Predicting future changes in temperature and precipitation in arid climate of Kutch, Gujarat: analyses based on LARS-WG model

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Keeping in mind the challenge of climate change faced by mankind in the 21st century, this study attempts to analyse and predict changes in critical climatic variables (rainfall and temperature) to develop strategies and make informed decisions about the future water allocation for different sectors and manage available water resources. The aim of this study is to verify the skills of LARS-WG in simulating weather data in arid climate of Kutch, Gujarat, and predict and analyse the future changes in them for the near (2011–2030), medium (2046–2065) and far (2080–2099) future periods. Data utilised, for this study, are daily rainfall, maximum and minimum temperature for the period of 1969–2013. LARS-WG is found to show reasonably good (excellent) skill in downscaling daily rainfall (temperature). The downscaled precipitation indicated no coherent change trends among various global climate models (GCMs) predictions for near, medium and far future periods. Ensemble means of rainfall predictions from 7 GCMs indicated 9–17% increase in monsoon (JJAS) rainfall compared to the base line during medium future; however, in the far future this increase is predicted to be reduced and remain in the range 3–12%. Winter minimum temperature is predicted to increase by 0.6–1°C during 2011–2030; for 2046–2065 and 2080–2099 this increase is predicted to be around 3.0 and 5.0°C respectively. Summer maximum temperature is predicted to increase by 0.1–0.2°C during 2011–2030; for 2046–2065 and 2080–2099 this increase is predicted to be around 1.1–1.5°C and around 3.0°C respectively.

Keywords: Arid climate, climate change, global climate models, precipitation, temperature.

CLIMATE change is considered to be the greatest challenge faced by mankind in the 21st 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, 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 to develop strategies and make informed decisions about the future water allocation for different sectors and management of available water resources.

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[1]. The computational grid of the GCMs is coarse (a grid box covers more than 40,000 sq. km), and thus they are unable to skilfully model the sub-grid scale climate features like topography or clouds of the area in question[2]. Consequently, GCMs to date are unable to provide reliable information of rainfall for hydrological modelling. 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 broadly be categorized as statistical and dynamical. Among the statistical downscaling methods, the use of stochastic weather generators is popular. They are not computationally demanding, are simple to apply and provide station-scale climate change information[3,4]. According to Wilks[5,6], when the climate change research community started looking for low-cost, computationally less expensive and quick methods of impact assessment, the weather generator emerged as the most suitable solution. Among the different weather generators, Long Ashton Research Station Weather Generator (LARS-WG), a stochastic weather generator, was found to be better than some other generators[7]. It is specially designed for climate change impact studies[8] and has been tested successfully for diverse climates of the world[7,9,10]. LARS-WG can be used for the simulation of weather data at a single site under both current and future climate conditions[11]. These data are in the form of daily time series for climate variables, namely precipitation (mm), maximum and minimum temperature (°C), and solar radiation ($MJm^{-2}\ day^{-1}$). Another advantage of LARS-WG is that the output of 15 GCMs with different scenarios has been incorporated into the model to deal better with the uncertainties of GCMs.

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

1. To verify the skills of LARS-WG in simulating weather data in arid climate of Kutch using observed metrological data.
2. To predict and analyse the future changes of temperature (daily maximum and minimum) and precipitation in the arid climate of Kutch downscaled by LARS-WG based on IPCC SRA2 scenario generated by predictions of seven GCMs. This study will provide reference results for future water resources planning and management in the region.

Materials and methods

Study area and data

Kutch district, Gujarat, which is characterized by arid climate has been chosen for the present study. Three locations, namely Bhuj, Kandla and Naliya of Kutch district with departmental meteorological observatory of India Meteorological Department (IMD) and having long-period good-quality meteorological data were selected (Table 1). The data series used in this study is from 1969 to 2013 and obtained from IMD, Ahmedabad.

In order to predict the local weather data, large-scale predictors simulated by GCMs are needed. In the new version of the LARS-WG, predictions based on various emission scenarios from 15 GCMs used in the IPCC AR4 have been incorporated (Table 2). Among the 15 GCMs used in the IPCC AR4, 7 GCMs had SRA2 emission scenario that stands among the worst case scenario (Table 3), as it sees the future world as heterogeneous and pays more attention to economic growth and population growth rather than environmental aspects[1]. These seven 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.

Methods

LARS-WG model description

LARS-WG is a stochastic weather generator used for simulating weather data at a single site under both current and future conditions. It is based on the series weather generator described by Racsko *et al.*[11]. It utilizes semi-empirical distributions for the lengths of wet and dry day series, daily precipitation and daily solar radiation. The simulation of precipitation occurrence is modelled as alternate wet and dry series, where a wet day is defined to be a day with precipitation >0.0 mm. The length of each series is chosen randomly from the wet or dry semi-empirical distribution for the month in which the series starts. In determining the distributions, observed series are also allocated to the month in which they start. Daily minimum and maximum temperatures are considered as stochastic processes with daily means and daily standard deviations conditioned on the wet or dry status of the day. The technique used to simulate the process is similar to that presented in Racsko *et al.*[11]. The seasonal cycles of means and standard deviations are modelled by finite Fourier series of order 3, and the residuals are approximated by a normal distribution. The Fourier series for the mean is fitted to the observed mean values for each month. The observed standard deviations for each month are adjusted to give an estimated average daily standard deviation by removing the estimated effect of the changes in the mean within the month. The adjustment is calculated using the fitted Fourier series already obtained for the mean. The observed residuals, obtained by removing the fitted mean value from the observed data, are used to analyse a time autocorrelation for minimum and maximum temperature.

