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Assessing the impact of climate variability and climate change on runoff in West Africa: the case of Senegal and Nakambe River basins

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Abstract

West Africa and its people are very vulnerable to climate variability and changes. Increasing the knowledge of plausible trends of rainfall dry spell lengths (DSL) in the rainy season, and of runoff, enables the assessment of vulnerability and adaptive capacity of the system. These predictions are crucial from a water management and policy perspective. The analyses based on regional climate models (RCMs) and observed datasets exhibit non-stationary behavior and an increase of DSL. Our results highlight the difficulty of selected RCMs to reproduce present climate and their divergence in predicting future climate. Impacts on water resources depend not only on climate forcing but also on land surface conditions. Copyright © 2011 Royal Meteorological Society

Keywords: climate change and variability; regional climate model; impact studies; droughts; runoff; West Africa

1. Introduction

Due to the close link between climate and socioeconomic activities, societies in West African are more vulnerable to rainfall variability and changes. The region has experienced a number of severe droughts since the end of the 1960s. Due to rapid population growth, the pressures on the environment and natural resources have been exacerbated, leading to profound changes in land uses. The impacts of historical climate variability and changes, combined with the effects of land use changes on hydrological processes and water resources, are now well documented (Descroix *et al*., 2009; Favreau *et al*., 2009; Séguis *et al*., 2011). There is evidence of contrasted responses by hydrological and hydrogeological systems, especially in the West African Sahel (Leduc *et al*., 2001; Mahé *et al*, 2005; Mahé and Paturel, 2009). However, there have been few attempts to deal with future climate variability and changes, and their impacts on runoff. This issue was one of the main concerns of the African Monsoon Multidisciplinary Analyses (AMMA) project (Polcher *et al*., 2011).

This article focuses on the analysis of the historic and regional climate model (RCM) predicted rainfall regime for the Senegal and Nakambe River basins and its impact on the monsoon dry spell lengths (DSL) on both basins. Impacts on river flows are also predicted for the Nakambe basin.

2. Materials and methods

2.1. Study area

The Senegal and Nakambe River basins, which are both strongly affected by climate and land use changes, were selected for this study (Figure 1).

The Senegal River basin, which covers approximately 300 000 km^2 at the Diama station, is characterized by irregular rainfall, with a decreasing South–North gradient. The basin is divided into the Sahelian zone in the North and the Sudanian and Guinean zones in the South. The main inflow to the Senegal River comes from the Fouta Djalon Mountains, where rainfall can exceed 2000 mm/year. Precipitation in the north of the basin is less than 200 mm/year (Andersen *et al*., 2001).

The Nakambe basin is located in the upper part of the Volta basin in Burkina Faso (between 14°1′N–10°9′N and 2°5′W–0°1′E). The climate is Sudano-Sahelian with a mean annual precipitation of around 700 mm. The basin area is 40 836 km^2 at Bagre station.

2.2. Datasets and models

The seasonal cycle of simulated rainfall was compared to the gridded observations by the Climate Research Unit (CRU, University of East Anglia, Norwich, UK) and Institut de Recherche pour le D'evelopment (IRD) rainfall datasets. The IRD dataset corresponds to on-site daily rainfall data, interpolated for a regular

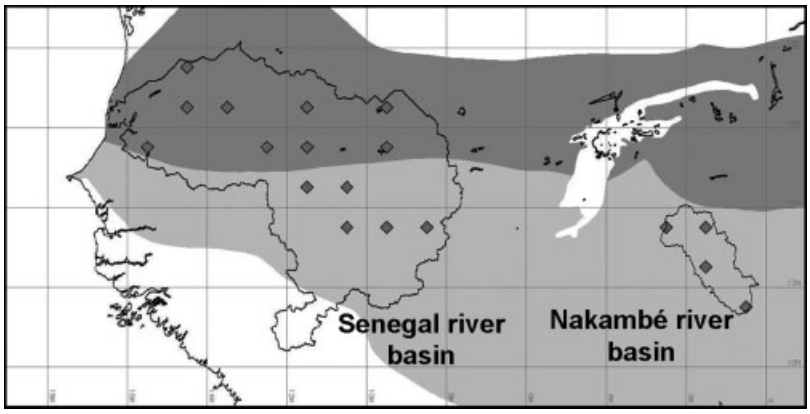

Figure 1. Selected points on both Senegal River basin and Nakambe River basin. Dark gray area represents the Sahelian Acacia Savanna (SAS), and light gray area the West Sudanian Savanna (WSS) (according to the definition of eco-regions in Olson *et al.*, 2001).

