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ORIGINAL PAPER

Prediction of temperature and precipitation in Sudan and South Sudan by using LARS-WG in future

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Abstract Global warming has brought great pressure on the environment and livelihood conditions in Sudan and South Sudan. It is desirable to analyze and predict the change of critical climatic variables, such as temperature and precipitation, which will provide valuable reference results for future water resources planning and management in the region. The aims of this study are to test the applicability of the Long Ashton Research Station Weather Generator (LARS-WG) model in downscaling daily precipitation and daily maximum (Tmax) and daily minimum (Tmin) temperatures in Sudan and South Sudan and use it to predict future changes of precipitation; Tmin and Tmax for nine stations in Sudan and South Sudan are based on the SRA2 scenario of seven General Circulation Models (GCMs) outputs for the periods of 2011–2030, 2046–2065, and 2080–2099. The results showed that (1) the LARS-WG model produces good performance in downscaling daily precipitation and excellent performance in downscaling Tmax and Tmin in the study region; (2) downscaled precipitation from the prediction of seven GCMs showed great inconsistency in these two regions, which illustrates the great uncertainty in GCMs' results in the regions; (3) predicted precipitation in rainy season JJA (June, July, and August) based on the ensemble mean of seven GCMs showed a decreasing trend in the periods of 2011–2030, 2046–2065, and 2080–2099 in Sudan; however, an increasing trend can be found in SON (September, October, and November) in the future; (4) precipitation in South Sudan has an increasing trend in most seasons in the future except in MAM (March, April, and May) season in 2011–2030; and (5) predictions from seven GCMs showed a similar and continuous increasing trend for Tmax and Tmin in all three future periods, which will bring severe negative influence on improving livelihoods and reducing poverty in Sudan and South Sudan.

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1 Introduction

As climate factors, such as temperature and precipitation, have critical influence on yields of agriculture in Sudan and South Sudan, there is an increasing number of studies exploring changing trends of precipitation and/or temperature (Alvi 1994; Alvi and Elagib 1996; Ayoub 1999; Elagib 2011b; Eldredge et al. 1988; Eltahir 1989; Osman and Shamseldin 2002; Osman et al. 2001; Xu et al. 2010; Zhang et al. 2012). Alvi (1994) analyzed meteorological data for the period of 1940 to 1990 to ascertain the climatic changes in Sudan and confirmed that the temperature was rising and rainfall was declining, a trend which may accelerate environmental degradation and desertification in Sudan. Alvi and Elagib (1996) made an attempt to thoroughly investigate the important hydrological features of the flood region in the South Sudan, which clearly indicated significant changes in the hydrological behavior of the region characterized by an increase in temperature levels and a substantial reduction in rainfall and river flows. Elagib (2010) investigated the temperature varieties by using four mean temperature variables (maximum, minimum, mean, and diurnal temperature ranges) in 14 selected observational stations throughout Sudan and South Sudan, which showed a mounting evidence of warming since the 1940s until 2005. Funk et al. (2011) reported that (1) summer rainfall decreased by 15–20 % across parts of western Sudan and South Sudan between the mid-1970s and late 2000s, placing already food-insecure populations at a greater risk and (2) temperatures have increased by more than 0.4 °C across much of central Sudan and South Sudan over the past 30 years, which may have much impact on availability of water resources in this region. These studies manifest that there are obviously rising trends of temperature and declining trends of precipitation recently in these two regions.

Several observational studies tried to ascertain the possible causes of the precipitation and/or temperature changes during the past decades in the region. For example, the precipitation anomaly of Sudan has been found related to Sea Surface Temperature Anomalies (SSTAs) in the Gulf of Guinea (Lamb 1978a; Lamb 1978b). Palmer (1986) also pointed out that the tropical Indian Ocean sea surface temperature (SST) had a strong influence on the Sahel rainfall. Camberlin (1995) found that the dry and wet conditions over the Sahel were usually associated with warm conditions in the tropical Indian Ocean. Osman and Shamseldin (2002) reported that rainfall regime was controlled by the southwesterly monsoon winds flowing from the Atlantic Ocean and the southeasterly monsoon winds flowing from the Indian Ocean. Also, Osman et al. (2001) investigated the influence of El Niño–southern oscillation (ENSO) and the Indian Ocean Sea SST on rainfall variability in the central and southern regions of Sudan and found that the driest years were associated with warm ENSO and Indian Ocean SST conditions. These studies have linked temporal components of the precipitation variability in Sudan to the atmospheric moisture transport, locally or globally, such as SST and ENSO, which is named West African Sudan-Sahel weather system (Bell and Lamb 2006). At more local scales, moisture advections and convergences are also significantly associated with the observed Sudan-Sahel rainfall and in wet (dry) situations, with a clear dominance of westerly (easterly) anomalies in the moisture flux south of 15°N (Cadet and Nnoli 1987; Fontaine et al. 2003). Zhang et al. (2012) pointed out that the decreasing precipitation in Sudan was associated with the weakening African summer monsoon and the summer moisture flux over Sudan tended to be decreasing after the late 1960s that decreased the northward propagation of moisture flux in North Africa.

Previous studies have shown a clear decrease in rainfall and increase in temperature in Sudan and South Sudan, which have had a severe impact on agriculture and other aspects in these two regions. An anxious question is whether these changes will continue to happen in the future in these two regions, which is a critical issue to the agricultural and water resources communities. It is, therefore, important and meaningful to study the future changes of temperature and precipitation in Sudan and South Sudan.

It is generally known that General Circulation Models (GCMs) are the most common tools to study future climate change at large scales (Xu 1999). GCMs have been extensively used to investigate issues of climate variability and climate change over Africa or West Africa (Biasutti and Giannini 2006; Caminade et al. 2006; Hulme et al. 2001; Kamga et al. 2005; Kamga 2001; Kim et al. 2008; Mariotti et al. 2011). However, these studies have illustrated a wide range of differences among precipitation predictions from various GCMs and scenarios in Africa. Biasutti et al. (2008) found that GCMs' projections of rainfall are characterized by a high level of uncertainty in the Sahel region. Druyan (2011) reported a large range of changes of Sahel rainfall in the twenty-first century, as simulated by a variety of climate models. Another key limitation of GCMs is the fairly coarse horizontal resolution, which limits their ability to resolve processes at local and regional scales (Wilby and Wigley 1997; Xu et al. 2005). To cope with this challenge, 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. The methods used to convert GCM outputs into local meteorological variables are usually referred to "downscaling" techniques (Goyal and Ojha 2012; Olsson et al. 2012; Segui et al. 2010). There are various downscaling methods available, which are mainly classified into two categories: dynamic and statistical downscaling methods. Among many statistical downscaling methods, LARS-WG (Long Ashton Research Station Weather Generator) (Racsko et al. 1991; Semenov and Barrow 1997; Semenov et al. 1998; Semenov and Stratonovitch 2010) has the advantage of less data demand. LARS-WG is a model simulating time series of daily weather at a site based on as little as a single year observed data and has been widely used in the assessment of climate change impact (Luo et al. 2010), hydrology (Allen et al. 2010; Hashmi et al. 2011) and other environment issues (Qian et al. 2005; Semenov and Stratonovitch 2010). 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. It is highly desirable to test the applicability of LARS-WG in downscaling weather data in data-scarce region like Sudan and South Sudan and predict the future changing trend of precipitation and temperature.

