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Research Article

Trend analysis in observed and projected precipitation and mean temperature over the Black Volta Basin, West Africa

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Abstract

The study analyzed the trends in observed (1981-2010) and future projected annual precipitation and mean temperature over the Black Volta River Basin using the Mann-Kendall test and the Sen's slope estimator. Projected changes in precipitation and temperature by multi-model ensemble runs over the Black Volta basin for the late (2051-2075) and end of the 21st century (2076-2100) horizons under two IPCC Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios was also analyzed. The results showed statistically significant (at the 5% significance level) increase of 111mm in the annual rainfall over the observed period. The future direction of this trend is uncertain as some ensemble members projected positive trends while others gave negative trends. However, both the positive and negative future trends in the rainfall were statistically non-significant. The results also showed that the studied basin has warmed over the observed period, with significant increase of 0.9°C in the mean annual temperature. Similarly, significant increasing trend in the mean annual temperature are projected by the ensemble runs under both RCPs for the late and end of the 21st century. Analyses of the average annual, intra-annual and seasonal precipitation indicated high uncertainty regarding the direction of the future rainfall. Mean annual precipitation change for the late 21st century ranged between -16% and +6% under the RCP4.5 scenario and between -27% and +14% under the RCP8.5 scenario. The end of the 21st century projections showed changes in mean precipitation amounts ranging between -23% and +2% and between -33% and +13% under the RCP4.5 and RCP8.5 scenarios, respectively. With regards to temperature, average annual projections by the ensemble runs showed increases over the basin under both RCP scenarios and for both time periods. Warming over the basin is projected to be higher under the RCP8.5 scenario than under the RCP4.5 scenario, with the end of 21st century period being warmer than the late 21st century. Average annual mean temperature increase across the model run ranged between 2.2°C and 2.6°C under the RCP4.5 scenario and between 3.5°C and 3.7°C under the RCP8.5 scenario for the end of the 21st century.

Keywords: *Climate change, precipitation, temperature, CORDEX West Africa, Black Volta Basin*

1. Introduction

The IPCC highlighted in their Fifth Assessment Report that each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (IPCC, 2014a). Indeed, the effects of rising temperatures are being felt globally and there is increasing pressure to put in effective and practicable adaptation measures at the regional and local levels. In West Africa, for example, temperatures are projected to increase by between 3°C and 6°C by the end of the 21st century under a range of scenarios. Whereas rainfall projections for the region are less certain many global models project a wetter main rainfall season with a slight delay in the start of the rainfall season towards the end of the 21st century (CDKN, 2014). Changes in climate are expected to increase the pressure on water availability, affect food security and impact on human health in the region (IPCC 2013, IPCC 2014b). The Black Volta River Basin in West Africa supports economic activities such as agriculture, hydro-power generation and domestic water supply in Burkina Faso, Cote D'lvoire and Ghana. These hydrological benefits are threatened by global change (Kasei, 2009). Therefore, information on the current climate as well as the projected changes in the future can be useful for the sustainable development and management of water and other natural resources in the region.

In the past, climate projections over West Africa were limited in part by the coarse resolution of GCMs (normally 100–400 km resolution) as well as the large spread among GCM projections (Hoerling *et. al.,* 2006;

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Giannini *et al*., 2008). More recently, however, the Coordinated Regional Downscaling EXperiment (CORDEX), an initiative founded by the World Climate Research Program of the World Meteorological Organization produced an ensemble of high-resolution historical and future climate projections at regional scales (Giorgi *et al*. 2009; Jones *et al*. 2011). For the Africa domain, the RCM simulations are at a grid resolution of 0.44°x 0.44° (approximately 50 km), which is an improvement over previous simulations for Africa. Studies conducted over the entire African continent (e.g. Nikulin *et al*., 2012; Panitz *et al*., 2014; Kim *et al*., 2014 and Dosio *et al*., 2015) and at the regional level (e.g. Klutse *et al*., 2014; Abiodun *et al*., 2015 and Endris *et al*., 2015) have shown that CORDEX RCMs simulate well the spatial and temporal distributions of the West African precipitation, with some seasonal and sub-regional biases.

In this study we analyzed the trends in historical (1981-2010) annual precipitation and mean temperature over the Black Volta River Basin using the Mann-Kendall test and Sen's slope estimator. The study also analyzed 12 ensemble runs together with 4 ensemble means of the runs generated from the combination of 2 RCMs driven by 3 GCMs for the IPCC medium-low (RCP4.5) and high (RCP8.5) emission scenarios for the late 21st century (2051-2075) and end of the 21st century (2076-2100). The trends in the projected annual precipitation and mean temperature were also evaluated.

2. Materials and Methods

2.1 Study area

The Black Volta River Basin (BVRB) is a major sub-basin of the Volta River Basin in West Africa. It is located between Latitude 7.0°N and 14.0°N and Longitude 5.3°W and 1.3°W (Annor, 2012). The basin is shared by Ghana, Burkina Faso, Cote D'Ivoire and Mali (Figure 1) and has a total area of about 142,056 km^2. The annual climate in the basin is characterized by two distinct periods of wet or rainy season and the dry season. Rainfall pattern in the northern half of the basin is mono-modal with peak in August/September while the South has a bi-modal pattern with peaks in May/June and August/September. The mean annual rainfall varies from less than 500mm in the extreme north of the basin in Mali to about 1,350 mm in the forested areas in south-eastern Ghana (MWH, 1998). About three-quarters of the annual rainfall occur between May and September (Obuobie *et al*., 2017). Studies in the evolution of rainfall in West Africa where the BVRB is located revealed that the region suffered strong rainfall deficit in the 1970's following wet periods in the 1950s and 1960s (Hubert and Carbonnel, 1987; Mahe *et al*., 2001; Nicholson and Palao, 1993; Nicholson, 2000). According to recent studies (Druyan, 2011; Ibrahim *et al*., 2014; Sylla *et al*., 2016) precipitation over some parts of West Africa has seen some recovery since the 1980s. Average monthly minimum temperature in the basin ranges between 18^{o}C to 25^{o}C while average maximum temperatures range from 30^{o}C to 37^{o}C. Agriculture represents the main economic activity of the basin, with the most commonly cultivated crops (usually under rain- fed conditions) being millet, sorghum, maize, groundnuts and yams (Barry et. al., 2005). The Basin's population was approximately 4.5 million in 2000 and projected to reach 8 million by 2025 (Annor, 2012). The population density ranges between 8 and 123 people/km2 (Allwaters Consult, 2012), and the population growth rate, around 3% per annum (Green Cross International, 2001).