grid of 1° (Diedhiou *et al.*, 1999): it has been used extensively (Janicot and Sultan, 2001; Messager *et al.*, 2004). The CRU dataset is a long-term climatology dataset that covers Africa, with a regular 0.5° grid. In addition, for the Nakambe basin, historical data from national stations were used for precipitation and potential evapotranspiration (PET) (1961–2004) and discharges (1955–2008 at the Wayen station).

RCM simulations from the ENSEMBLES and IMPETUS projects were also considered for climate variability analysis. The global climate models (GCMs) cannot account for the regional heterogeneity of climate variability and change; therefore they are not suitable in order to produce the fine-scale climate projections needed to assess impacts (Paeth *et al.*, 2011). Dynamical downscaling, such as RCMs, can be used to undertake this issue. The RACMO KNMI and REMO MPI (Paeth *et al.*, 2005) models (both driven by ECHAM5 GCM), and the RCA SMHI RCM (driven by HadCM3 GCM), were selected for this study.

2.3. Non-stationary analysis

In order to analyze trends in the frequency distributions of average annual precipitation and maximum length of dry spells, the Generalized Additive Models for Location Scale and Shape (GAMLSS) technique was used, considering four different two-parameter distribution (Gumbel-GU-, Gamma-GA-, Lognormal-LN-, and Weibull-WEI-). According to Rigby and Stasinopoulos (2005), GAMLSS are semi-parametric regression models. GAMLSS allows the modeling of pdf parameters of response variables (annual rainfall amount or DSL) as a function of an explanatory variable (time) through non-parametric smoothing functions. Hence, GAMLSS is a powerful tool to analyze hydrological time series which have non-stationary behavior (Villarini *et al.*, 2009). A detailed description about the GAMLSS hypothesis, model selection, and examples can be found in Rigby and Stasinopoulos (2005).

2.4. Hydrological model

For hydrological modeling of the Nakambe basin, the GR2M model was employed (Maklouf, 1994). It is a conceptual, semi-distributed (0.5° × 0.5°) and monthly model with two parameters. This model has been extensively used for hydrological modeling of Sahelian basins (Ouedraogo, 2001; Mahé *et al.*, 2005; Diello, 2007; Ardoin-Bardin *et al.*, 2009). The analysis of the impacts of climate variability and change on runoff and water resources was carried out on the Nakambe basin. The GR2M hydrological model was calibrated and validated using historical observed data from the IRD and synoptic stations. Once calibrated and validated, the model was forced by the three RCMs' future climate dataset (RACMO, RCA/SMHI and REMO). In this study, we do not consider land use change scenarios, which means model parameters remain constant over simulations. The PET was calculated using the Makkink method (Xu and Singh, 2002) from climate variables provided by the RCMs. The PET and precipitation data from RCMs were bias corrected based on the monthly and annual averages of observations over the 1961–1990 period.

3. Results and discussion

3.1. Analysis of rainfall seasonal cycle

In order to carry out a regional analysis, the selected basins were subdivided according to eco-regions defined by Olson *et al.* (2001). These eco-regions are the Sahelian Acacia Savanna (SAS) and the West Sudanian Savanna (WSS) (Figure 1). Since the spatial distribution of the IRD dataset does not constitute a continuous grid, 14 cells in the Senegal River basin (9 cells in SAS and 5 cells in WSS) and four cells in the Nakambe river basin were selected for the analysis.