Motivated by the above-mentioned factors, the main objectives of the study are: (1) to verify the skills of LARS-WG in simulating weather data in Sudan and South Sudan by using historical metrological data and (2) to predict and analyze the future changes of temperature (daily maximum and minimum) and precipitation in Sudan and South Sudan downscaled by LARS-WG based on IPCC

SRA2 scenario generated by seven GCMs' predictions. This study will not only contribute to method selection in predicting local-scale future climate scenarios in the data-scarce regions like Sudan but also provide valuable reference results for future water resources planning and management in the region.

2 Study region and data

Sudan extends gradually from the desert in the north, with its hot dry climate and almost no vegetation cover, through the African Sahel zone in the center (dry to semidry climate) with its light and dense savanna, to the subtropical region in South Sudan with heavier rains and dense tree cover. South Sudan is bordered by Sudan to the north and includes the vast swamp region of the Sudd formed by the White Nile. The most part of Sudan lies in the dry and semidry region and South Sudan is a subtropical region with heavier rains and dense tree cover. Temperatures do not vary greatly with the season in Sudan and South Sudan; however, rainfall and the length of the rainy season are drastically varying. Except in the northeast region, from January to March, the country is under the influence of dry northeasterly winds, and during this period, there is almost no rainfall countrywide except for a small area in north eastern Sudan where the winds pass over the Mediterranean bringing occasional light rains (Zhang et al. 2012). By early April, rainy season starts from South Sudan as the moist south westerlies reach South Sudan, and by August, the southwesterly flows extend to the northern Sudan limits. The dry northeasterlies begin to strengthen in September and to push south and cover the entire Sudan by the end of December.

However, regional- and local-scale analysis of centennial and decadal variability in heavy precipitation is limited by data availability and quality. Indeed, the number of rain gauge stations in Sudan dropped from around 2,000 in the 1970s to only 200 at the present time (Elagib 2011a) and it is difficult for researchers to obtain long-term meteorological data series, especially for daily data. One way to collect meteorological data is from some public databases. Global Historical Climatology Network-Daily (GHCN-D) is a database that addresses the critical need for historical daily temperature, precipitation, and snow records over global land areas. It is designed jointly by the National Climatic Data Center, Arizona State University and the Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory in the USA (Peterson and Vose 1997). Like GHCN monthly database, GHCN-D is a composite of climate records from numerous sources that were merged and then subjected to a suite of quality assurance reviews. Therefore, daily precipitation records, daily maximum temperature (Tmax), and daily minimum temperature (Tmin) records of nine stations in Sudan and South Sudan were obtained from these data sources and used in this study for model calibration and validation. The locations of these stations are shown in Fig. 1 and specific characteristics of the stations are listed in Table 1. The data series used in this study is from 1961 to 1990, which is what is available in the database. Some of the stations have some missing data that do not exceed 5 % of all the data and were replaced by the long-term average values of that missing day.

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. Considering the civil situation of Sudan and South Sudan, SRA2 emission scenario that pays more attention to local tradition and population growth was chosen in this study. Among the 15 GCMs, seven of them had SRA2 scenario and were used to predict the future change of local-scale precipitation and temperature in three periods: 2011–2030, 2046–2065, and 2080–2099 (as listed in Table 2).

3 Methods

3.1 LARS-WG model

LARS-WG is a stochastic weather generator and is used for simulating weather data at a single site under both current and future conditions (Racsko et al. 1991; Semenov and Barrow 1997; Semenov et al. 1998; Semenov and Stratonovitch 2010). LARS-WG uses observed daily weather data for a given site to compute a set of parameters for probability distributions of weather variables as well as correlations between them, which are used to generate synthetic weather time series of arbitrary length by randomly selecting values from the appropriate distributions. To approximate probability distributions of dry and wet series of daily precipitation, Tmax and Tmin, LARS-WG uses a semiempirical distribution (SED) that is defined as the cumulative probability distribution function (CDF). The number of intervals (n) used in SED is 23 in the new version, which offers more accurate representation of the observed distribution compared with the ten used in the previous version. For each climatic variable v, a value of a climatic variable v_i corresponding to the probability p_i is calculated as:

$$v_i = \min\{v : P(v_{obs} \le v) \ge p_i\} i = 0, \ldots, n \quad (1)$$

where $P()$ denotes probability based on observed data $\{v_{\mathrm{obs}}\}$. For each climatic variable, two values, p_0 and p_n, are fixed as $p_0=0$ and $p_n=1$, with corresponding values of $v_0=\min\{v_{\mathrm{obs}}\}$