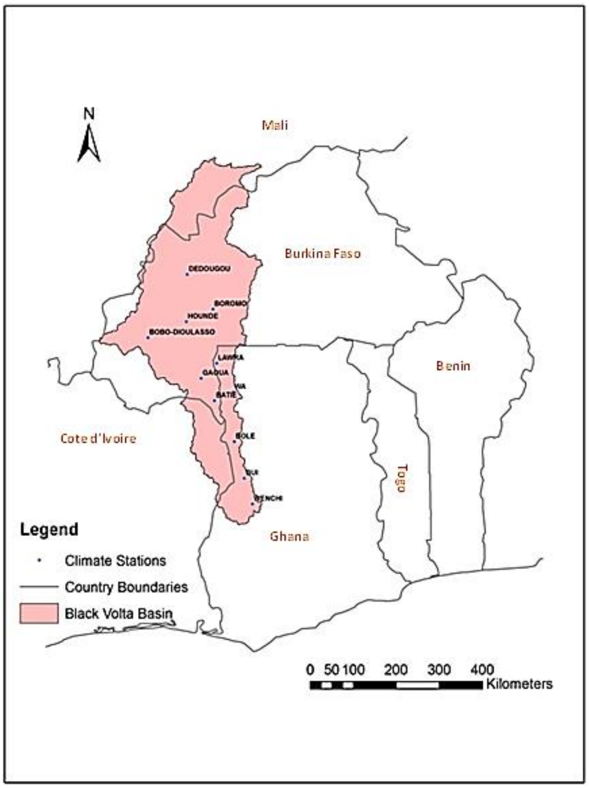


Fig.1 Map of Black Volta Basin with Meteorological stations used in the study

2.2 Data set and model description

The data used in this study included observed (1981-2010) precipitation and mean temperature series for eleven climate stations (Table 1) in the BVRB obtained from the Meteorological Agencies in Ghana and Burkina Faso. Model simulation data covering 1981-2005 (control period) and 2051-2100 (future period) for RCP 4.5 and RCP 8.5 were obtained from the CORDEX West African project. As mentioned earlier, the simulation data consisted of projections from 2 RCMs driven by 3 GCMs for a total of 3RCM/GCM pairs (Table 2). The 2 RCMs, were the Rossby Centre of the Swedish Meteorological and Hydrological Institute (SMHI) regional climate model - fourth generation (RCA4) and the Regional Atmospheric Climate Model (RACMO). Simulations from these models were used as they were the only data available to us at the time of the study. The RCA4 is based on HIRLAM, a numerical weather prediction model and is an improvement of the RCA3 (Samuelsson *et al*. 2011). It has undergone physical and technical changes to make it applicable for any domain worldwide (Strandberg *et al*., 2014). Within the CORDEX project framework, the SMHI applied the RCA4 model to (Strandberg *et al*., 2014) downscale the ERA-Interim Reanalysis (1980-2010) and eight (8) different GCMs from the Coupled Model Intercomparison Project 5 (CMIP5) archives over the African domain (Jones *et al*., 2011, Nikulin *et al*., 2012). The data are available for RCP 2.6, RCP4.5 and 8.5 and cover the period 1951-2100. The Regional Atmospheric Climate Model (RACMO) is on the other hand a hydrostatic limited-area model developed and maintained by the modeling group at the Royal Netherlands Meteorological Institute (KNMI) (van Meijgaard *et al*., 2008). The first version of the model, RACMO1 combines the HIRLAM model with the physics of ECHAM4. The second version, RACMO2, was developed based on the ECMWF-NWP release cy23r4 and the Numerical Weather Prediction (NWP) model HIRLAM version 5.0.6 (Lenderink *et al*., 2003). Climate change simulations generated with RACMO22T model, driven by the EC-EARTH for RCP 4.5 and 8.5 within the CORDEX project are used in this study.

Table 1 Climate stations used in this study

No.	Station Name	Latitude (°)	Longitude (°)
1	Batie (BF)	9.86	-2.9
2	Bobo-Dioulasso (BF)	11.17	-4.3
3	Bole (GH)	9.03	-2.48
4	Boromo (BF)	11.73	-2.92
5	Bui (GH)	8.28	-2.27
6	Dedougou (BF)	12.46	-3.48
7	Gaoua (BF)	10.33	-3.18
8	Hounde (BF)	11.48	-3.5
9	Lawra (GH)	10.63	-2.85
10	Wa (GH)	10.05	-2.5
11	Wenchi (GH)	7.75	-2.1

*BF=Burkina Faso; GH=Ghana

Table 2 RCMs with driving GCMs from CORDEX used in this study

Regional Climate Model (RCM)	Global Climate Model (GCM)	GCM/RCM Combination
RCA4 (SMHI) (Samuelsson *et al.* 2011; Kupiainen *et al.* 2011; Strandberg *et al.* 2014)	MPI-ESM-LR (MPI-M)(Stevens *et al.* 2013)	RCA4/ MPI-ESM-LR
RCA4 (SMHI) (Samuelsson *et al.* 2011; Kupiainen *et al.* 2011; Strandberg *et al.* 2014)	CCCma-CanESM2 (Chylek *et al.*, 2011)	RCA4/CCCma-CanESM2
KNMI Regional Climate Model, (RACMO22T) (van Meijgaard *et al.* 2008)	ICHEC-EC-EARTH (Hazeleger *et al.* 2010)	RACMO22T/ ICHEC-EC-EARTH

2.3 Trend analysis of observed and projected annual precipitation and mean temperature

Assessment of trends in observed (1981-2010) and projected (2051-2075 and 2076-2100) annual precipitation and mean temperature over the basin was carried out using the non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall 1975; Gilbert 1987). The MK test has been widely applied in analyzing trends in climatologic and hydrologic time series (Mavromatis and Santhis, 2011; Karpouzos *et al*., 2010; Yue and Wang 2004). According to the test, a null hypothesis H_0, which assumes that there is no trend in the series (the data is independent and randomly ordered), is tested against an alternative hypothesis, H_1, which assumes otherwise (Onoz and Bayazit, 2012). For this study, the null hypothesis was tested at the significance level $\alpha=0.05$ for both annual precipitation and mean temperature. P-values less than 0.05 indicated the existence of statistically significant trends while P-values greater than 0.05 indicated that trends in the series were statistically insignificant. The magnitude (slope) of the trends were estimated using the Sen's slope estimator (Sen, 1968). A brief explanation of the procedure for the MK test and the Sen's estimator are presented in Appendix A1 and A2 respectively. The trend analysis was performed at the basin scale. The basin data on rainfall and temperature were obtained as averages of data from the 11 climate stations used in the study.