The seasonal cycle of rainfall over the 1970–1990 period from the IRD, CRU and simulated rainfall datasets, for the selected eco-regions, was estimated

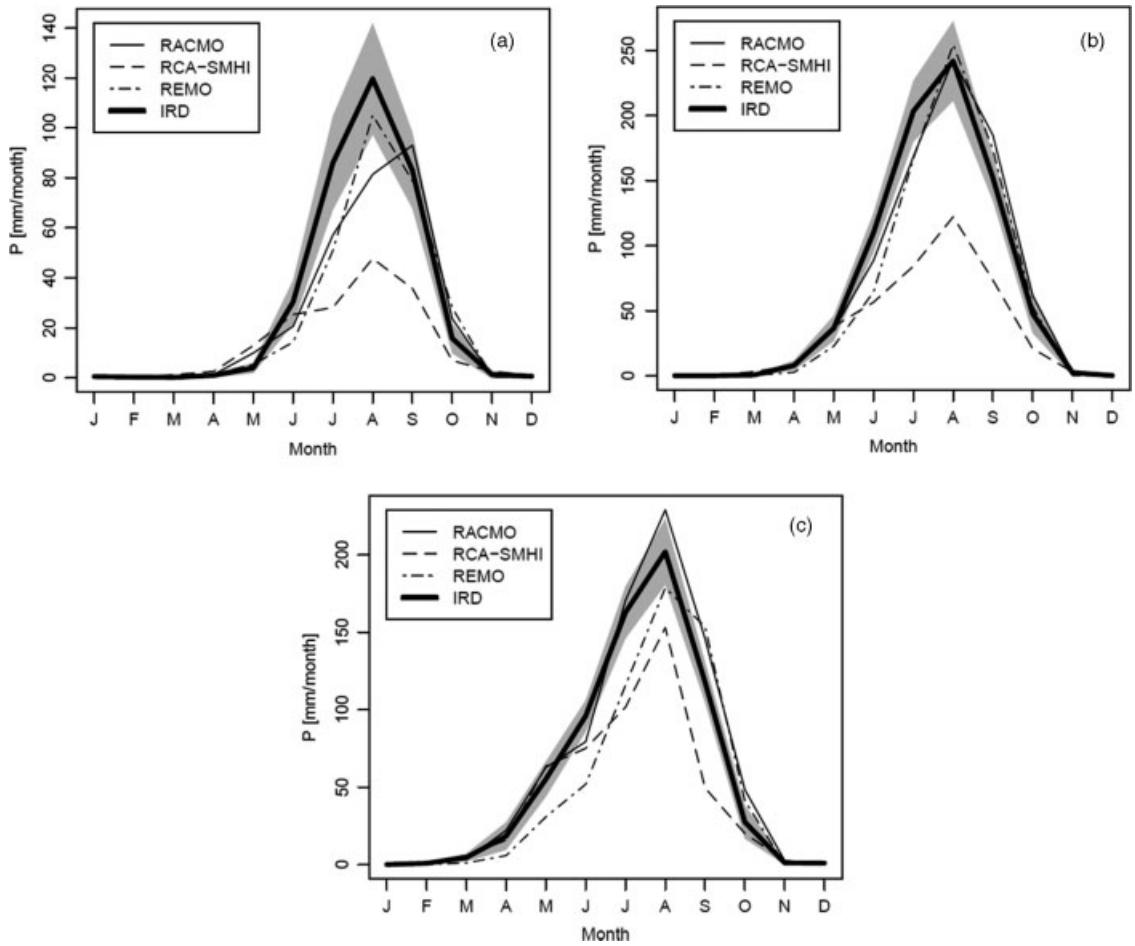

Figure 2. Analysis of regional seasonal cycle of rainfall over the period 1970–1990. (a) Senegal basin SAS eco-region, (b) Senegal basin WSS eco-region and (c) Nakambe basin. Gray area corresponds to 95% confidence interval.

Table I. Analysis of the abilities of selected RCMs to represent the seasonal cycle of rainfall (time period 1970–1990).

				P_{MEAN} (mm/year)	
				IRD	**CRU**
Senegal basin SAS	14.9%	30.6%	12.7%	342.3	314.8
Senegal basin WSS	6.8%	24.4%	8.2%	803.0	723.4
Nakambe basin	7.1%	15.5%	12.1%	687.1	692.9

and compared (Table I and Figure 2). The good fit between IRD and CRU is observed (in general, the CRU monthly rainfall cycle falls into the 95% confidence interval assessed with IRD data).Compared to observations, the RCMs differ in how they reproduce the seasonal cycle, due mainly to their different dynamical schemes and physical parameterizations of the West African monsoon (Paeth *et al.*, 2011). For both basins, the RACMO model seems to present a better ability.