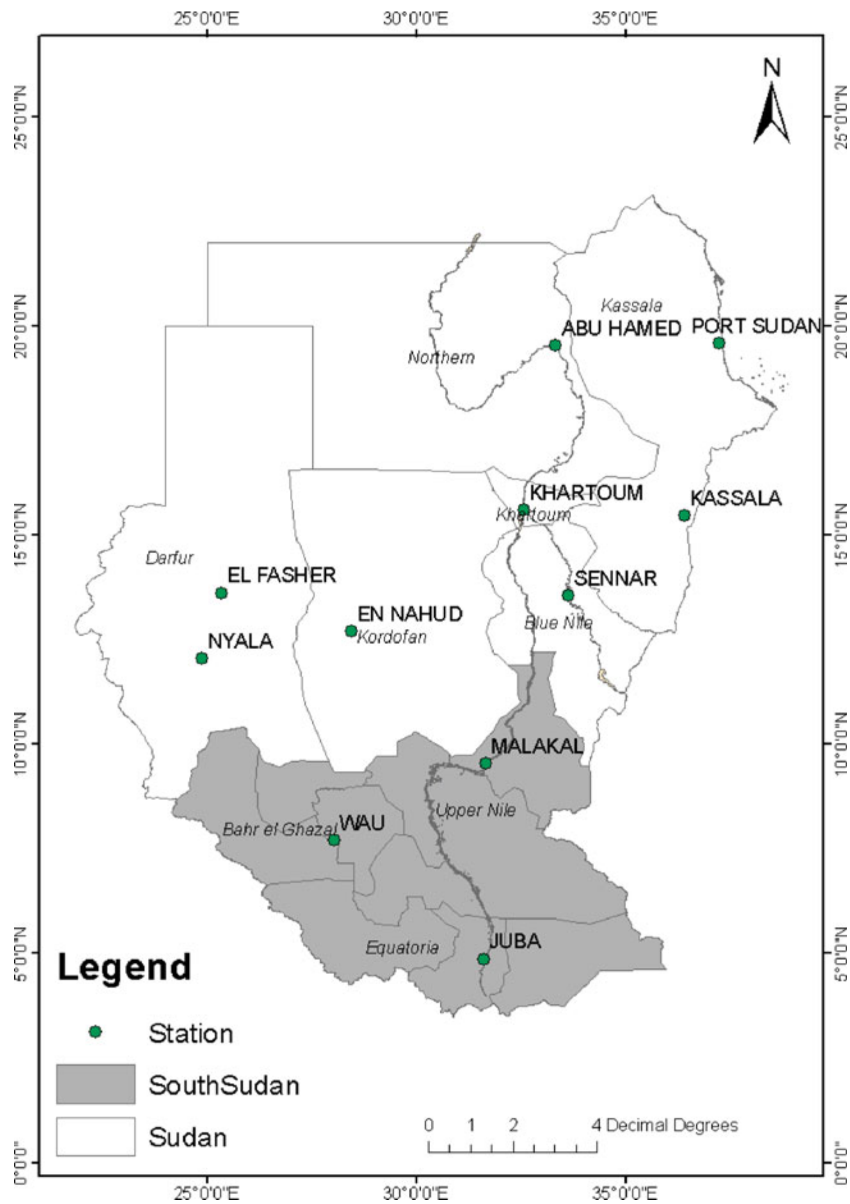

Fig. 1 The location of the weather stations in Sudan and South Sudan used in this study

Table 1 The information of metrological stations in Sudan and South Sudan

Region	Station	Type	Long.	Lat.	Elv. (m)	Length of data	Missing data (%)
Sudan	Abu Hamed	T	19.53	33.32	312	1961–1990	0.664
	Port Sudan	T	37.22	19.58	2	1961–1990	0.033
	Khartoum	P	32.55	15.60	380	1961–1987	2.939
	Kassala	T, P	36.40	15.47	500	1961–1990	0.041
	Sennar	T, P	33.62	13.55	418	1961–1990	0.046
	En Nahud	T, P	28.43	12.70	564	1961–1990	0.493
	El Fasher	P	25.33	13.62	730	1961–1987	0.009
	Nyala	T, P	24.88	12.05	674	1961–1990 (no 1962, 1979)	1.232
South Sudan	Malakal	T, P	31.65	9.55	388	1961–1991	0.05
	Wau	T, P	28.02	7.70	438	1961–1988	2.102
	Juba	T, P	31.60	4.87	457	1961–1990 (no 1971)	0.094

Table 2 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°

and v_n=max{v_{obs}}. To approximate the extreme values of a climatic variable accurately, some p_i are assigned close to 0 for extremely low values of the variable and close to 1 for extremely high values; the remaining values of p_i are distributed evenly on the probability scale.

Because the probability of very low daily precipitation (<1 mm) is typically relatively high and such low precipitation has very little effect on the output of a process-based impact model, we use only two values, v_1=0.5 mm and v_2= 1 mm to approximate precipitation within the interval [0,1] with the corresponding probabilities calculated as $p_i=P(v_{obs\leq}v_i)$ i=1, 2. To account for extremely long dry and wet series, two values close to 1 are used in SEDs for wet and dry series, p_{n-1}=0.99 and p_{n-2}=0.98.

For maximum and minimum temperatures, two values close to 0 and two values close to 1 are used to account for extremely low and high temperatures, i.e., p_2=.01, p_3=0.02, p_{n-1}=0.99 and p_{n-2}=0.98. All p_i values ($0<i<n$). In the new version of LARS-WG (5.5), the maximum and minimum temperatures for dry and wet days are approximated by SEDs calculated for each month (Semenov and Stratonovitch 2010).

3.2 Outline of the stochastic weather generation process 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 modeling procedure can be referred to Semenov (2002):

3.2.1 Model calibration

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

3.2.2 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 is to analyze and compare the statistical characteristics of the observed and synthetic weather data to assess the 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.

3.2.3 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.

3.3 Generation of climate scenarios

By perturbing parameters of distributions for a site with the predicted changes of climate derived from global or regional climate models, a daily climate scenario for this site could be generated and used in conjunction with a process-based impact model for assessment of impacts. To generate climate scenarios at a site for a certain future period and an emission scenario, the LARS-WG baseline parameters, which are calculated from observed weather for this site for a baseline period, for instance, 1961–1990, are adjusted by the Δ-changes for the future period and the emissions predicted by a GCM for each climatic variable for the grid covering the site. 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 (5.5) for the time periods of 2011–2030, 2046–2065, and 2080–2099 to predict the future change of precipitation and temperature in Sudan and South Sudan. Semenov and Stratonovitch (2010) introduced and used the procedure to generate the local-scale climate scenarios based on the IPCC AR4 multimodel ensemble to assess the changes in probability of heat stress around flowering for wheat at several locations in Europe.

4 Results and discussions

4.1 Results of calibration and validation of LARS-WG

The daily data during the period of 1961–1990 were used to calibrate and validate the model for each station. To access the ability of LARS-WG, in addition to 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 results have been listed in Table 3, where the numbers show how many tests give significant different results at the 5 % significance level out of the total number of tests of eight or 12. A large number indicates a poor performance of the generator. It can be seen from Table 3 that the average number of significant different results for seasonal wet and dry series distributions was three out of eight; the average number of significant results for the daily rainfall distributions (RainD) is 1.67 out of 12; for the monthly means (RMM) is 1.44 out of 12; and for the monthly variance (RMV) is four out of 12, respectively. The average numbers of significant results for TminD, TminM, TmaxD, and TmaxM are either zero or close to one. 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.

For illustrative purposes, the comparisons of monthly mean and standard deviation of the simulated and observed rainfall were drawn in Figs. 2 and 3 for all stations, respectively. It can be seen from Fig. 2 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 (Fig. 3) as it is known for being difficult to simulate well the standard deviations in most statistical downscaling studies. Figure 4 shows that LARS-WG-simulated monthly mean daily Tmax and Tmin values match very well with the observed values of the study stations for all months, which also verifies that the new version of LARS-WG has great capacity in simulating the extreme temperature.