2.4 Statistical downscaling/bias correction and generation of ensemble runs

The statistical downscaling/bias-correction of the future precipitation and temperature data obtained from the RCMs for the eleven (11) climate stations were done with the Quantile-Quantile (Q-Q) transformation technique (Maraun *et al*., 2010; Themeßl *et al*., 2011). Prior to its use on the future climate data, the Q-Q technique was adapted to each station using the statistics of the observed climate at the stations. The Q-Q transformation procedure is described in detail by Amadou *et al*., (2015) and Sarr *et al*., (2015). A brief description is given in Appendix A3. Twelve ensemble runs consisting of RCM/GCM outputs for the RCP 4.5 and RCP 8.5 were generated for the two 25-year periods: 2051-2075 (referred to as the late 21st century or 2060s) and 2076-2100 (the end of the 21st century or 2080s). Four additional scenarios based on the ensemble mean of the RCM/GCM pairs were also generated. In total, sixteen ensemble runs were formed (Table 3) and used in the analysis.

Table 3 Model scenarios used in this study

Scenario Number	Model Scenarios
1	RACMO22T/ICHEC-EC-EARTH (RCP4.5/2060s)
2	RACMO22T/ICHEC-EC-EARTH (RCP4.5/2080s)
3	RACMO22T/ICHEC-EC-EARTH (RCP8.5/2060s)

4	RACMO22T/ICHEC-EC-EARTH (RCP8.5/2080s)
5	RCA4/CanESM2 (RCP4.5/2060s)
6	RCA4/CanESM2 (RCP4.5/2080s)
7	RCA4/CanESM2 (RCP8.5/2060s)
8	RCA4/CanESM2 (RCP8.5/2080s)
9	RCA4/MPI-ESM-LR (RCP4.5/2060s)
10	RCA4/MPI-ESM-LR (RCP4.5/2080s)
11	RCA4/MPI-ESM-LR (RCP8.5/2060s)
12	RCA4/MPI-ESM-LR (RCP8.5/2080s)
13	Ensemble of RCMs (RCP4.5/2060s)
14	Ensemble of RCMs (RCP4.5/2080s)
15	Ensemble of RCMs (RCP8.5/2060s)
16	Ensemble of RCMs (RCP8.5/2080s)

2.5 Assessment of model-uncorrected-simulation and model-corrected –simulation against observed climate

Plots of average monthly precipitation and temperature of the model- uncorrected and -corrected data were made at one of the stations of the Basin (Bobo-Dioulasso) and compared with plots of the observed data to assess the superiority of the corrected data over the uncorrected. The comparison was also to establish the importance of bias correction in climate change assessment study. The assessment was done by comparing the annual mean values, and standard deviations of the model-uncorrected and –corrected data to the observed data. In addition, plots of monthly precipitation, monthly mean temperature, and probability of exceedence of defined precipitation classes were made to assess the accuracy with which the model-uncorrected and –corrected data mimic the observed.

2.6 Estimation of changes in precipitation and temperature

Projected changes in precipitation and mean temperature over the basin were assessed under the RCP 4.5 and RCP 8.5 scenarios using the downscaled and bias-corrected RCM runs for the late- and end of the 21st century. Relative changes (%) were calculated for precipitation while absolute changes (°C) were computed for the mean temperature. The changes were determined and discussed at the annual, intra-annual and seasonal time steps. Prior to analysis, the bias-corrected data from the 11 climate stations were averaged to obtain basin average data.

3. Results and discussion

3.1 Trends in observed annual precipitation and temperature

Trend analysis of annual precipitation over the basin revealed a statistically significant increase (Sen's slope = 3.7 mm/year, p-value = 0.02;) of 111mm over the 30-year period (1981-2010). The lowest annual precipitation in the observed period was 744mm (1981) and highest, 1188mm (1991) as shown in Figure 2. Our findings of increasing precipitation in the Black Volta is in agreement with findings of Sylla *et al.* (2016), which observed statistically significant positive trends in precipitation over West Africa. The aforementioned study noted that Burkina Faso, located in the northern half of our study area, is one of the countries which experienced an increase in precipitation during the 1983-2010 period. In a similar study, Maidement *et al.* (2015) reported statistically significant increases in annual rainfall across the Sahel between 1983 and 2010. Other studies in the Sahel by Nicholson (2005), Mahé and Paturel (2009) and more recently Ibrahim *et al.* (2014) for example also revealed that annual precipitation in the region has increased since the end of the 1990s.

Consistent with the IPCC report (IPCC, 2013) the analysis of observed mean temperature over the BVRB indicated a statistically significant increase (5% level of significance; p-value = 0.00; Sen's slope = 0.03) of 0.9°C over the 30-year period (0.3°C per decade). According to Sylla *et al.* (2016), countries such as Ghana and la Cote d'lvoire, both located in the BVRB, experienced the most significant warming signals during the 1983-2010 period. Figure 3 shows the increase in mean temperature over the basin for the period of analysis.

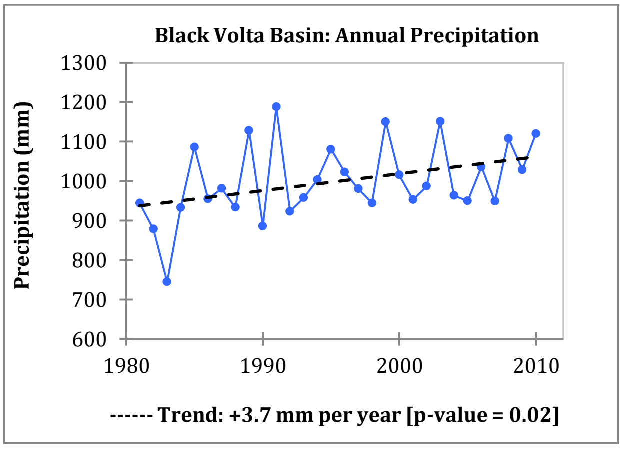


Fig.2 Trend analysis of annual precipitation over the Black Volta River Basin (1981-2010)

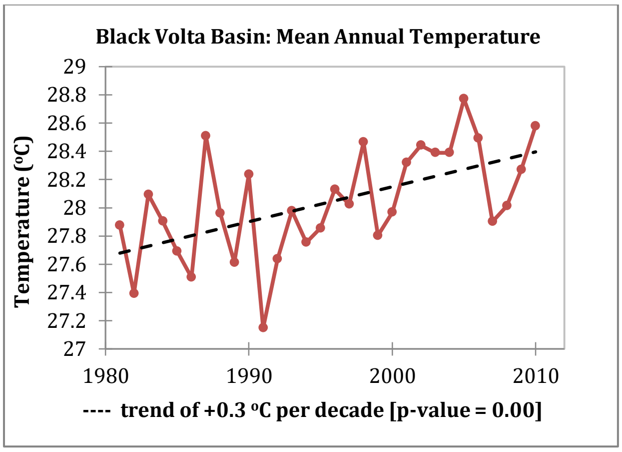


Fig.3 Trend analysis of mean temperature over the Black Volta River Basin (1981-2010)

