equal to the baseline values. During 2080-2099, except GFCM3 and MPEH5 rest 5 GCMs' (CNCM3, INCM3, HADCM3,IPCM4, NCCCM) have predicted more rainfall than the values of the baseline period. This clearly indicates that at the study site there are no coherent change trends among various GCMs' predictions of precipitation during 2011-2030, 2046-2065 and 2080-2099. This kind of uncertainty in rainfall predictions from different GCMs are not uncommon (Chen *et al.*, 2013; Semenov and Stratonovitch, 2010). Contrary to rainfall predictions, simulations from the 7 GCMs have coherent results for both the maximum and minimum temperatures for Rajkot. The box plots [Figs. 3(b&c)] indicate that during near (2011-2030), medium (2046-2065) and far future (2080-2099) periods at the study site, in general, both the minimum and maximum temperature would increase by at least 0.5, 1.5 and 3.0 °C respectively compared to the base line temperature.

Considering the differences in prediction from the 7 GCMs used in this study, an effort has been made to compute ensemble means of rainfall and temperature predictions from 7 GCMs to further illustrate the future changes during near, medium and far future periods and the differences between the ensemble means and baseline values for the seasonal rainfall and minimum and maximum temperatures have been presented in

Figs. 4(a-c) for the periods of 2011-2030, 2046-2065 and 2080-2099. The data in Fig. 4(a) reveal that at Rajkot predicted rainfall during monsoon season (JJAS) showed an increase in near future, *i.e*., 2011-2030, medium future (2046-2065) and far future (2080-2099) periods to the tune of 2, 11 and 14% respectively compared to the baseline value. Model studies indicating tropospheric warming leading to enhancement of atmospheric moisture content could be the reason for this increasing trend. For maximum and minimum temperature for all the seasons and for all the three future periods consistent increase is observed. Summer maximum temperature is predicted to increase by 0.5, 1.7 and 3.3 °C during 2011-2030, 2046-2065 and 2080-2099 respectively and winter minimum temperature is predicted to increase by 0.8, 2.2 and 4.5 °C during 2011-2030, 2046-2065 and 2080-2099 respectively.

At Rajkot, though the increase in monsoon rainfall is predicted to be only 2% during 2011-2030; yet, during 2046-2065 and 2080-2099 this increase is substantial and ranges between 11-14%. However no uncertainty is observed for both the summer maximum and winter minimum temperature with regards to their rising trend, a possible fallout of global warming.

4. Conclusions

The performance of statistical downscaling model LARS-WG was tested in generating daily rainfall, maximum and minimum temperature at Rajkot, Saurashtra. After successful performance the model has been used to downscale future changes of precipitation, Tmin and Tmax for the study site from the seven GCM outputs of SRA2 scenario for the three time windows, *i.e*., near (2011-2030) medium (2046-2065) and far (and 2080-2099) future periods. Following conclusions are drawn from the study:

(*i*) LARS-WG has been found to generate satisfactorily daily rainfall, maximum and minimum temperature at Rajkot.

(*ii*) No coherent change trends have been observed among various GCMs' projections of precipitation during 2011-2030, 2046-2065 and 2080-2099. This indicates that there are great uncertainties in the projection of future rainfall using a single GCM and hence more GCMs should be considered in the study of climate change to reduce the uncertainty of GCMs.

(*iii*) LARS-WG showed more skill in downscaling temperature data as the downscaled Tmax and Tmin from the projections of seven GCMs showed consistent results (increasing trend).

(*iv*) Projected rainfall in monsoon season (JJAS) based on the ensemble mean of seven GCMs showed an increase in rainfall in near future, *i.e*., 2011-2030 by only about 2%; however, during 2046-2065 and 2080-2099 this increase is substantial and ranges between 11-14% compared to the baseline value.

(*v*) Summer (MAM) maximum temperature is projected to increase by 0.5, 1.7 and 3.3 °C during 2011-2030, 2046-2065 and 2080-2099 respectively.

(*vi*) Winter (DJF) minimum temperature is projected to increase by 0.8, 2.2 and 4.5 °C during 2011-2030, 2046-2065 and 2080-2099 respectively.

(*vii*) This study will provide valuable reference results for developing future sustainable water resources and heat action plan for Rajkot, Saurashtra.

Acknowledgements

The authors are thankful to Dr. K. J. Ramesh, DG, IMD, New Delhi for his encouragement in carrying out the study. They are also thankful to the anonymous referee for his constructive comments which immensely helped in improving the paper.

The contents and views expressed in this research paper are the views of the authors.