4.2 Generations of future climate scenarios

From the above analysis, it can be concluded that the LARS-WG model has good performance in most stations in generating daily precipitation and daily Tmax and Tmin, and it was then used to predict daily precipitation and daily Tmax and Tmin for the nine stations for the periods of 2011–2030, 2046–2065, and 2080–2099 based on the A2 scenarios generated from seven GCMs. The results of the precipitation and temperature predictions by using LARS-WG were plotted on Figs. 5–8 for illustrative purposes. In Fig. 5, the box–whisker plots showed the distribution of precipitation, Tmax, and Tmin data for Sudan and South Sudan downscaled from seven GCMs by using LARS-WG in the period of 2080–2099 comparing with the current observation (1961–1990). The plot elements and the statistics are as follows: the length of the box represents the interquartile

Table 3 Results of the statistical tests comparing the observed data for 9 sites with 500 years of 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

Sites	WDSeries	RainD	RMM	RMV	TminD	TminM	TmaxD	TmaxM
Abu Hamed	–	–	–	–	0	2	0	1
Port Sudan	–	–	–	–	0	1	0	2
Khartoum	4	4	2	5	–	–	–	–
Kassala	4	1	2	5	0	2	0	4
El Fasher	1	2	0	4	–	–	–	–
Sennar	4	4	2	5	0	1	0	2
En Nahud	3	0	1	3	0	2	0	1
Nyala	3	0	1	5	0	0	0	0
Malakal	3	1	0	3	0	1	0	0
Wau	3	2	4	4	0	2	0	2
Juba	2	1	1	2	0	0	0	0
Average	3	1.67	1.44	4	0	1.22	0	1.33
Total tests	8	12	12	12	12	12	12	12

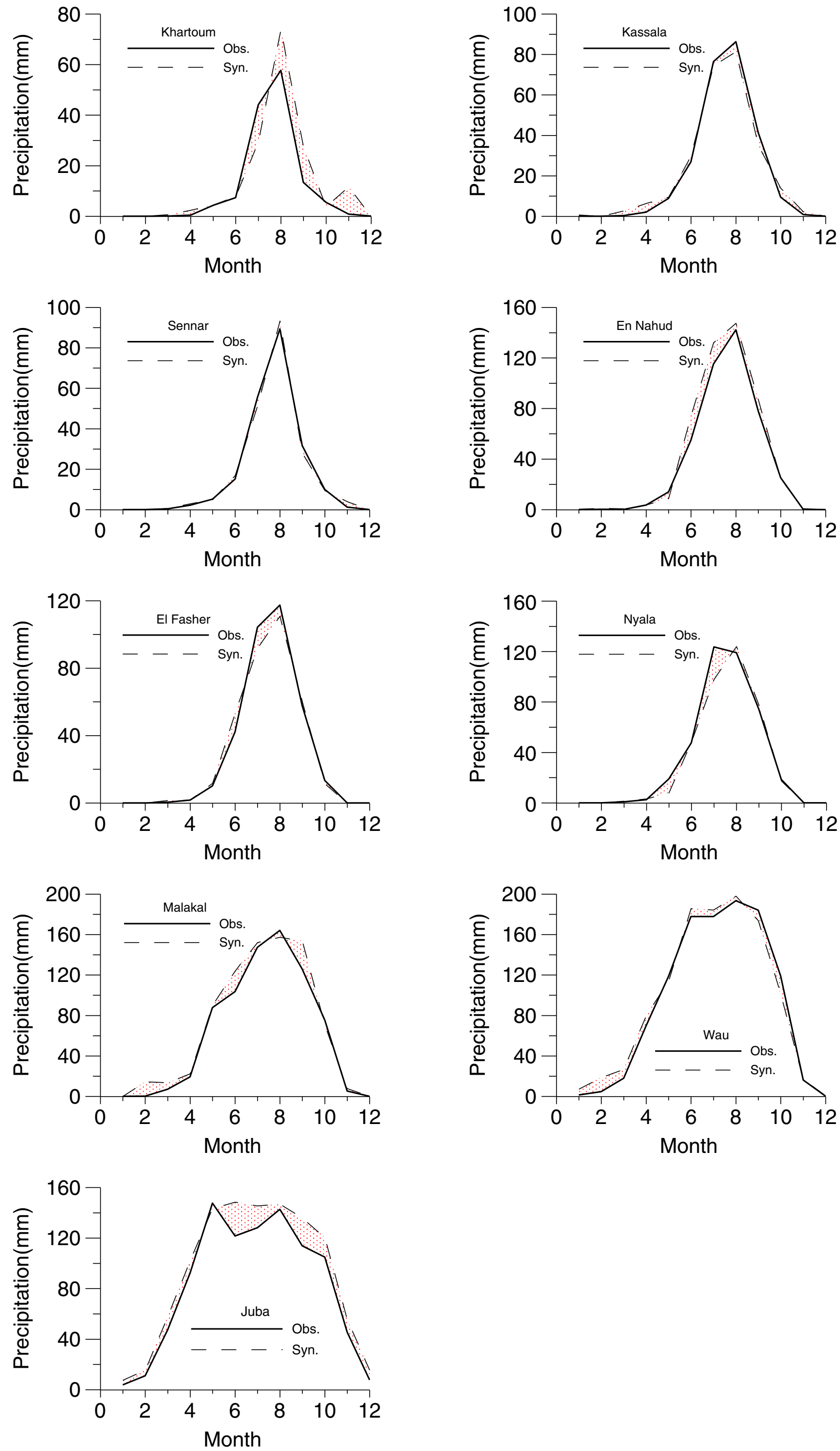

Fig. 2 A comparison of the observed mean monthly precipitation at each station to the LARS-WG-simulated values in the period 1961–1990

range (the distance between the 25th and 75th percentiles), the horizontal line in the box interior represents the group median, and the vertical lines (called whiskers) issuing from the box extends to the group minimum and maximum values. In Fig. 5, each box–whisker plot represents the prediction from one GCM and it is easy to find that there are no coherent change trends among various GCMs' predictions of precipitation during 2080–2099 in both regions. In Sudan, the precipitation predictions from GFCM21 and IPCM4 during 2080–2099 are less than the values of baseline period; however, those from HADCM3, INCM3, and NCCCS are more than the values of the baseline period. In South Sudan, the precipitation predictions from HADCM3, INCM3, MPEH5, and NCCCS during 2080–2090 are more than the values of the baseline period. This showed great differences of the predictions from the seven