Table 1. Location of weather stations in the Kutch region

Stations	Latitude (°N)	Longitude (°E)	Altitude (m)
Bhuj	23.15	69.48	80.48
Kandla	23.00	70.13	14.36
Naliya	23.15	68.51	20.10

Outline of the stochastic weather generation process by LARS-WG

In LARS-WG, the process of generating synthetic weather data can be divided into three distinct steps, which are briefly described as follows. More detailed description of the modelling procedure is given in Semenov[12].

Model calibration

Model calibration is done to use the function 'SITE ANALYSIS' in LARS-WG, which analyses observed weather data (e.g. precipitation, maximum and minimum temperature) to determine their statistical characteristics and stores this information in two parameter files.

Model validation

The parameter files derived from observed weather data during the model calibration process are used to generate synthetic weather data having the same statistical characteristics as the original observed data. Model validation helps analyse and compare the statistical characteristics of the observed and synthetic weather data to assess the

Table 2. Specifications of climate change scenarios

Climate change scenario	Specifications
A1B	Rapid economic growth, maximum population growth during half a century and then decreasing trend, rapid modern and effective technology growth.
A2	Rapid world population growth, heterogeneous economics in the direction of regional conditions throughout the world.
B1	Population convergence throughout the world, change in economic structure (pollutant reduction and introduction to clean technology resources).

Table 3. Selected seven global climate models (GCHs) from IPCC AR4 incorporated into the LARS-WG 5.0 in the present study

GCM	Research centre	Grid
CNCM3	Centre National de Recherches, France	1.9° × 1.9°
GFCM21	Geophysical Fluid Dynamics Lab, USA	2.0° × 2.5°
HADCM3	UK Meteorological Office, UK	2.5° × 3.75°
INCM3	Institute for Numerical Mathematics, Russia	4° × 5°
IPCM4	Institute Pierre Simon Laplace, France	2.5° × 3.75°
MPEH5	Max-Planck Institute for Meteorology, Germany	1.9° × 1.9°
NCCCS	National Centre for Atmospheric, USA	1.4° × 1.4°

ability of LARS-WG to simulate the precipitation, Tmax and Tmin at the chosen sites in order to determine whether or not it is suitable for use in the study.

Generation of synthetic weather data

The parameter files derived from observed weather data during the model calibration process can also be used to generate synthetic data corresponding to a particular climate change scenario simulated by GCMs.

Climate scenarios

In this study, the local-scale climate scenarios based on the SRA2 scenario simulated by the selected seven GCMs are generated using LARS-WG (5.0) for the time periods 2011–2030, 2046–2065 and 2080–2099, to predict the future change in precipitation and temperature in the Kutch region. Semenov and Stratonovitch[13] introduced and used the procedure to generate the local-scale climate scenarios based on the IPCC AR4 multimodel ensemble.

Results and discussion

Results of calibration and validation of LARS-WG

The LARS-WG model was calibrated and validated at each of the three locations in the study region using daily weather data for 1969–2013. To assess the ability of LARS-WG, in addition to the graphic comparison, some statistical tests were also performed. The Kolmogorov–Smirnov (K–S) test is performed for 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 for 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 for 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 hypothesis 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 indicates that the simulated climate is unlikely to be the same as the observed climate; hence it must be rejected. A *P*-value of 0.05 is the significance level used in this study. Significant differences between the observed and simulated data may arise from the model smoothening the observed data, errors in the observed data, random variation in the observed data, and unusual climate phenomenon at a climate station making a particular year's climate different. The test results have been listed in Table 4, where the numbers show how many tests give significantly different results at the 5% significance level out of the total number of tests (8 or 12). A large number indicates poor performance of the generator. It can be seen from Table 4 that the average number of significantly different results for seasonal wet and dry series distributions is 1.33 out of 8; the average number of significant results for the daily rainfall distributions (RainD) is 2 out of 12; for the monthly means (RMM) it is 1 out of 12; and for the monthly variance (RMV) it is 3.67 out of 12. The average number of significant results

Table 4. Results of the statistical tests comparing the observed data for three sites with synthetic data generated through LARS-WG for the seasonal distributions of wet and dry series (WD Series), 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	WD series	RainD	RMM	RMV	TminD	TminM	TmaxD	TmaxM
Bhuj	1	4	1	3	0	2	0	3
Kandla	2	1	2	7	0	3	0	4
Naliya	1	1	0	1	0	0	0	2
Average	1.33	2	1	3.67	0	1.67	0	3
Total tests	8	12	12	12	12	12	12	12