3.2. Analysis of DSL

Dry spells in the monsoon season were identified and analyzed. The DSL was defined as the number of consecutive days with rainfall of less than 1 mm/day between 1 May and 30 September over the period 1970–1990. However, some dry spells could have days corresponding to both the monsoon season and the offseason. In this case, only the days in the monsoon season were considered in the definition of the DSL. Therefore, monsoon dry spells that belong to several years could be presented. The basic statistics of the DSL (mean μ_{DSL} and standard deviation σ_{DSL}) were estimated from the daily IRD dataset and the RCMs, for the selected sites. The root mean square error (RMSE) of these statistics, as a percentage of IRD values, was calculated (Table II). The mean DSL in the Sahelian region (SAS) is double that in the Sudanian region. The variability of DSL (σ_{DSL}) is also greater in the SAS region.

In general, the mean DSL (μ_{DSL}) is better represented by the RACMO model, followed by REMO and RCA/SMHI models. According to the different eco-regions defined, the REMO model presents a better ability to simulate DSL for the Senegal basin SAS eco-region, while the RACMO model shows good behavior in the Senegal basin WSS eco-region and the Nakambe basin. The RCA/SMHI exhibits poor fit of μ_{DSL} and σ_{DSL} in all regions considered (Table II).

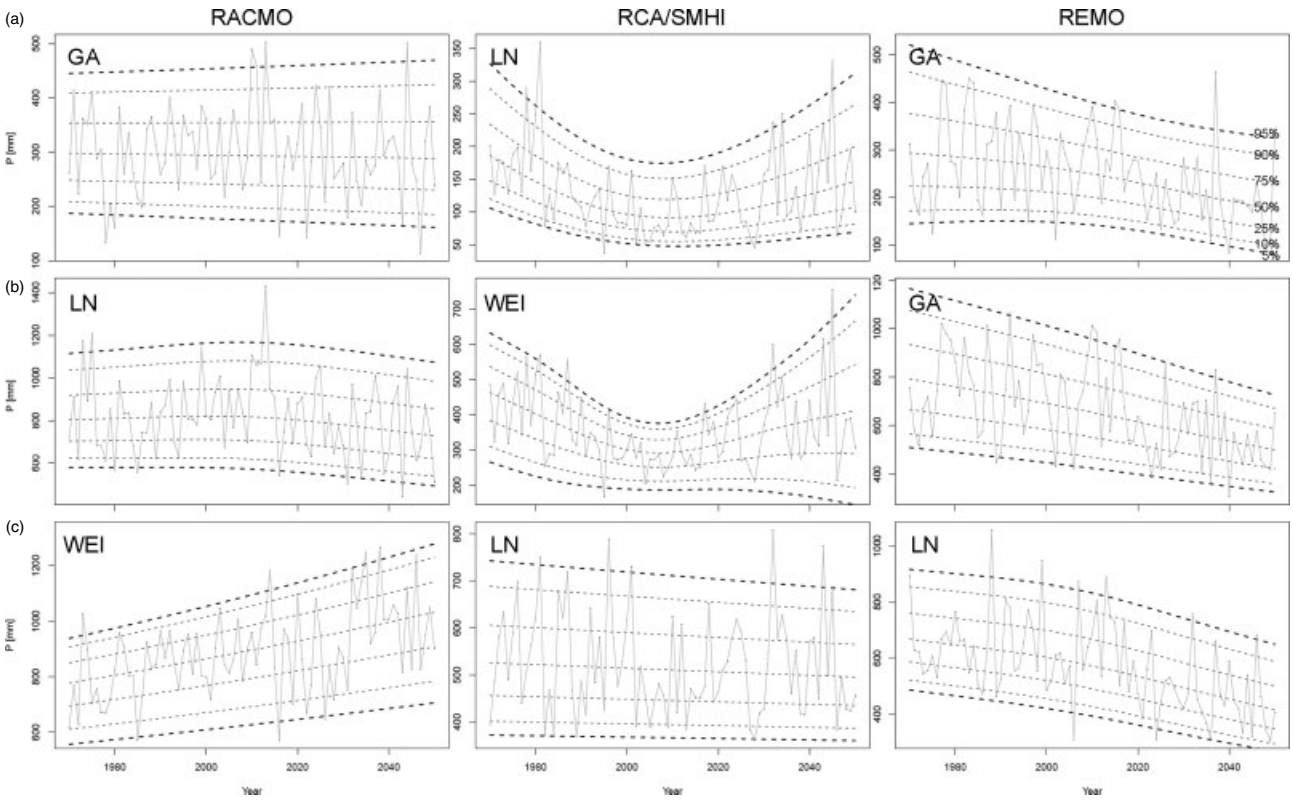

Figure 3. GAMLSS analysis of annual rainfall using RCMs: (a) Senegal basin SAS, (b) Senegal basin WSS and (c) Nakambe basin. The centile curves (5–95%) are shown by dashes.

Table II. Analysis of abilities of selected RCMs to represent the statistics of DSL (time period 1970–1990).

RMSE related with DSL	RACMO	RCA/SMHI	REMO	IRD
RMSE of mean of DSL μ				μ_{IRD} (day)
Senegal basin SAS	16.6%	72.5%	34.1%	6.5
Senegal basin WSS	13.1%	60.6%	27.3%	2.5
Nakambe basin	15.2%	40.6%	24.1%	2.3
RMSE of standard deviation of DSL σ				σ_{IRD} (day)
Senegal basin SAS	46.0%	32.6%	13.3%	12.1
Senegal basin WSS	7.9%	22.4%	53.0%	3.1