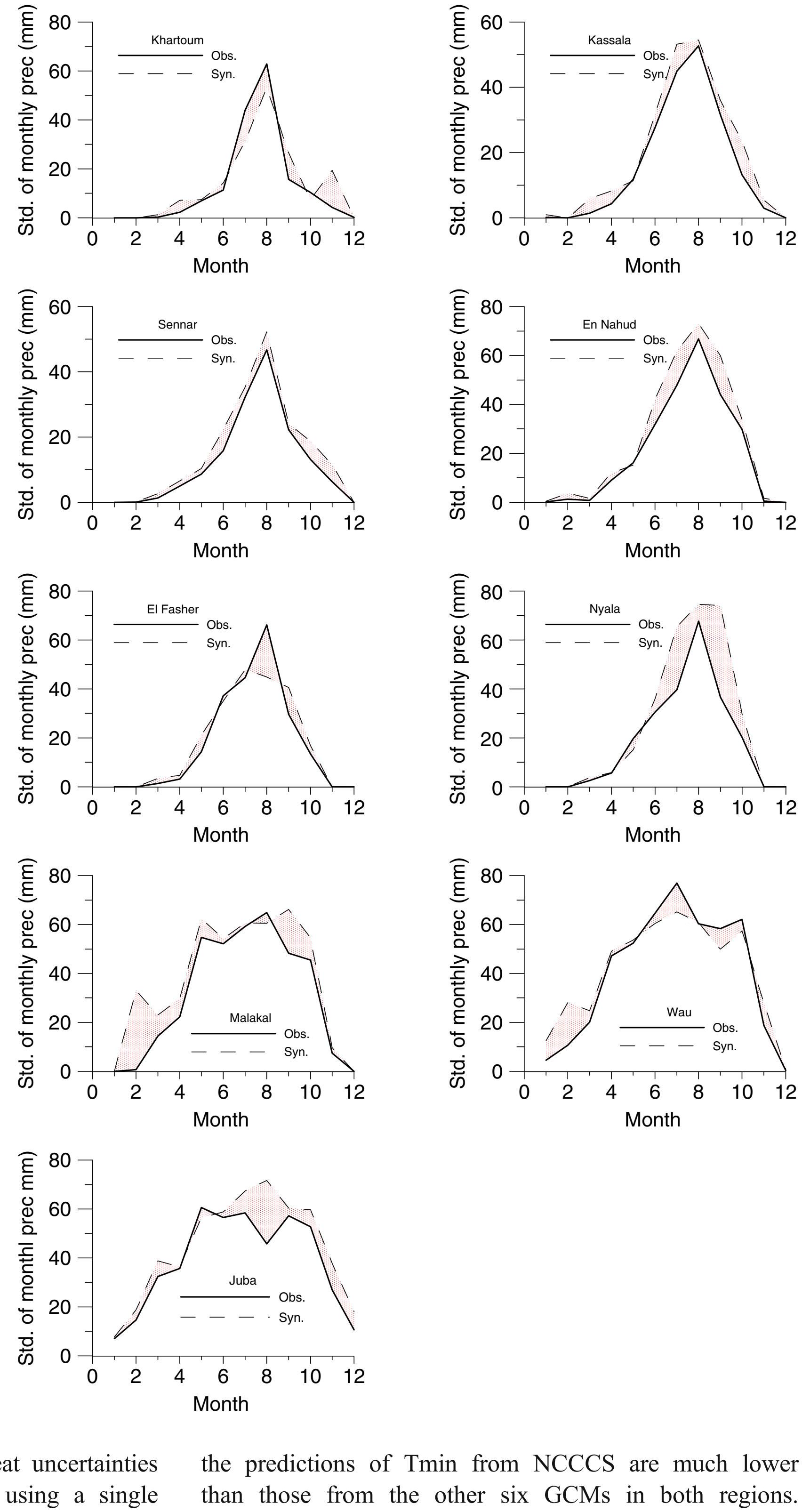

Fig. 3 A comparison of the standard deviation of observed monthly precipitation at each station to the LARS-WG-simulated values in the period 1961–1990

GCMs, which indicates that there are great uncertainties in predicting the future precipitation by using a single GCM. Differently from precipitation simulations, the predictions of Tmax and Tmin from these seven GCMs have coherent change trends for both regions during 2080–2099. The predictions of Tmax from INCM3 and NCCCS are lower than those from other five GCMs and the predictions of Tmin from NCCCS are much lower than those from the other six GCMs in both regions. Although there are differences among the temperature predictions from seven GCMs, it can be seen that Tmax and Tmin have increasing trends in the periods of 2080–2099 as compared with the current climate (1961–1990) from the Fig. 5. It can be summarized that