Table 4 Basic statistics of uncorrected and bias- corrected RCA4/ CanESM2 model simulations of historical (1981-2005) temperature and precipitation at Bobo-Dioulasso

Variables	**Mean**			**Standard Deviation**		
	Observed	Corrected	Uncorrected	Observed	Corrected	Uncorrected
Temperature	27.56	27.58	27.12	2.01	1.99	1.87
Precipitation	83.03	79.40	80.38	90.25	91.14	81.57

3.2 Assessment of the model- corrected and –uncorrected simulations of the observed climate

Figures 4, 5 and 6 present the trends in monthly precipitation, the probability of exceedance of precipitation events and the trends in mean monthly temperature, respectively, at the Bobo-Dioulasso station in the north of the basin in Burkina Faso. The plots were based on station observed data as well as the RCA4/CanESM2 model-corrected and –uncorrected data for the precipitation and mean temperatures. As shown in Figure 4, both the model-corrected and–uncorrected simulations show a double peak in the precipitation while the observed data has a single peak. However, the double peak in the corrected simulation is weak while the uncorrected exhibits a strong double peak.

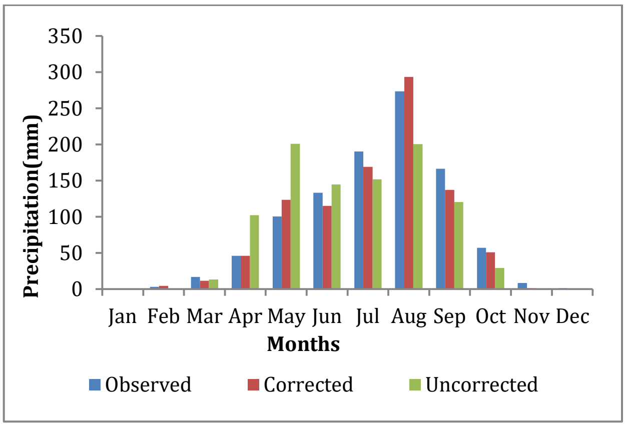


Fig.4 RCA4/ CanESM2 bias-corrected and –uncorrected precipitation and observed data at the Bobo-Dioulasso station (1981-2005)

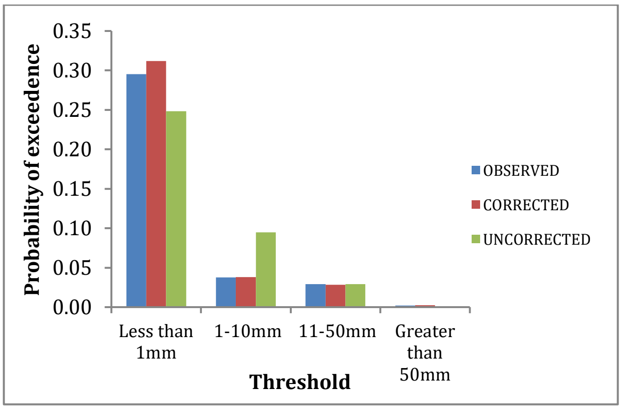


Fig.5 Probability of exceedance of precipitation thresholds for the bias-corrected and uncorrected RCA4/ CanESM2 model simulates of historical precipitation at the Bobo-Dioulasso station (1981-2005)

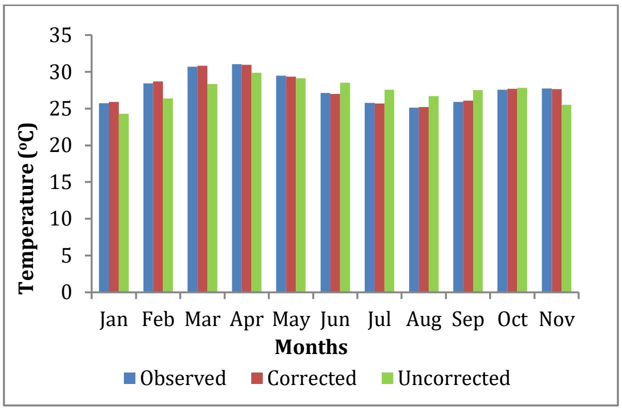


Fig.6 Uncorrected and bias-corrected RCA4/ CanESM2 model simulated data and historical mean temperature at the Bobo-Dioulasso station (1981-2005)

In addition, the corrected simulation fairly reproduces the monthly amounts though it shows a slight over estimation of the May and August rainfall and underestimates that of March, June, July and September through November. The uncorrected simulation, on the other hand, heavily over-estimated the precipitation in April and May and underestimated the amounts for July through to November. As Figure 5 shows, the model corrected data overestimated the probability of precipitation events less than 1mm while the uncorrected data showed an underestimation. In addition, the uncorrected data overestimated highly the probability of precipitation exceedance between 1mm and 10mm. Results of the mean monthly temperature (Figure 6) shows that the corrected model data represents well the observed monthly temperature at the Bobo-Dioulasso station, with slight under- and over-estimations. The uncorrected output, on the other hand, underestimates the monthly temperature values in January through April and overestimates them from June through September. The mean and standard deviation of the precipitation and temperature at the station (Table 4) also confirms the closeness of the corrected data to the observed data, relative to the uncorrected data. As rightly pointed out by Ehret *et. al.* (2012), climate simulations often exhibit systemic deviations from the observed climate. Our results show that bias correction is without doubt important for climate change impact assessment.

3.3 Projected changes in precipitation

The analysis of average annual precipitation over the basin for the late- and end of the 21st century showed high level of uncertainties, with mixed signals of increases and decreases in precipitation amounts across the models (Table 5).