Nakambe basin	17.3%	24.7%	73.7%	2.1

3.3. Analysis of future trends

Changes in annual precipitation

Applying GAMLSS, we calculated the time variation of the frequency distribution of yearly precipitation. Figure 3 presents the regional results obtained with the different RCMs. The centiles (5–95%) which show the time evolution of the fitted model from GAMLSS are also presented. Table III presents the annual precipitation changes between 1990 and 2050. The RACMO model predicts a slight decrease in the amount of rainfall for the Senegal basin, and an increment for the Nakambe basin, while the REMO model predicts a decrease in the amount of annual rainfall (about 30%) in all regions. The RCA/SHMI model shows a strong increase trend (about 25–30%) on the Senegal basin and a small decrease in the Nakambe basin. The RCMs do not converge on future precipitation changes in Western Africa. As mentioned below, this is mainly due to model errors and processes representation in RCMs, rather than to differences in driving GCMs (Paeth *et al.*, 2011).

Changes in the annual maximum DSL in the monsoon season

In each region, the time series of the annual maximum DSL for each year (AMDSL) for the monsoon season were built, taking into account the maximum dry spell in the year considering all selected sites. Table III shows the AMDSL changes between 1990 and 2050. An increase of AMDSL is generally predicted. Our findings are coherent with the results of García Galiano and Giraldo Osorio (2010), working with REMO ensemble members and empirical cumulative density function on the Senegal River basin. For the RACMO and REMO models, the increase on the Senegal basin SAS eco-region is projected at between 3 and 25% (3–35 days), whereas on the Senegal basin WSS eco-region the estimated increment is about 12–36% (6–12 days). On the Nakambe basin an increase of AMDSL between 16 and 47% (3–18 days) is projected by both RACMO and REMO. Only the RCA/SMHI model shows a decrease of the AMDSL on the Senegal basin (between 15 and 24%).