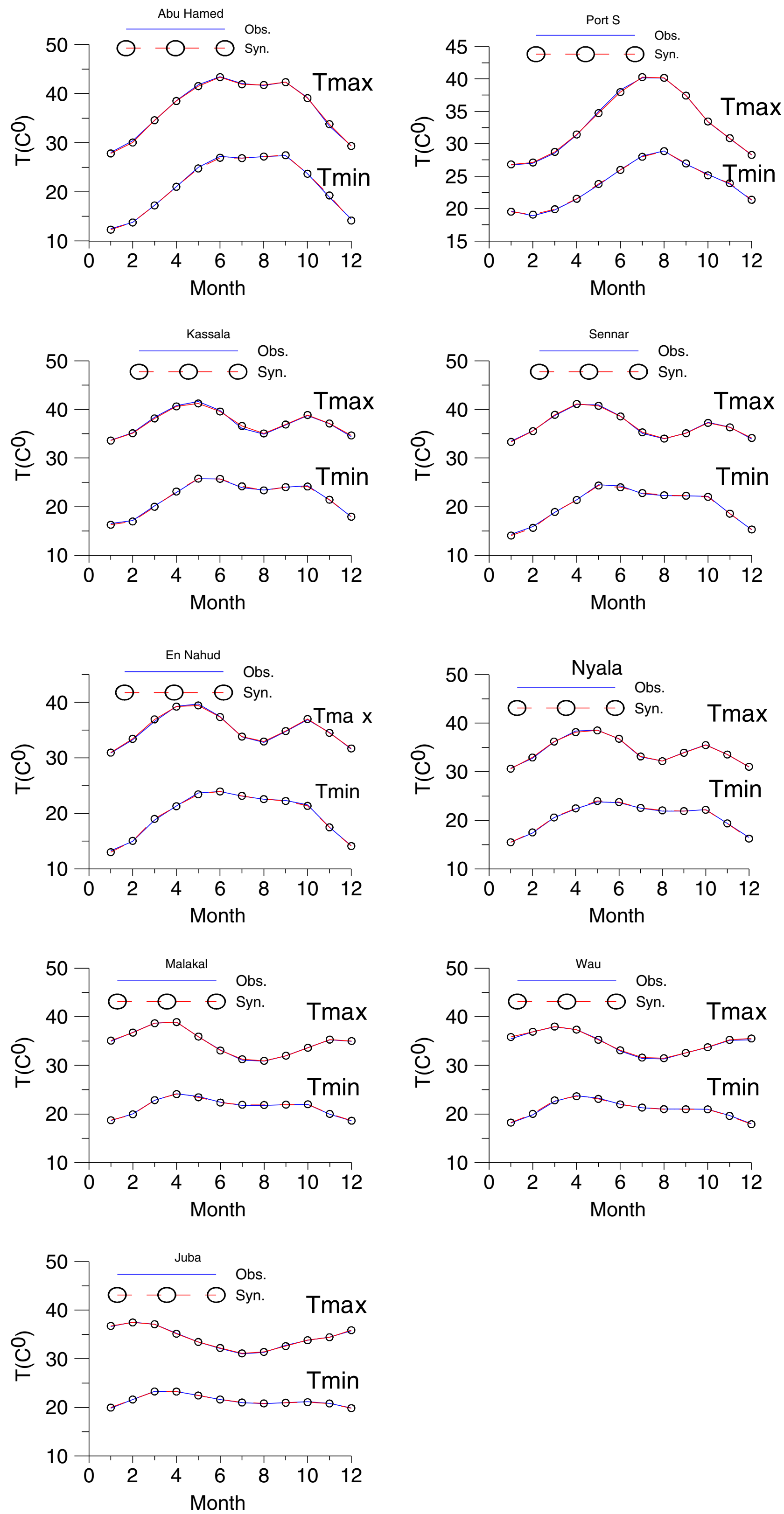

Fig. 4 A comparison of the mean monthly observed Tmin and Tmax at each station to that of LARS-WG-simulated values in the period 1961–1990

a similar and continuous increasing trend in both Tmax and Tmin can be found for both regions from all seven GCMs in the future.

The ensemble means of precipitation predictions from seven GCMs were calculated to further illustrate the future change in the period of 2011–2030, 2046–2065, and 2080–

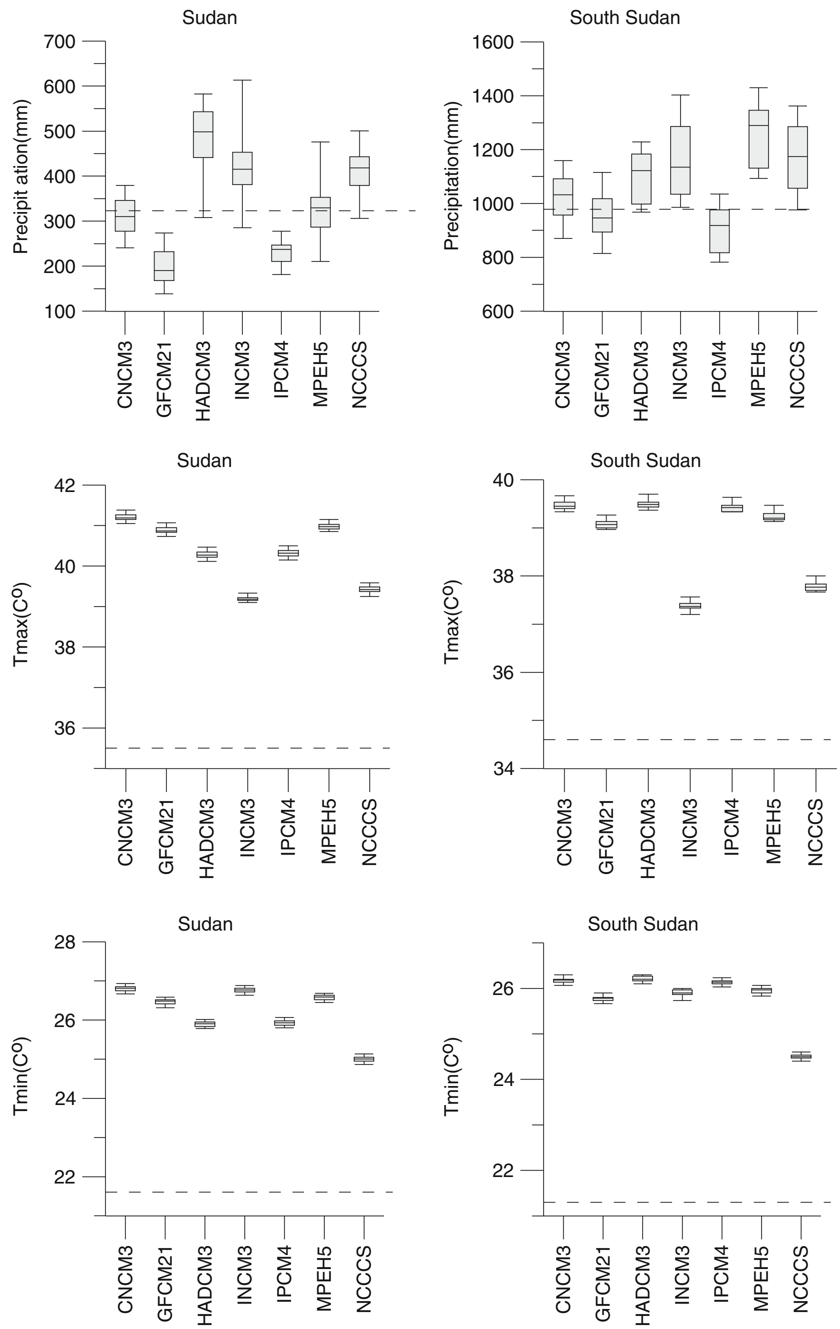

Fig. 5 Box–whisker plots show the change of precipitation for each station downscaled from 7 GCMs by using LARS-WG during 2080–2099 compared with the value of the current period (1961–1990). In the plot the minimum, maximum, and median percentiles of precipitation from GCMs in this period are shown. The *dashed line* is the value of the observation in the baseline period

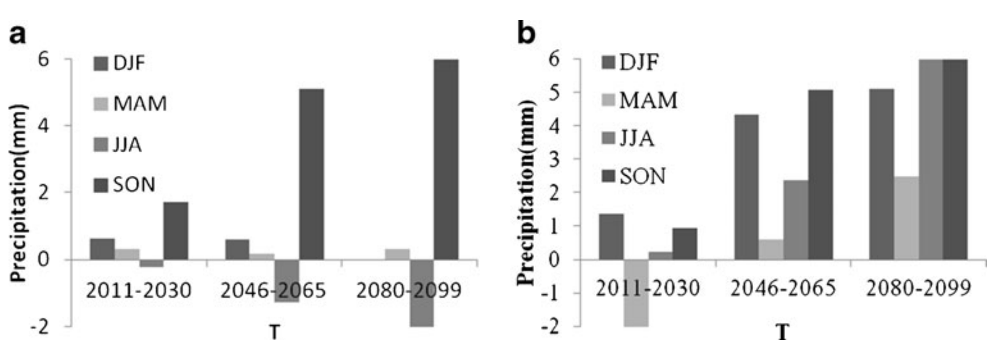

Fig. 6 The differences of precipitation between the future periods (2011–2030, 2046–2065, and 2080–2099) and the current period (1961–1990) in Sudan (**a**) and South Sudan (**b**) through calculating the mean ensemble of 7 GCMs