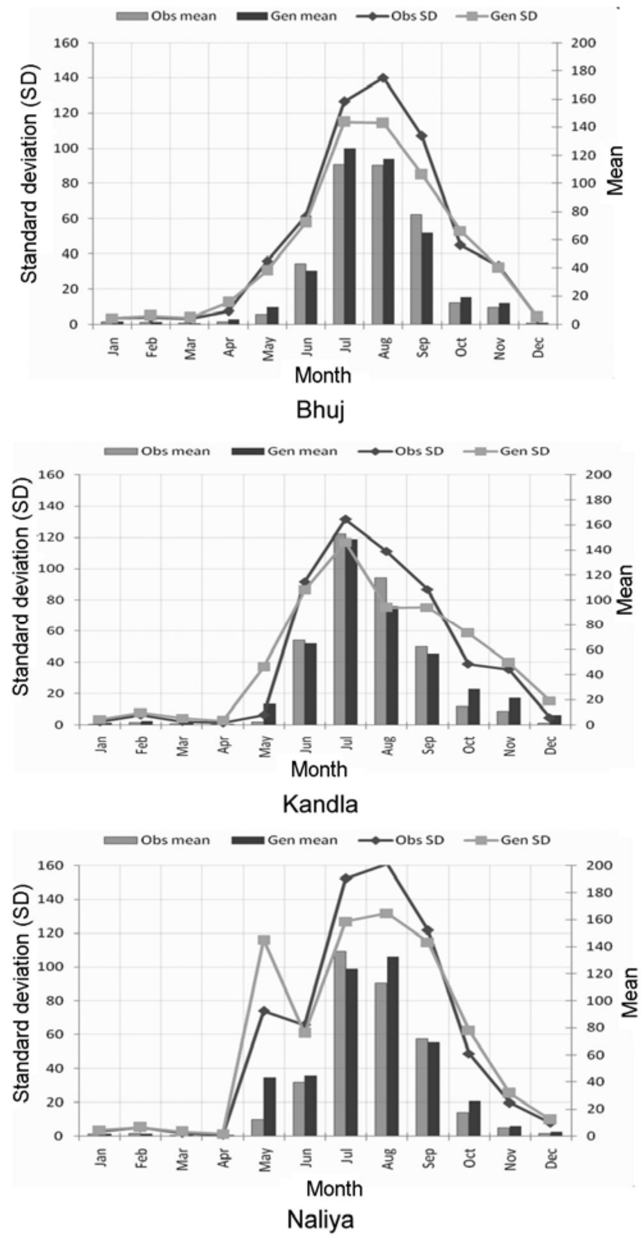

Figure 1. Comparison of the mean monthly observed and LARS-WG simulated rainfall (mm) and standard deviation at three locations in the Kutch region, Gujarat during 1969–2013.

for both TminD and TmaxD is zero, and that for TminM and TmaxM is 1.67 and 3 respectively. From these numbers, it can be noted that the model is more capable in simulating the monthly means and the daily rainfall distributions of each month in comparison to the monthly variances of rainfall and monthly mean of daily maximum temperature (TmaxM).

The comparisons of monthly mean and standard deviation of the simulated and observed rainfall are presented in Figure 1 for all the three stations. It can be seen from the figure that there are good matches between monthly mean of the simulated and observed precipitation. Although the performance of the standard deviation is not as good as that of the mean, the results are reasonably good (Figure 1) considering the fact that it is difficult to simulate well the standard deviations in most statistical downscaling studies. Figure 2 shows that LARS-WG simulated monthly mean daily Tmax and Tmin values match well with the observed values of the study stations for all months, which also verifies that this version of LARS-WG has better capacity in simulating the extreme temperature.

Generation of future climate scenarios

From the above analysis, it can be concluded that the LARS-WG model shows good performance in all the three stations in generating daily precipitation and daily Tmax and Tmin. It has been used to predict daily precipitation, and daily Tmax and Tmin for the three stations of the study area for the periods of 2011–2030, 2046–2065 and 2080–2099 based on the SRA2 scenarios generated from seven GCMs. The results of the precipitation and temperature predictions using LARS-WG are presented in Figures 3–5 as box plots which are favourable 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 Figures 3–5 each box–whisker plot