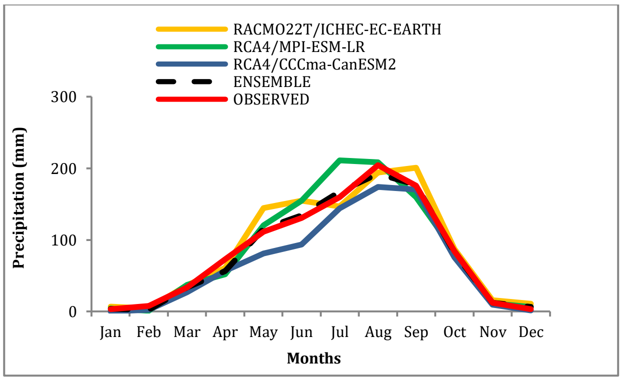
Table 5 Projected changes in precipitation for the late and end of 21st century in the Black Volta River Basin under RCPs 4.5 and 8.5

RCMs	Baseline (1981-2010) observed mean value (mm)	Late-Century (2051-2075)				End-of-Century (2076-2100)			
		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
		Ave (mm)	% change	Ave (mm)	% change	Ave (mm)	% change	Ave (mm)	% change
RACMO22T/ ICHEC-EC-EARTH	999.48	1064.12	6.47	1091.52	9.21	999.37	-0.01	1126.88	12.75
RCA4/MPI-ESM-LR		1050.77	5. 13	1136.19	13.68	1021.95	2.25	1094.23	9.48
RCA4/ CCCma-CanESM2		836.55	-16.30	728.64	-27. 10	767.69	-23.19	665.25	-33.44
ENSEMBLE		983.81	-1.57	985.45	-1.40	929.67	-6.98	926.12	-3.74

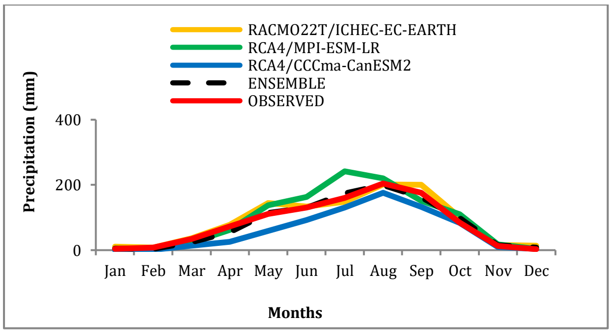
Relative to the baseline, mean annual precipitation for the late 21st century ranged between -16% and +6%, with a mean of -2% under the RCP4.5 scenario and between -27% and +14%, with a mean of -1% under the RCP8.5 scenario. The end of the 21st century projection showed precipitation changes of between -23% and +2%, with a mean of -7% under the RCP4.5 scenario. The high emission RCP8.5 scenario projects changes ranging between -33% and +13%, with a mean of -4%. From the results, it is established that the uncertainty in the projections increases with increasing RCP forcing and increasing time frames. Similar observations were made by Sylla *et al.* (2016).

Figure 7 and 8 show the projected changes in intra-annual precipitation over the BVRB for the late and end of 21st century, respectively. As shown in both graphs (7a and 7b), future rainfall projections by the models show high variability consistent with findings for the West African region reported in the IPCC 5th Assessment report (IPCC, 2013). The variability is mostly pronounced during the wet season. Precipitation amount for the month of July for example is projected to range between +51mm and -16mm under the RCP 4.5 scenario and between +81mm and -30mm under the RCP8.5 scenario in the 2060s. From the months of October through December however, the variability is highly reduced, especially under the RCP4.5 scenario. The end of the 21st century rainfall projections also shows substantial variability, in this case especially in the months of February through September, which reduces from October through December.

Changes in precipitation for the dry (January-March) and wet (August-October) seasons are presented in Figures 9 and 10. In the late 21st century, the ensemble runs project a change in the range of +6% to -35% in the dry season precipitation, with a mean change of 11% for the RCP4.5 scenario. The change in wet season precipitation is projected to range from +4% to -10%, with a mean of -3%. Under the RCP8.5 scenario, the change in dry and wet season precipitations are projected to range from +22% to -67%, with a mean of -26%, and +9% to -16%, with a mean of -1%. Similarly, the dry and wet season precipitations over the basin for the end of the 21st century are projected to range between +20% and -48%, with a mean of -11% and from -2% to -16%, with a mean of -8% for the RCP4.5 scenario. The high emission RCP8.5 scenario projections show a rate of change in dry season precipitation ranging from +48% and -68%, with a mean of -18% while for the wet season the projected changes are between +16% and -23%. The high variability in the projections across the models and the opposing change in signals are indications of uncertainty surrounding precipitation projections in the basin. Whereas a decrease in precipitation over the region may cause droughts, affect agriculture development and cause a decline in hydropower generation, increases in precipitation may cause floods in the basin.