References

Chen, H., Guo, J., Zhang, Z. and Xu, C. Y., 2013, "Prediction of temperature and precipitation in Sudan and South Sudan by using LARSWG in future", *Theor. Appl. Climatol*., **113**, 363-375.

Dibike, Y. B. and Coulibaly, P., 2005, "Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models", *Journal of Hydrology*, **307**, 145-163.

Fiseha, B. M., Melesse, A. M., Romano, E., Volpi, E. and Fiori, A., 2012, "Statistical downscaling of precipitation and temperature for the upper Tiber basin in central Italy", *International Journal of Water Sciences*, **1**, 3, 1-14.

Goyal, M. K. and Ojha, C. S. P., 2012, "Downscaling of precipitation on a lake basin: evaluation of rule and decision tree induction algorithms", *Hydrol Res*., **43**, 3, 215-230.

Hashmi, M. Z., Shamseldin, A. Y. and Melville, B. W., 2012, "Downscaling of future rainfall extreme events: a weather generator based approach", In 18th World IMACS/MODSIM Congress, Cairns, Australia, 13-17.

Kilsby, C. G. and Jones, P. D., 2007, "A daily weather generator for use in climate change studies", *Environmental Modelling and Software*, **22**, 1705-1719.

Maraun, D., Wetterhall, F., Ireson, A. M., Chandler, R. E., Kendon, E. J., Widmann, M., Brienen, S., Rust, H. W., Sauter, T., Themebl, M., Venema. V. K. C., Chun, K. P., Goodess, C. M., Jones, R. G., Onof, C., Vrac, M. and Thiele-Eich, I., 2010, "Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user", *Reviews of Geophysics*, **48**, 3, 1-34.

Olsson, J., Willén, U. and Kawamura, A., 2012, "Downscaling extreme short term regional climate model precipitation for urban hydrological applications", *Hydrol Res*., **43**, 4, 341-351.

Racsko, P., Szeidl, L. and Semenov, M. A., 1991, "A serial approach to local stochastic weather models", *J. Ecological Modelling*, **57**, 27-41.

Reddy, K. S., Kumar, M., Maruthi, V., Umesha, B., Vijayalaxmi and Nageswar Rao, C. V. K., 2014, "Climate change analysis in southern Telangana region, Andhra Pradesh using LARS-WG model", *Current Science*, **107,** 54-62.

Richardson, C. W., 1981, "Stochastic simulation of daily precipitation, temperature and solar radiation", *Wat. Resour. Res*., **17**, 182-190.

Richardson, C. W. and Wright, D. A., 1984, "WGEN: A model for generating daily weather variables", US Department of Agriculture, Agricultural Research Service, ARS-8. USDA, Washington, DC.

Sarkar, Jayanta, Chicholikar, J. R. and Rathore, L. S., 2015, "Predicting future changes in temperature and precipitation in arid climate of Kutch in Gujarat: analyses based on LARS-WG model", *Current Science*, **109**, 11, 2084-2093.

Segui, P. Q., Ribes, A., Martin, E., Habets, F. and Boe, J., 2010, "Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins", *J. Hydrol*., **383**, 1-2, 111-124.

Semenov, M. A., Brooks, R. J., Barrow, E. M. and Richardson, C. W., 1998, "Comparison of the WGEN and LARS-WG stochastic weather generators in diverse climates", *J. Climate Research,* **10**, 95-107.

Semenov, M. A. and Barrow, E. M., 1997, "Use of a Stochastic Weather Generator in the Development of Climate Change Scenarios", *Climatic Change*, **35**, 4, 397-414.

Semenov, M. A., 2007, "Development of high-resolution UKCIPO2 - based climate change scenarios in the UK", *Agricultural and Forest Meteorology*, **144**, 1-2, 127-138.

Semenov, M. A. and Stratonovitch, P., 2010, "Use of multi-model ensembles from global climate models for assessment of climate change impacts", *Clim. Res*., **41**, 1, 1-14.

Wilby, R. L. and Wigley, T. M. L., 1997, "Downscaling general circulation model output: A review of methods and limitations", *Prog. Phys. Geogr*., **21**, 4, 530-548.

Wilks, D. S., 1992, "Adapting stochastic weather generation algorithms for climate change studies", *Climatic Change*, **22**, 67-84.

Wilks, D. S., 1999, "Multisite downscaling of daily precipitation with a stochastic weather generator", *Climate Research*, **11**, 125-136.

Xu, C. Y., Widén, E. and Halldin, S., 2005, "Modelling hydrological consequences of climate change - progress and challenges", *Adv. Atmos. Sci*., **22**, 6, 789-797.