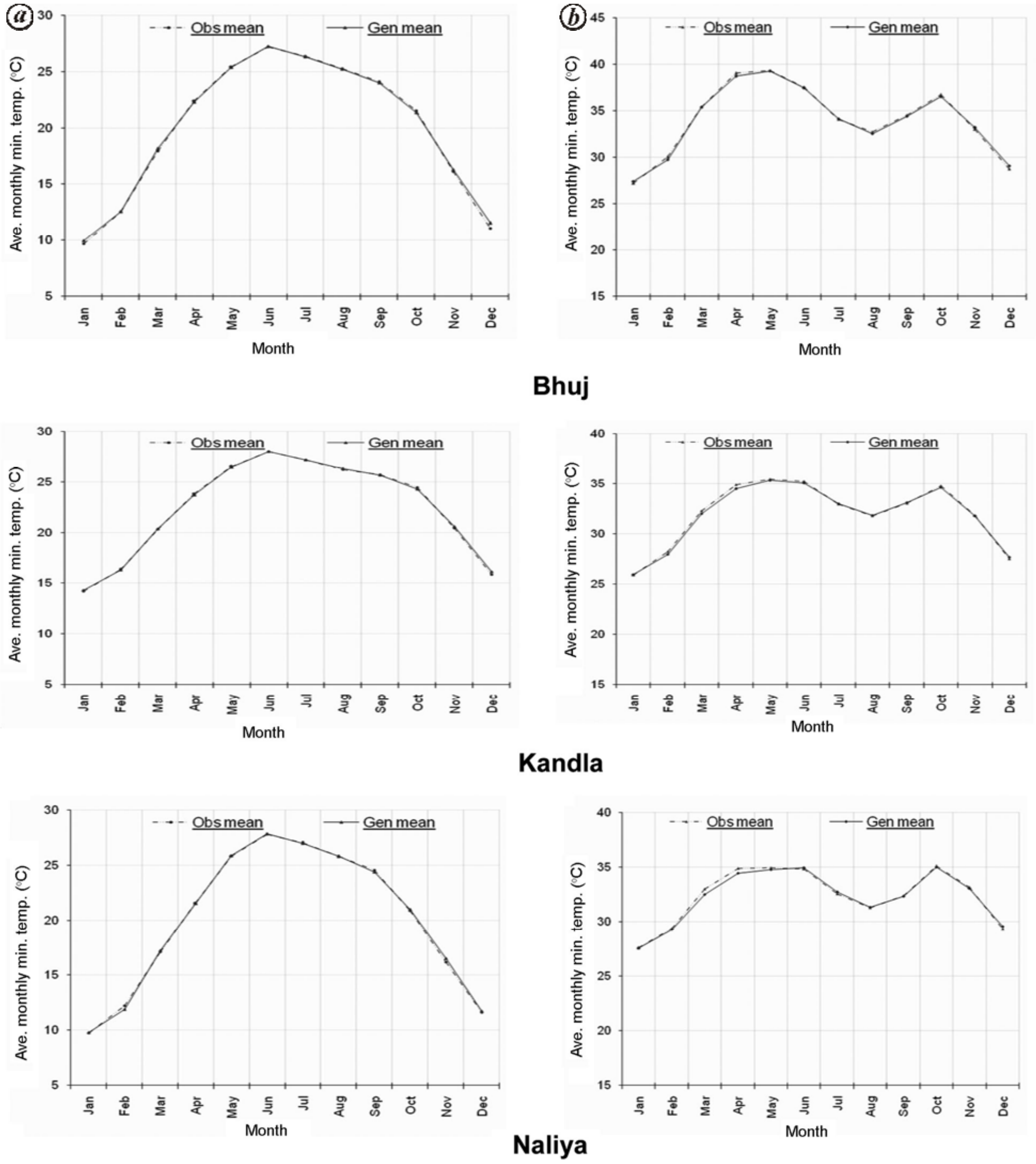

Figure 2. Comparison of the mean monthly observed and LARS-WG simulated (***a***) minimum and (***b***) maximum temperature at the three locations in the Kutch region during 1969–2013.

represents the prediction from one GCM. The plots in Figure 3 reveal that there are no coherent change trends among various GCM predictions of precipitation during 2011–2030, 2046–2065 and 2080–2099. During near future, i.e. 2011–2030, in Bhuj, four GCMs predict less rainfall compared to the baseline period and three GCMs predict rainfall close to that during baseline period; at Kandla and Naliya majority of the GCMs predict more rainfall than the baseline (Figure 3). During medium future, i.e. 2046–2065 and far future (2080–2099), in Kandla and Naliya majority of the GCMs predict rainfall either close to or more than the baseline (Figure 3); however, in Bhuj, the predictions during medium and far future are incoherent. This is indicative of the fact that there are uncertainties in the prediction of future rainfall using a single GCM. However, the scenario is entirely