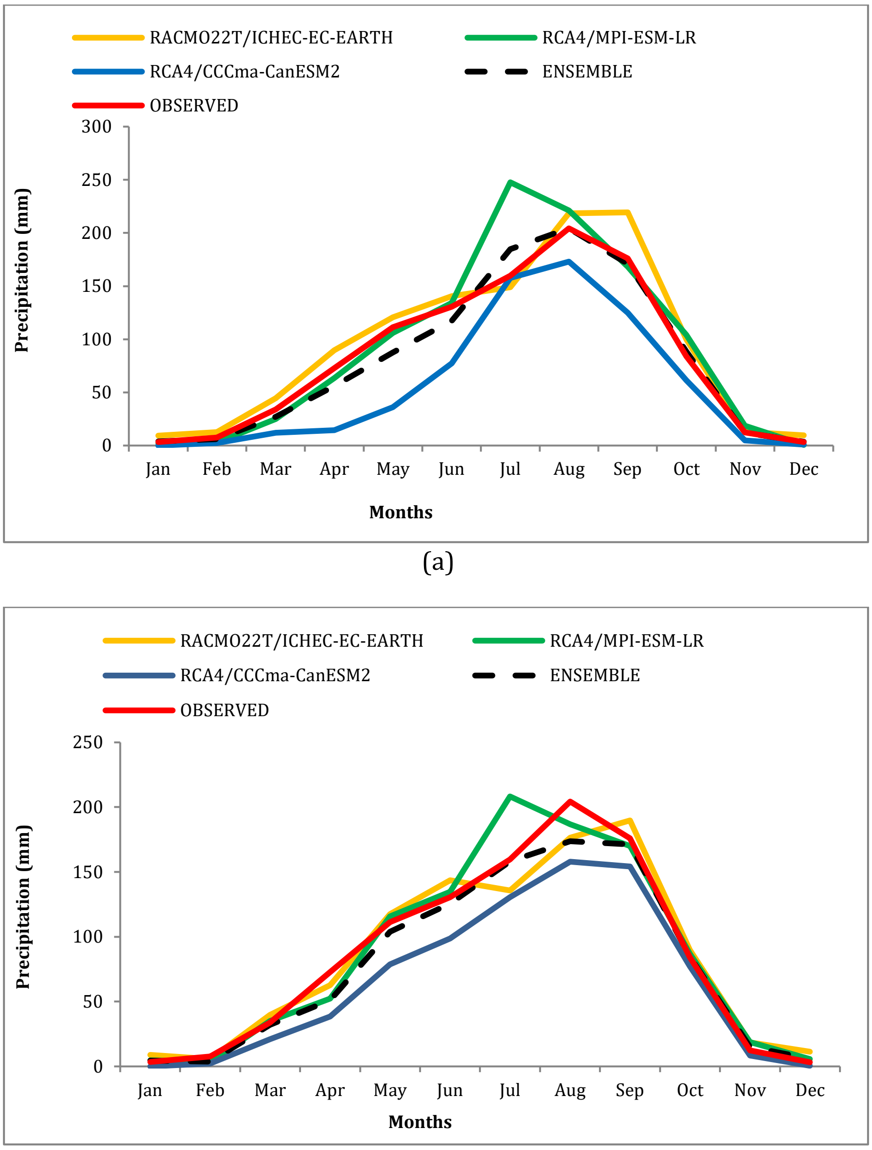


(a)



(b)

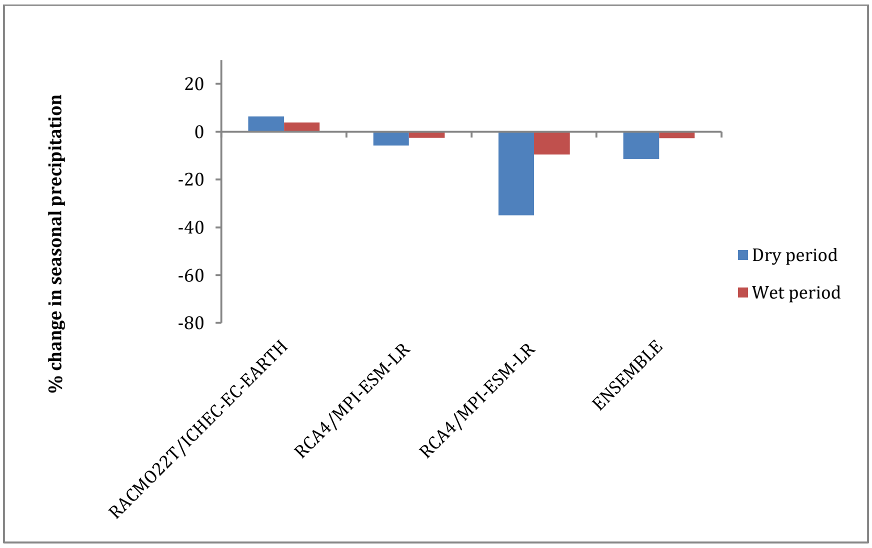
Fig.7 Observed and projected intra-annual precipitation under (a) RCP4.5 and (b) RCP8.5 for the 2060s (2051-2075)



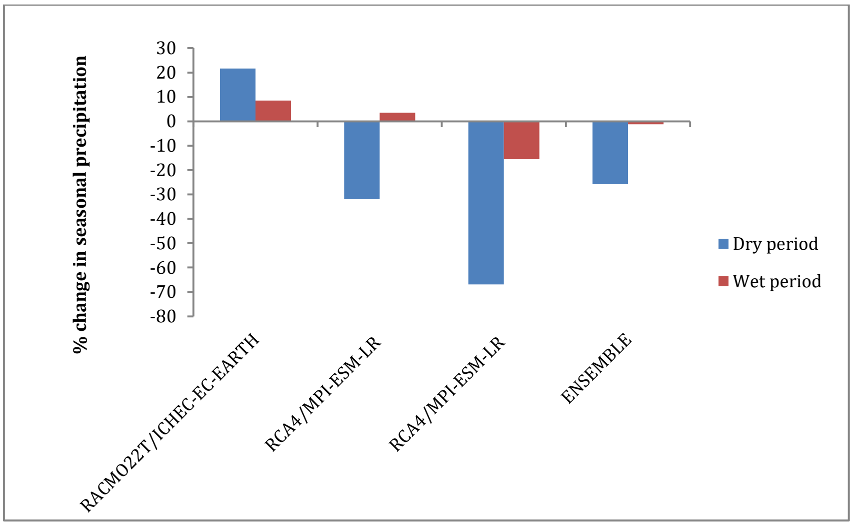
(a)

(b)

Fig. 8 Observed and projected intra-annual precipitation under (a) RCP4.5 and (b) RCP8.5 for the 2080s (2076-2100)

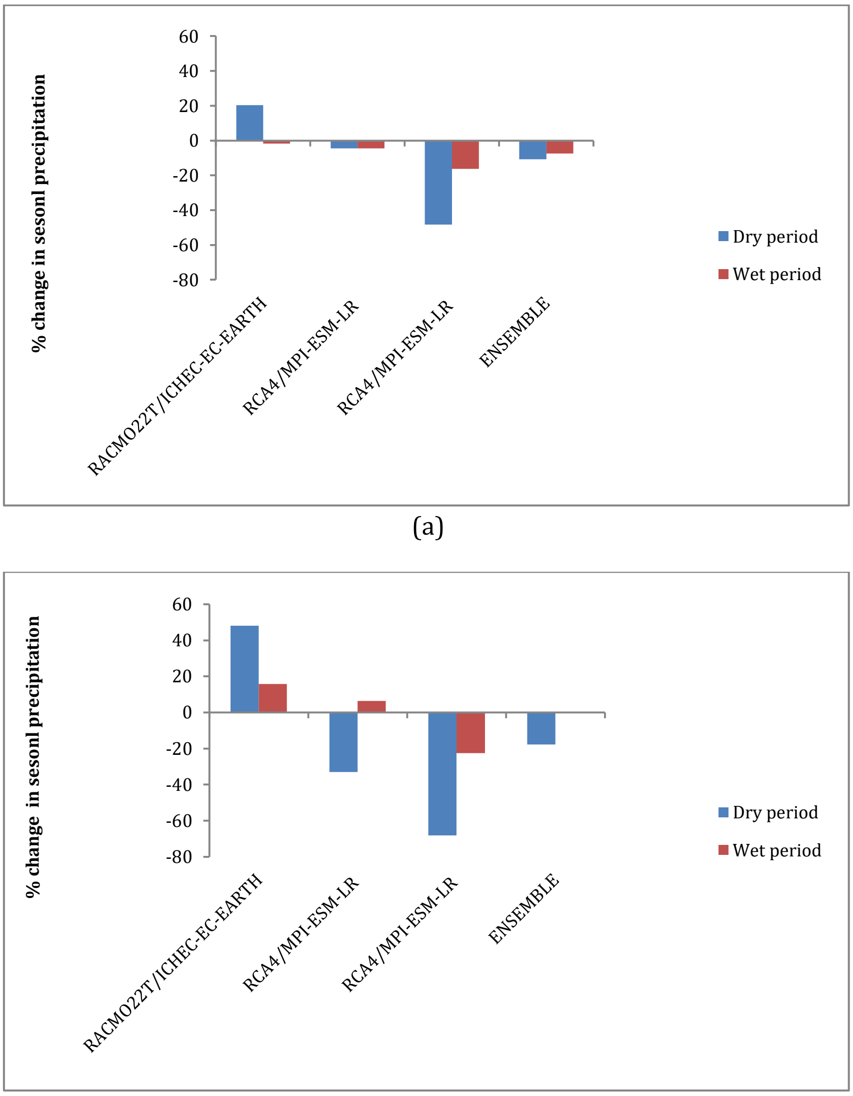


(a)