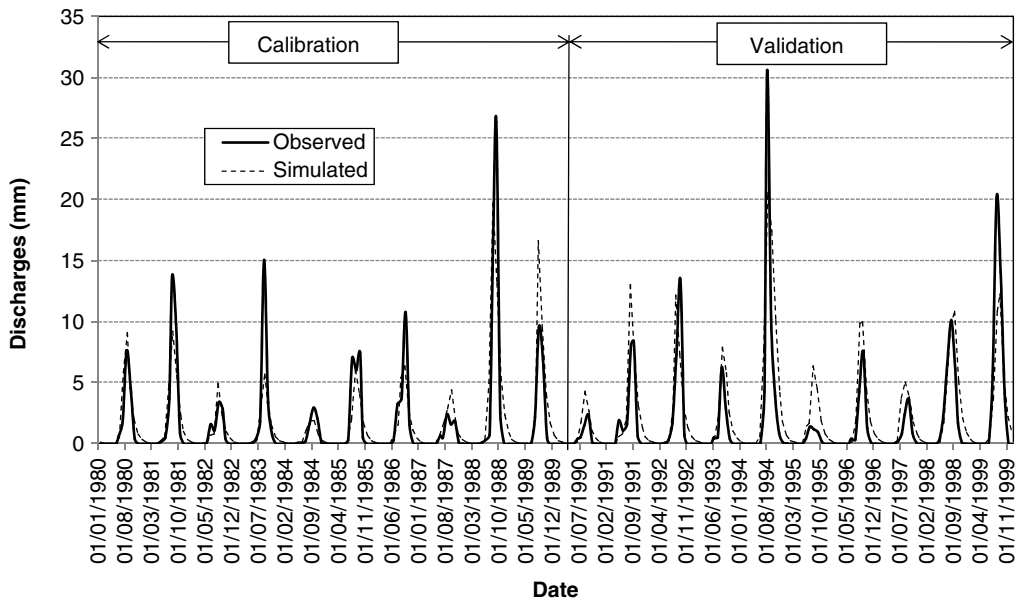

Figure 4. Comparison between simulated and observed hydrographs in calibration and validation of the GR2M model on the Nakambe basin.

Table III. Projected values for 2050 against the 1990 value for each RCM. The IRD values have been estimated for the period 1970–1990.

	RACMO		RCA/SMHI		REMO		IRD
	1990	2050	1990	2050	1990	2050	1970–1990
Mean annual precipitation (mm)							
Senegal basin SAS	303.1	298.5	123.5	163.2	458.0	352.3	342.3
Senegal basin WSS	834.2	748.6	340.4	422.7	741.8	509.8	803.0
Nakambé basin	822.9	1018.0	529.2	505.0	640.9	431.5	687.1
Annual maximum DSL—95% centile (day)							
Senegal basin SAS	92.3	95.1	171.2	146.3	138.6	173.6	180.3
Senegal basin WSS	32.7	44.4	43.3	33.0	55.9	62.5	48.7
Nakambé basin	21.4	24.8	19.3	19.7	39.3	57.8	31.5

3.4. Analysis of impacts on runoff

The hydrological model GR2M calibration was performed for the period 1980–1989 with a Nash performance coefficient (Nash and Sutcliffe, 1970) of 72%. The model validation was done using the 1990–1999 period, and the results were quite similar to those obtained by the calibration process (Nash coefficient of 71%). The good fit between simulated and observed hydrographs in calibration and validation is shown in Figure 4.

An extended analysis of the historical discharges on the Nakambe River basin was carried out by Mahé *et al*. (2005) and Mahé and Paturel (2009). These previous studies showed that conversely to rainfall decrease, river discharges increased strongly in this basin after the 1970s compared to the period before 1970. This increase reached 193% for the period 1974–2008 compared to the period 1955–1973. In the last decade 1991–2000, discharges were 2.2 times higher than before 1970 (Figure 5).

With regard to precipitation, future trends of river discharges differ from one RCM to another. Compared to the decade 1991–2000, the RACMO and REMO models predict an increase of discharges for coming decades. This increase goes up to 156% during the decade 2031–2040 for RACMO and 68% during 2011–2020 for REMO. The RCA/SMHI model shows first a decrease of discharges (up to 17%) for the two decades 2011–2020 and 2021–2030, and then an increase (up to 36%) for the decades 2031–2040 and 2041–2050, compared to 1991–2000. These trends in river discharges are not in concordance with climate forcing variables. In fact, compared to the decade 1991–2000, the PET shows the same magnitude of decrease (1–5%) for all the RCMs (not shown). In the case of precipitation, trends differ between the models. The RCA/SMHI and REMO models show a decreasing trend of rainfall for future decades, while the RACMO model predicts a general increase trend compared to the decade 1991–2000 (not shown). If this increase of precipitation predicted by the RACMO model induces an increase in river discharges, the decrease of precipitation indicated by RCA/SMHI and