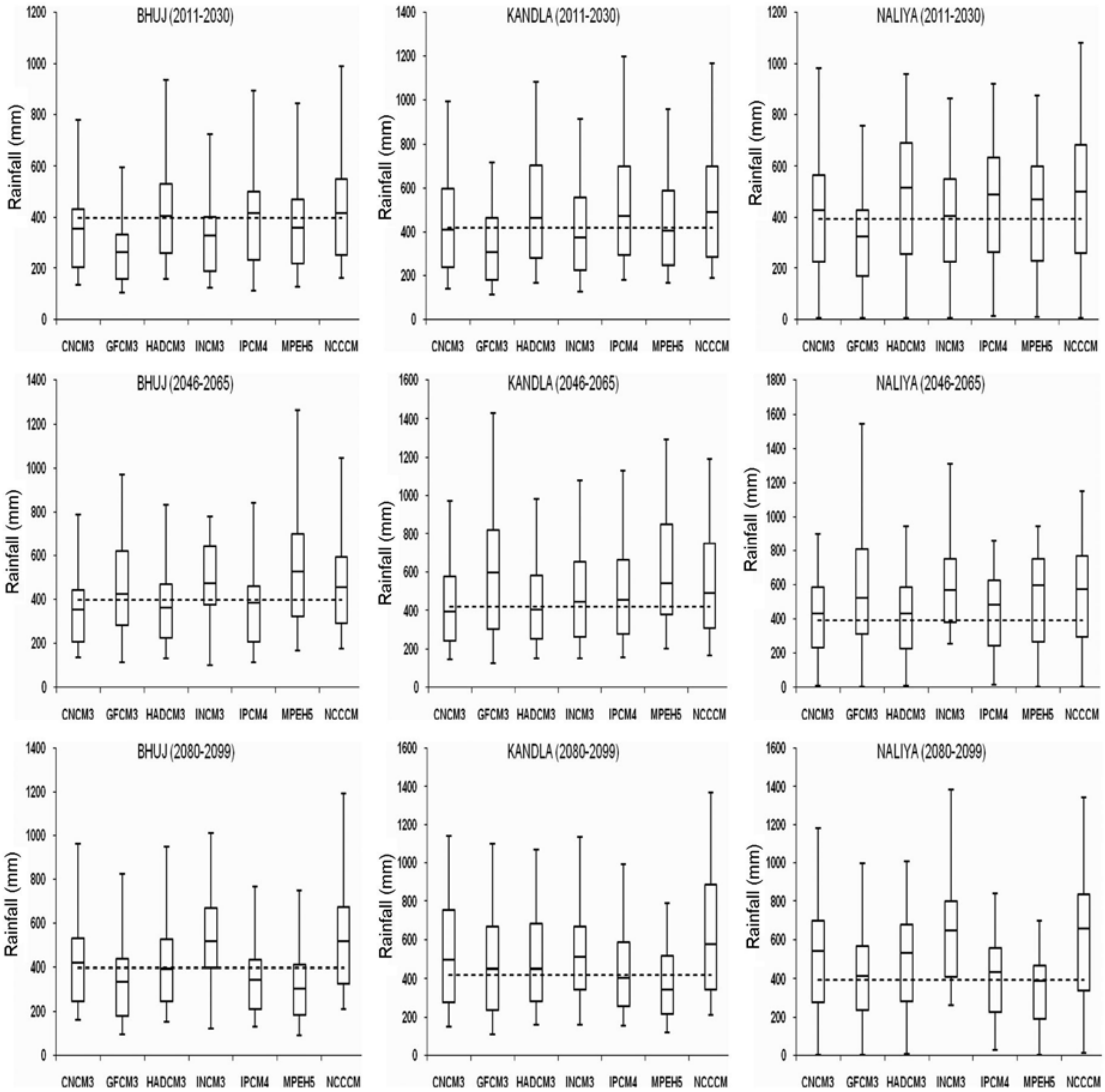

Figure 3. Box–whisker plots showing the distribution of rainfall for the Kutch downscaled from seven global climate models (GCMs) for the future (near (2011–2030), medium (2046–2065) and far (2080–2099)) periods compared to the current period (1969–2013). Dashed line shows the value of observation in the baseline period.

different when GCM prediction of minimum and maximum temperature is considered for the near, medium and far future periods (Figures 4 and 5). Similar results were also obtained by Chen *et al.*[14] while analysing data for Sudan. The box plots indicate that during near, medium and far future periods at all the three locations of the Kutch region, in general, minimum and maximum temperatures would increase by at least 0.4°C, 1.5°C and 3.0°C compared to the baseline temperature.

In view of the differences in prediction from the seven GCMs, an effort has been made to compute ensemble means of rainfall and temperature predictions from these GCMs to further illustrate the changes during near, medium and far future periods. The differences between the ensemble means and baseline values for the seasonal rainfall, and minimum and maximum temperatures are presented in Figure 6 for the periods 2011–2030, 2046–2065 and 2080–2099. The data therein reveal that though monsoon rainfall (JJAS) in the near future, i.e. 2011–2030 is predicted to decrease, more so in Naliya than Bhuj and Kandla, however, there is substantial increase in predicted monsoon rainfall during 2046–2065, and 2080–2099. With regards to minimum and maximum temperature, consistent increase in both is observed for all the seasons during all the three periods. Winter minimum temperature is predicted to increase by 0.6°–1°C during 2011–2030; for 2046–2065 and 2080–2099, this increase is predicted to be around 3.0°C and 5.0°C respectively.