(b)

Fig. 9 Changes in mean seasonal precipitation for the 2060s (2051-2071) under (a) RCP4.5 and (b) RCP8.5 scenarios, relative to the baseline (1981-2010)



(a)

(b)

Fig. 10 Changes in mean seasonal precipitation for the 2080s under (a) RCP4.5 and (b) RCP8.5 scenarios, relative to the baseline (1981-2010)

Table 6 Projected changes in temperature (°C) for the late and end of 21st century in the Black Volta River Basin under RCPs 4.5 and 8.5

RCM/GCM pairs	Baseline (1981-2010) Observed mean values	2051-2075				2076-2100			
		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
	Tmean (°C)	Tmean (°C)		Tmean (°C)		Tmean (°C)		Tmean (°C)	
		Ave	Change	Ave	Change	Ave	Change	Ave	Change
RACMO22T/ICHEC-EC-EARTH	27.9	30.0	2.1	30.7	2.8	30.2	2.3	31.4	3.5
RCA4/MPI-ESM-LR		29.9	2.0	30.6	2.7	30.1	2.2	31.4	3.5
RCA4/CCCma-CanESM2		30.2	2.3	30.9	3.0	30.5	2.6	31.6	3.7
ENSEMBLE		30.0	2.1	30.7	2.8	30.2	2.3	31.4	3.5

3.4 Projected changes in temperature

In agreement with the IPCC (2013) report, results of the temperature projections for the basin (Table 6) point towards a warmer climate in the late- and end of the 21st century under both RCP scenarios, relative to the baseline (1981-2005). The projected increases in temperature by the ensemble runs are significant. The magnitude of the projected increase in mean temperature over the basin is greater in the 2080s compared to the 2060s. As expected, the increase in temperature is higher in the RCP8.5 scenario than in the RCP4.5 scenario. The mean annual temperature for 2060s is projected to rise by between 2.0°C and 2.3°C for the RCP4.5 scenario and 2.7 °C and 3.0°C for the RCP8.5 scenario. By the end of the 21st century, larger temperature increases between 2.2°C and 2.6°C is projected for the RCP4.5 scenario and from 3.5°C to 3.7°C for the RCP8.5 scenario. These projected changes in temperature for the basin are in line with the projected range for West Africa (Sylla *et al.*, 2016).

3.5 Trends in projected annual precipitation and mean temperature

The Man-Kendall trend test showed increases and decreases in future precipitation over the basin (Table 7) with majority of the trends (about 67%) being in the positive direction. The projected trend ranges from a decrease of 5.5mm/year to an increase of 3.6mm/year for the RCP4.5 scenario in the late century period. For the RCP8.5 scenario, the trend ranges from a decrease of 2.7mm/year to an increase of 8.6mm/year. The end of the century projected trend ranges from a decline of 3mm/year to an increase of 4.9mm/year under the RCP4.5 and from a decline of 2.7mm/year to an increase of 8.6mm/year under the RCP8.5 scenario. All the trends were however statistically insignificant at the 5% level of significance. Unlike temperature, precipitation projection in the West African Region is in general associated with higher uncertainties (Rowell 2012; Orlowsky and Seneviratne 2012). Trend analysis of temperature, revealed statistically significant (5% level of significance) increases in agreement with the IPCC (2013) report.

Table 7 Results of the Mann-Kendall test for annual precipitation (mm) for the late and end of 21st century in the Black Volta River Basin under RCPs 4.5 and 8.5

Model runs	Mann-Kendall Statistic (S)	Sen's slope	p-value	Trend
RACMO22T/ICHEC-EC-EARTH (RCP4.5/2060s)	-50.00	-5.53	0.26	Not significant
RACMO22T/ICHEC-EC-EARTH (RCP4.5/2080s)	-46.00	-2.96	0.30	Not significant
RACMO22T/ICHEC-EC-EARTH (RCP8.5/2060s)	18.00	2.53	0.70	Not significant
RACMO22T/ICHEC-EC-EARTH (RCP8.5/2080s)	18.00	2.54	0.70	Not significant
RCA4/CanESM2 (RCP4.5/2060s)	18.00	1.54	0.70	Not significant
RCA4/CanESM2 (RCP4.5/2080s)	42.00	4.90	0.34	Not significant
RCA4/CanESM2 (RCP8.5/2060s)	74.00	8.56	0.09	Not significant
RCA4/CanESM2 (RCP8.5/2080s)	74.00	8.56	0.09	Not significant
RCA4/MPI-ESM-LR (RCP4.5/2060s)	28.00	3.55	0.53	Not significant
RCA4/MPI-ESM-LR (RCP4.5/2080s)	12.00	1.86	0.80	Not significant
RCA4/MPI-ESM-LR (RCP8.5/2060s)	-28.00	-2.67	0.53	Not significant
RCA4/MPI-ESM-LR (RCP8.5/2080s)	-26.00	-2.67	0.56	Not significant

Table 8 Results of the Mann-Kendall test for mean annual temperature (°C) for the late and end of 21st century in the Black Volta River Basin under RCPs 4.5 and 8.5

Model runs	Mann-Kendall Statistic (S)	Sen's slope	P-value	Trend
RACMO22T/ICHEC-EC-EARTH (RCP4.5/2060s)	104.00	0.03	0.02	Significant increase
RACMO22T/ICHEC-EC-EARTH (RCP4.5/2080s)	108.00	0.02	0.01	Significant increase
RACMO22T/ICHEC-EC-EARTH (RCP8.5/2060s)	152.00	0.03	0.00	Significant increase