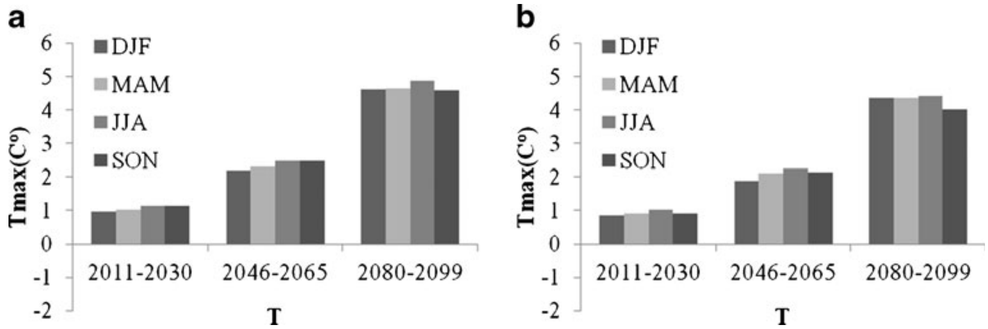

Fig. 7 The differences of the maximum temperature between the future periods (2011–2030, 2046–2065, and 2080–2099) and the current period (1961–1990) in Sudan (**a**) and South Sudan (**b**) through calculating the mean ensemble of 7 GCMs

2099, and the differences between the ensemble means and baseline values for the seasonal precipitation were plotted in Fig. 6 for the periods of 2011–2030, 2046–2065, and 2080–2099. It is seen that in Sudan, the precipitation in JJA (June, July, and August) shows a decreasing trend in the periods of 2011–2030, 2046–2065, and 2080–2099. This result is consistent with other early studies in Africa. Mariotti et al. (2011) conducted RegCM3 and one GCM ECHAM4 to project climate change over Africa in the twenty-first century and indicated that there was a decreasing trend in JJA season in the West Sahel regions. An obvious increasing trend of precipitation in SON (September, October, and November) can be found in Sudan in the future. In South Sudan, the precipitation showed increasing trends in all seasons in the future except in JJA in 2011–2030. From the above discussions, it can be inferred that Sudan and South Sudan have different change trends of precipitation in the main rainy season JJA in the future. The increases of Tmax and Tmin during the three future periods, i.e., 2011–2030, 2046–2065, and 2080–2099, as compared with the current climate (1961–1990) are about 1.0–1.5 °C, 2.5–3.0 °C, and 4.5–5.5 °C, respectively, in these two regions (as shown in Figs. 7 and 8). The temperature predictions in the future in Sudan and South Sudan are consistent with other earlier studies (Caminade et al. 2006; Kamga et al. 2005; Mariotti et al. 2011). From the above analysis, it is certain that the warming will last for a long time in Sudan and South Sudan in the future, which will force the environment to become less hospitable to plants. These warming effects appear to be amplifying the effects of drought and can combine with decreases in rainfall in JJA season to reduce crop yield.

5 Conclusions

In the present study, we first tested the applicability of the LARS-WG model in downscaling daily precipitation and daily maximum (Tmax) and daily minimum (Tmin) temperatures in Sudan and South Sudan and then used LARS-WG to downscale future changes of precipitation, Tmin, and Tmax for nine stations in Sudan and South Sudan from the seven GCM outputs of SRA2 scenario for the periods of 2011–2030, 2046–2065, and 2080–2099. Due to limitations of data availability, nine stations of precipitation and temperature data for the period of 1961 to 1990 were used for calibrating the downscaling model and for comparison with future scenarios. From the study, it is concluded that:

- The LARS-WG model is able to perform well in downscaling daily precipitation and excellent in downscaling Tmax and Tmin in the study region;
- The downscaled precipitation from the predictions of seven GCMs has different changing trends in the future three periods. This also illustrates that more GCMs should be considered in the study of climate change to reduce the uncertainty of GCMs;
- The precipitation prediction in main rainy season JJA in Sudan shows a decreasing trend in the future, which will bring more difficulty in Sudan's agriculture productivity.

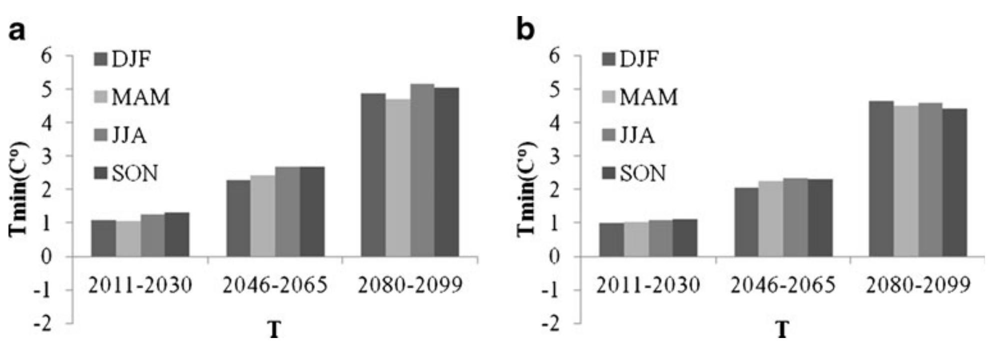

Fig. 8 The differences of the minimum temperature between the future periods (2011–2030, 2046–2065, and 2080–2099) and the current period (1961–1990) in Sudan (**a**) and South Sudan (**b**) through calculating the mean ensemble of 7 GCMs

However, South Sudan will receive more rainfall in the future as precipitation predictions in most seasons showed increasing trends in South Sudan;

- The downscaled Tmax and Tmin from the predictions of seven GCMs showed consistent results for all the stations in the future, i.e., a continuous and similar increasing trend for both Tmax and Tmin in all three future periods in the two regions.

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References

Allen, D.M., Cannon, A.J., Toews, M.W., Scibek, J. (2010) Variability in simulated recharge using different GCMs. Water Resources Research 46.