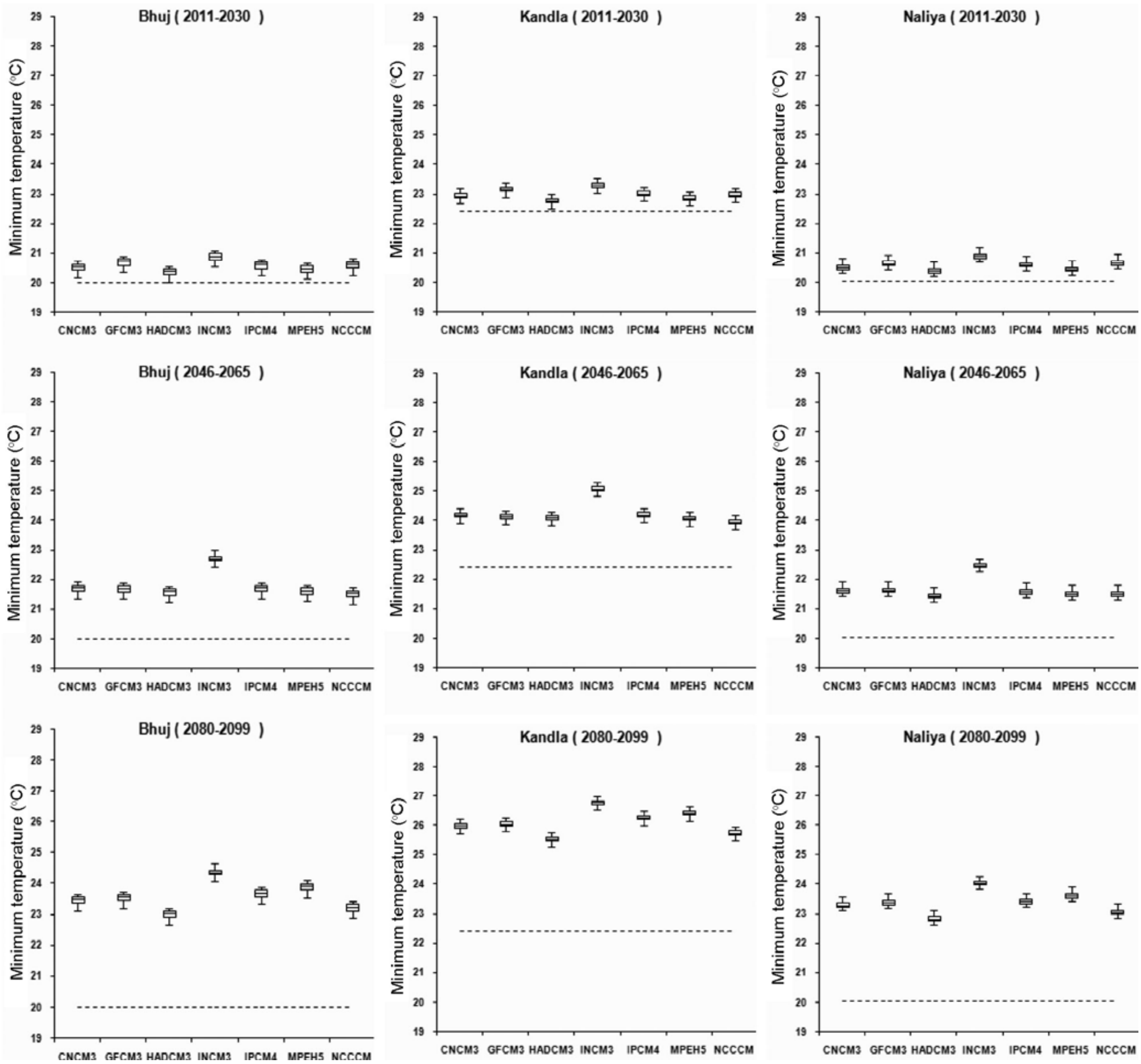

Figure 4. Box–whisker plots showing the distribution of minimum temperature for the Kutch region downscaled from seven GCMs for the future (near (2011–2030), medium (2046–2065) and far (2080–2099)) periods compared to the current period (1969–2013). Dashed line shows the value of observation in the baseline period.

Summer maximum temperature is predicted to increase by 0.1°–0.2°C during 2011–2030; for 2046–2065 and 2080–2099, this increase is predicted to be around 1.1°–1.5°C and around 3.0°C respectively.

The above analyses indicate that though there are uncertainties in predicting future rainfall scenario in the Kutch region, yet during 2046–2065 and 2080–2099 there is an unmistakable trend of increase in monsoon rainfall at all the three locations (Figure 6). Model studies indicating tropospheric warming leading to enhancement of atmospheric moisture content could be the reason for this increasing trend. In general, both minimum and maximum temperatures at all the three locations during 2011–2030, 2046–2065 and 2080–2099 show unmistakable rising trend, a fallout of global warming, which will make the Kutch climate more hostile.