RACMO22T/ICHEC-EC-EARTH (RCP8.5/2080s)	190.00	0.06	< 0.00	Significant increase
RCA4/CanESM2 (RCP4.5/2060s)	-4.00	-0.00	0.94	Not significant
RCA4/CanESM2 (RCP4.5/2080s)	-44.00	-0.01	0.32	Not significant
RCA4/CanESM2 (RCP8.5/2060s)	130.00	0.02	0.00	Significant increase
RCA4/CanESM2 (RCP8.5/2080s)	132.00	0.02	0.00	Significant increase
RCA4/MPI-ESM-LR (RCP4.5/2060s)	26.00	0.00	0.56	Not significant
RCA4/MPI-ESM-LR (RCP4.5/2080s)	-28.00	-0.01	0.53	Not significant
RCA4/MPI-ESM-LR (RCP8.5/2060s)	164.00	0.02	0.00	Significant increase
RCA4/MPI-ESM-LR (RCP8.5/2080s)	148.00	0.03	0.00	Significant increase

For the late century increase in trends up to 0.03°C/year is projected by both RCP4.5 and RCP8.5 scenarios. The projected trend for the end of the century ranges from a decrease 0f 0.01°C/year to an increase of 0.02°C/year for the RCP4.5 scenario and from 0.02°C/year to 0.06 °C/year for the RCP8.5 scenario. The decreasing trends are however not significant at the 5% level as shown in Table 8.

Conclusion

In this study, we first analyzed the trends in observed (1981-2010) annual precipitation and mean temperature over the Black Volta River Basin using the Man-Kendall test and the Sen's slope estimator. We also analyzed projected changes in precipitation and mean temperature over the basin using simulation data set by 2 Regional Climate Models for the late (2051-2075) and end of the 21st century (2076-2100) periods under two IPCC Representative Concentration Pathways (RCP4.5 and RCP8.5). Lastly, we assessed the trends in the future annual precipitation and temperature.

The trend analysis of the observed annual precipitation and mean temperature showed statistically significant increases, indicating that the basin was wetter and warmer in the 1981-2010 period. Relative to the baseline, annual precipitation amounts showed positive and negative signals across the models. Similar to the annual precipitation, the intra-annual and seasonal precipitation analysis also showed high uncertainty in the future rainfall amounts, with higher variability in the wet season compared to the dry season. Temperature projections by the models unanimously suggested warming of the basin during the 2060s and 2080s with increases ranging between 2.0°C (2060s under RCP4.5) and 3.7°C (2080s under RCP8.5).

Trend analysis of annual future precipitation pointed in both positive and negative directions. The trends were however statistically insignificant at the 5% level of significance. Trends in the annual mean temperature however, showed mostly statistically significant (5% level of significance) increases in future temperature over the basin. A few of the model runs showed statistically insignificant decreasing trends. High temperatures may affect water availability and use in the basin. Since a good number of the basin's population depend on agriculture for their livelihood, problems related to water scarcity in the basin may worsen the poverty situation in the basin. Measures to cope with the increasing temperature over the basin should therefore be explored and developed well ahead of time.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix A1

The Mann-Kendall trend test

The Mann-Kendall test statistic (S), is calculated according to:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(xj - xi) \tag{1}$$

Where, $x_{1,}x_{2,}x_{3\dots,}x_n$ represent n data points and x_j represents the data point at time j.

with

$$sgn\left(x_{j\_}x_i\right) = \begin{pmatrix} +1\ if\ \left(x_j - x_k\right) > 0 \\ 0\ if\ \left(x_j - x_k\right) = \ \ 0 \\ -1\ if\ \left(x_j - x_k\right) < 0 \end{pmatrix} \tag{2}$$

The test statistic (S) is assumed to be approximately normal, with E(S) = 0 for sample size n ≥ 8 and variance as follows:

$$Var\ (S) = \frac{[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18} \tag{3}$$

Where t represents the number of ties up to sample i. The standardized MK test statistics (Zmk) is estimated as follows:

$$Z_{mk} = \begin{array}{c} \frac{S-1}{\sqrt{V(S)}}\ if\ S > 0 \\ 0\ is\ S +\ 0 \\ \frac{S+1}{\sqrt{V(S)}}\ if\ S < 0 \end{array} \tag{4}$$

The standardized MK test statistics (Zmk) follows the standard normal distribution with a mean of zero and variance of one. A positive (negative) value of Zmk indicates an 'upward trend' (downward) trend.

Appendix A2

The non-parametric Sen's slope estimator

In this test, the slope Qi estimates N pairs of data values which are computed using

$$Qi = \frac{xj - xk}{j - k} \quad (5)$$

where xj and xk are data values at time j and k respectively, and j>k. The Sen's estimator of the slope is the median of these N values of Qi. The N values of Qi are ranked from the smallest to the largest and the Sen's estimator is computed by:

$$Q_{med} = Q\left[\frac{(n+1)}{2}\right], if\ N\ is\ odd \quad (6)$$

or

$$Q_{med} = \frac{1}{2}\left(Q\frac{n}{2} + Q\left[\left(\frac{n+2}{2}\right)\right]\right), if\ N\ is\ even \quad (7)$$

Q_{med} is then tested with a two-sided test which is carried out at 100(1 – α)% confidence interval to obtain the true slope for the non-parametric test in the series. The positive slope Qi is obtained as an increasing trend and the negative slope Qi as a decreasing trend.

Appendix A3

The Q-Q transformation procedure

The observed data covering the present horizon (1981-2010) was split into two, one half for calibration and the other half for validation. The calibration period consisted of every odd year starting from the beginning of the present horizon (i.e. years 1, 3, 5, etc.) while the validation was done on even years (i.e. years 2, 4, etc.). The daily time series of the month were extracted for both calibration and validation periods from both observation and RCA4 projection data.

Two empirical cumulative distribution functions, F_{obs} and F_{RCM} , were then developed. F_{obs} was generated using observed data covering the calibration period while the F_{RCM} was generated using the RCA4 projections for the calibration period.

The probability mass function (PMF) of precipitation occurrence (i.e intensity greater than 1mm/day) and probability density function (PDF) of precipitation intensity on wet/rainy days, maximum and minimum temperatures were built. The quantile-quantile transformation was applied to produce improved (corrected) future RCM simulations of a variable if it was noticed that the PDF (or (PMF) of a corrected variable was closer to the PDF of the observations than the PDF (or PMF) of the raw non-corrected variable.

Thus, the bias-corrected RCA4 projections ,X_{CORR}, were generated for the entire period of the uncorrected projection data using the transformation: $X_{CORR} = F_{obs}^{-1}(F_{RCM}(X_{RCM}))$, where X_{RCM} refers to the uncorrected RCA4 projection data.

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