Alvi SH (1994) Climatic changes, desertification and the Republic of Sudan. GeoJournal 33(4):393–399

Alvi SH, Elagib NA (1996) Study of hydrology and drought in the flood region of Sudan. Water Int 21(2):76–82

Ayoub AT (1999) Land degradation, rainfall variability and food production in the Sahelian zone of the Sudan. Land Degradation Dev 10(5):489–500

Bell MA, Lamb PJ (2006) Integration of weather system variability to multidecadal regional climate change: the West African Sudan-Sahel zone, 1951–98. J Climate 19(20):5343–5365

Biasutti M, Giannini A (2006) Robust Sahel drying in response to late 20th century forcings. Geophys Res Lett 33(11)

Biasutti M, Held IM, Sobel AH, Giannini A (2008) SST forcings and Sahel rainfall variability in simulations of the twentieth and twenty-first centuries. J Climate 21(14):3471–3486

Cadet D, Nnoli N (1987) Water vapour transport over Africa and the Atlantic Ocean during summer 1979. Q J R Meteorol Soc 113 (476):581–602, Quarterly Journal of the Royal Meteorological Society 113(476): 581–602

Camberlin P (1995) June–September rainfall in north-eastern Africa and atmospheric signals over the tropics: a zonal perspective. Int J Climatol 15:773–783

Caminade C, Terray L, Maisonnave E (2006) West African monsoon response to greenhouse gas and sulphate aerosol forcing under two emission scenarios. Clim Dyn 26(5):531–547

Druyan LM (2011) Studies of 21st-century precipitation trends over West Africa. Int J Climatol 31(10):1415–1424

Elagib NA (2010) Trends in intra- and inter-annual temperature variabilities across Sudan. Ambio 39(5–6):413–429

Elagib NA (2011a) Changing rainfall, seasonality and erosivity in the hyper-arid zone of Sudan. Land Degrad Dev 22(6):505–512

Elagib NA (2011b) Evolution of urban heat island in Khartoum. Int J Climatol 31(9):1377–1388

Eldredge E, Khalil SE, Nicholds N, Abdalla AA, Rydjeski D (1988) Changing rainfall patterns in western Sudan. J Climatol 8(1):45–53

Eltahir EAB (1989) A feedback mechanism in annual rainfall, Central Sudan. J Hydrol 110(3–4):323–334

Fontaine B, Roucou P, Trzaska S (2003) Atmospheric water cycle and moisture fluxes in the West African monsoon: mean annual cycles and relationship using NCEP/NCAR reanalysis. Geophys Res Lett 30(3)

Funk C, Eilerts G, Verdin J, Rowland J, Marshall M (2011) A climate trend analysis of Sudan. U.S. Geol Surv Fact Sheet 2011–3072:1–6

Goyal MK, Ojha CSP (2012) Downscaling of precipitation on a lake basin: evaluation of rule and decision tree induction algorithms. Hydrol Res 43(3):215–230

Hashmi MZ, Shamseldin AY, Melville BW (2011) Comparison of SDSM and LARS-WG for simulation and downscaling of extreme precipitation events in a watershed. Stoch Env Res Risk A 25(4):475–484

Hulme M, Doherty R, Ngara T, New M, Lister D (2001) African climate change: 1900–2100. Climate Research 17(2):145–168

Kamga AF, Jenkins GS, Gaye AT, Garba A, Sarr A, Adedoyin A (2005) Evaluating the National Center for Atmospheric Research Climate System model over West Africa: present-day and the 21st century A1 scenario. J Geophys Res-Atmos 110(D3)

Kamga FM (2001) Impact of greenhouse gas induced climate change on the runoff of the Upper Benue River (Cameroon). J Hydrol 252 (1–4):145–156

Kim U, Kaluarachchi JJ, Smakhtin VU (2008) Generation of monthly precipitation under climate change for the upper blue nile river basin, Ethiopia. J Am Water Resour Assoc 44(5):1231–1247

Lamb P (1978a) Case studies of Tropical Atlantic surface circulation patterns during recent Subsaharan weather anomalies: 1967 and 1968. Mon Wea Rev 106:482–491

Lamb P (1978b) Large-scale Tropical Atlantic surface circulation patterns associated with Subsaharan weather anomalies. Tellus Ser A-Dyn Meteorol Oceanogr 30(240–251)

Luo QY, Bellotti W, Hayman P, Williams M, Devoil P (2010) Effects of changes in climatic variability on agricultural production. Clim Res 42(2):111–117

Mariotti, L., Coppola, E., Sylla, M.B., Giorgi, F., Piani, C. (2011) Regional climate model simulation of projected 21st century climate change over an all-Africa domain: comparison analysis of nested and driving model results. Journal of Geophysical Research-Atmospheres 116.

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

Osman YZ, Shamseldin AY (2002) Qualitative rainfall prediction models for central and southern Sudan using El Niño–Southern Oscillation and Indian Ocean sea surface temperature indices. Int J Climatol 22(15):1861–1878

Osman YZ, Shamseldin AY, Abdo GM (2001) El Niño–Southern Oscillation and rainfall variability in central and southern Sudan. Water Int 26(2):177–184

Palmer T (1986) Influence of the Atlantic, Pacific and Indian oceans on Sahel rainfall. Nature 322:251–253

Peterson TC, Vose RS (1997) An overview of the Global Historical Climatology Network temperature database. Bull Am Meteorol Soc 78(12):2837–2849

Qian BD, Hayhoe H, Gameda S (2005) Evaluation of the stochastic weather generators LABS-WG and AAFC-WG for climate change impact studies. Clim Res 29(1):3–21

Racsko P, Szeidl L, Semenov M (1991) A serial approach to local stochastic weather models. Ecol Model 57(1–2):27–41

Segui PQ, Ribes A, Martin E, Habets F, 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. (2002) LARS-WG: a stochastic weather generator for use in climate impact studies. http://www.rothamsted.ac.uk/mas-models/larswg.php User Manual: 1–27.

Semenov MA, Barrow EM (1997) Use of a stochastic weather generator in the development of climate change scenarios. Clim Chang 35(4):397–414

Semenov MA, Brooks RJ, Barrow EM, Richardson CW (1998) Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates. Clim Res 10(2):95–107

Semenov MA, 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 RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. Prog Phys Geogr 21(4):530–548

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

Xu C-Y, Zhang Q, El Tahir MEH, Zhang Z (2010) Statistical properties of the temperature, relative humidity, and net solar radiation in the Blue Nile–eastern Sudan region. Theor Appl Climatol 101(3–4):397–409

Xu CY (1999) From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. Prog Phys Geogr 23(2):229–249

Zhang Z, Xu C-Y, El-Tahir M, Cao J, Singh V (2012) Spatial and temporal variation of precipitation in Sudan and their possible causes during 1948–2005. Stoch Environ Res Risk Assess 26(3):429–442