The results of this study may prove useful for sectors like water resources, agriculture, etc. for their future sustainable management and planning. The data generated in this study can be used in process-oriented crop models for properly managing agricultural resources of the region to benefit agriculture sector, they may also be

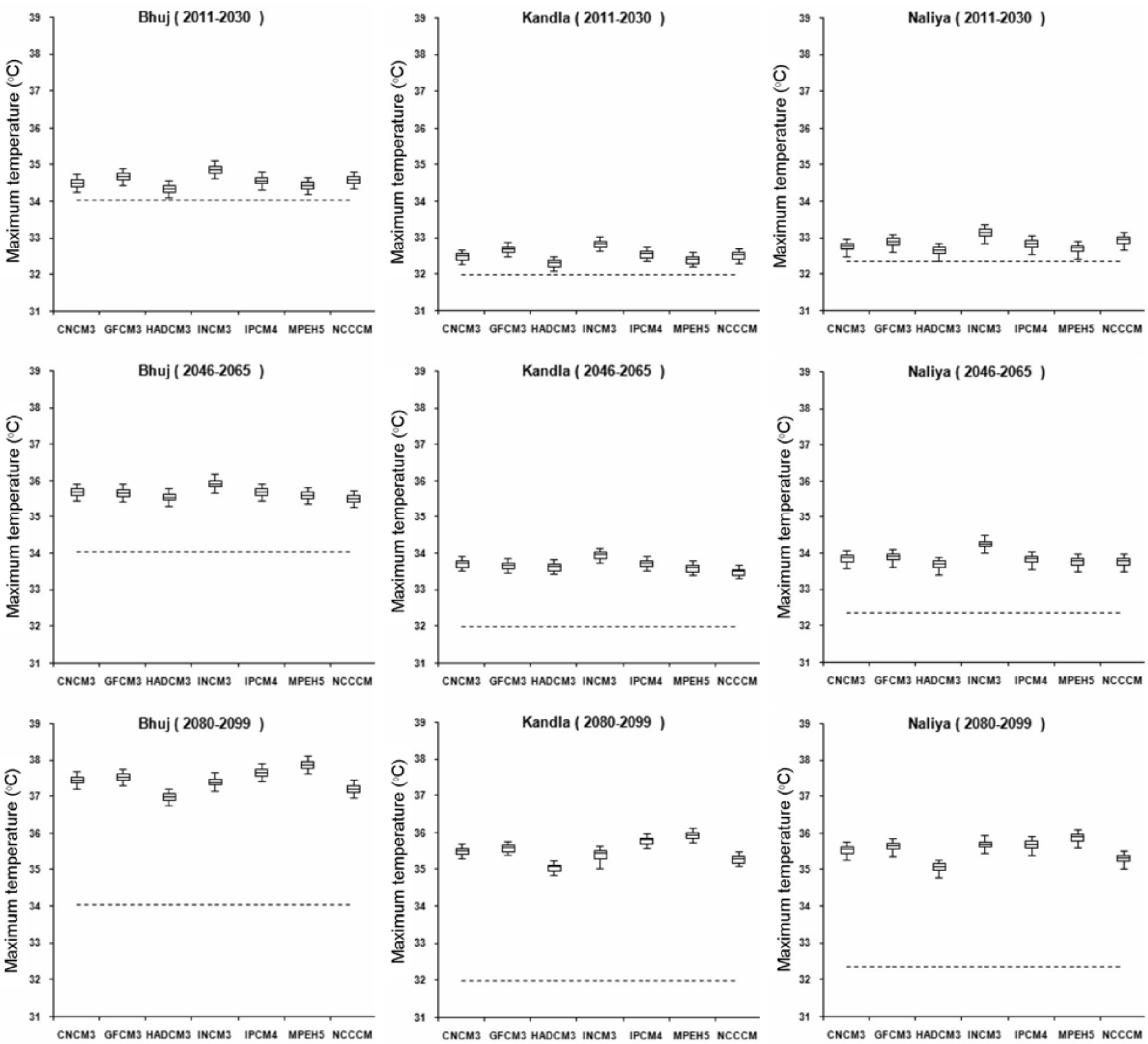

Figure 5. Box–whisker plots showing the distribution of maximum temperature for the Kutch region downscaled from seven GCMs for the future (near (2011–2030), medium (2046–2065) and far (2080–2099)) periods compared to the current period (1969–2013). Dashed line shows the value of observation in the baseline period.

useful for extreme rainfall and temperature analyses for developing future sustainable water resources and heat action plan for the region.

Conclusion

In the present study, applicability of LARS-WG has been tested in downscaling daily rainfall, and maximum and minimum temperature in the arid Kutch climate (three locations). After ascertaining the applicability of the model, it has been used to downscale future changes of precipitation, Tmin, and Tmax for the three stations in Kutch from the seven GCM outputs of SRA2 scenario for the periods of 2011–2030, 2046–2065 and 2080–2099. The following conclusions can be arrived at from the present study:

1. The LARS-WG model has been found to perform reasonably well in downscaling daily precipitation. The performance is excellent in downscaling Tmax and Tmin in the study region.
2. At all the three locations of Kutch, the downscaled precipitation from the predictions of the seven GCMs indicates no coherent change trends among various GCM predictions of precipitation during 2011–2030, 2046–2065 and 2080–2099. This is indicative of the fact that there are great uncertainties in the prediction