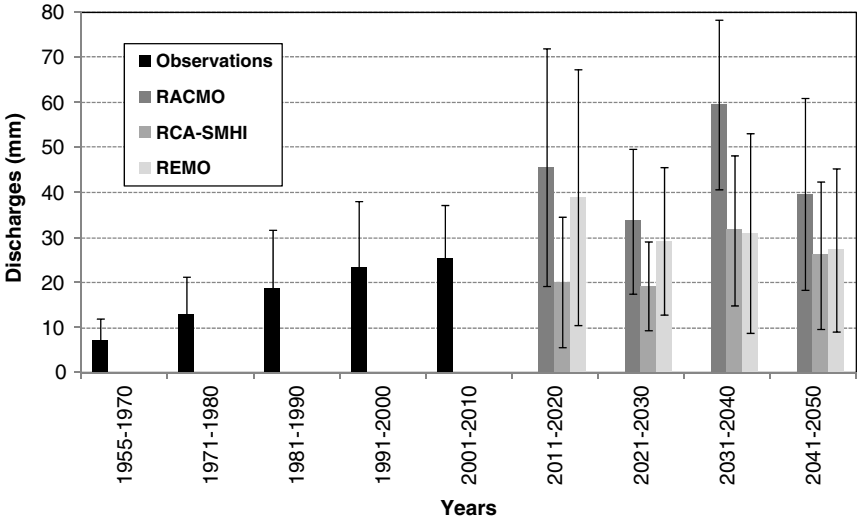

Figure 5. Evolution of decadal discharges (observed and predicted) on the Nakambe basin.

REMO will result in a general increase of river flows (mainly for REMO).

These results highlight the difficulty in predicting the response of hydrosystems in this semi-arid region. A decrease in precipitation will not necessarily induce a decrease in runoff and river discharges. This has already been demonstrated by observations (Mahé *et al.*, 2005). Several authors attributed this contradictory hydrological response of Sahelian catchments to land use changes (Leduc *et al.*, 2001; Favreau *et al.*, 2009; Mahé and Paturel, 2009; Séguis *et al.*, 2011) and the extension of hydrographic networks (Leblanc *et al.*, 2008). Indeed, the increase of crusted and cultivated areas to the detriment of natural vegetation cover since the 1960s has led to a decrease of soil infiltration capacity and an enhancement of surface runoff (Mahé *et al.*, 2005). Thus, in addition to reducing errors in RCMs and building reliable climate predictions in West Africa for impact assessment, another remaining challenge resides in developing land use scenarios and integrating them into hydrological modeling. Future research actions should be oriented in this direction in order to develop reliable decision support tools enabling better adaptation to climate variability and change in the Sahel.

4. Conclusion

From observed and RCMs data, plausible trends in rainfall and frequency of dry spells and mean annual rainfall are identified and analyzed on two West African river basins (Senegal and Nakambe). A non-stationary behavior of the annual series of maximum of DSL in the monsoon season is reflected in temporal changes in mean and variance. Impacts analysis on runoff in the Nakambe basin was also undertaken.

From the comparison of RCMs selected against observed rainfall dataset, we conclude that the RACMO model presents the best ability to represent the seasonal cycle of precipitation, particularly in the WSS eco-region of both basins. REMO appears better to represent the seasonal cycle in the Senegal basin SAS eco-region. Also, RACMO represents the DSL distribution better than the other models, whereas REMO adequately estimates the mean of DSL, but it is not satisfactory with standard deviation. Finally, the RCA/SMHI model does not present good behavior in the simulation of analyzed variables (precipitation or DSL).

For 2050, a decrease of annual precipitation projected is observed for both RACMO and REMO models in all regions (except in the Nakambe basin, where RACMO predicts an increase in annual rainfall). On the other hand, the AMDSL 2050 projection from the RACMO and REMO model presents an increase, especially in the WSS eco-region of both the Senegal and Nakambe basins.

Impact assessment on water resources on the Nakambe River basin generally show an increase trend of discharges for coming decades compared to 1991–2000. These trends in river flows highlight the influence of land uses and covers in analyzing hydrological response and water resources availability in the Sahel. In order to generalize these results, the analysis should be extended to other basins in the region and more RCM outputs from ENSEMBLES should be utilized. A remaining challenge which can guide future research on assessing climate change impacts on water resources in the Sahel will be the elaboration of land use scenarios to be integrated in hydrological models.

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