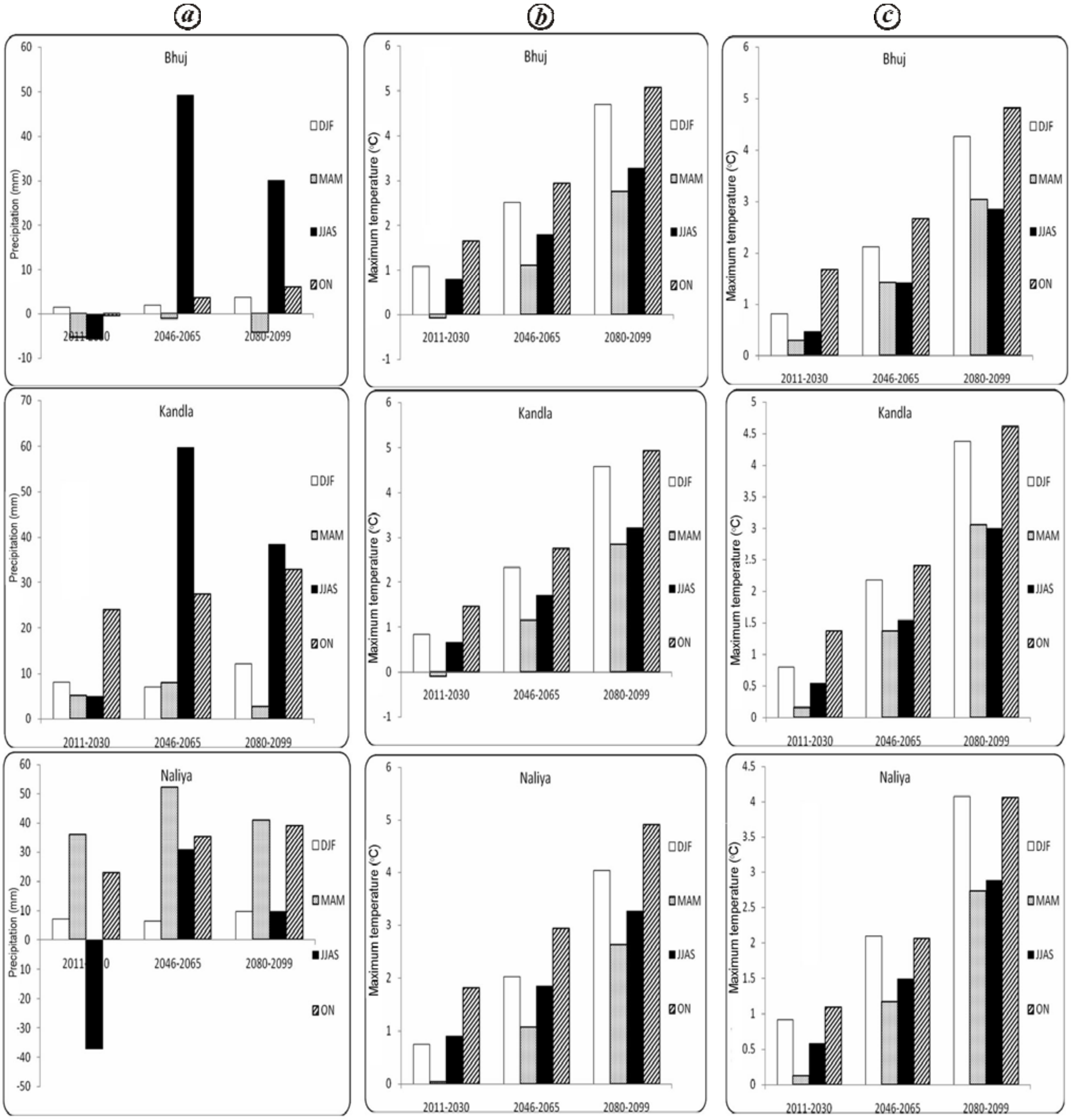

Figure 6. The difference in (***a***) rainfall, (***b***) minimum temperature and (***c***) maximum temperature between the future (near (2011–2030), medium (2046–2065) and far (2080–2099)) periods and the current period (1969–2013) in the Kutch region by calculating the mean ensemble of seven GCMs.

of future rainfall using a single GCM and hence more GCMs should be considered in the study of climate change to reduce their uncertainty.

3. Contrary to rainfall, the downscaled Tmax and Tmin from the predictions of seven GCMs show consistent increasing trend for all the stations of the study region. In general, at all the three locations daily average Tmax and Tmin would increase by at least 0.4°C, 1.5°C and 3.0°C during 2011–2030, 2046–2065 and 2080–2099 respectively, compared to the baseline temperature.
4. Ensemble means of rainfall predictions from the seven GCMs indicate 9–17% increase in monsoon (JJAS) rainfall compared to the baseline during medium future period of 2046–2065. However, the increase is predicted to be reduced and remain in the range of 3–12% in the far future (2080–2099).

5. Winter minimum temperature is predicted to increase by 0.6°–1°C during 2011–2030; for 2046–2065 and 2080–2099, this increase is predicted to be around 3.0°C and 5.0°C respectively.
6. Summer maximum temperature is predicted to increase by 0.1°–0.2°C during 2011–2030; for 2046–2065 and 2080–2099, this increase is predicted to be around 1.1°–1.5°C, and around 3.0°C respectively.

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