P2.10 Assessment of global climate characterization of duration, intensity and frequency of daily rainfall: Application to African Sahel

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1. INTRODUCTION

The present work is carried out in the context of an international cooperative project between Canadian International Development Agency (CIDA) and the CILSS organization (Comité permanent Inter-États de Lutte contre la Sécheresse au Sahel), a major institution regularly implicated in the assessment of vulnerability and risks associated to climate variability and change in Sahelian countries (western Africa). This cooperation has been developed to reinforce scientific and institutional capacities within the CILSS countries to adapt to climate change. This includes various contributions from Environment Canada (EC), the AGRHYMET (AGRiculture HYdrology METeorology located in Niamey, Niger) research centre, and the University of Québec at Montréal (UQÀM, Canada). Beyond the socio-economic investigation under the coordination of AGRHYMET and UQÀM, one of key mandate was to better characterize the rainfall regime over all this monsoon region, and to assess various climate modeling tools (i.e. from existing global climate models to downscaling methods) and their capacity to develop useful and plausible climate change scenarios in that area. All this characterization and evaluation of modeling tools, related to the precipitation regime, must have considered their relevance for the hydrologic cycle and agriculture impact studies.

Indeed, the West African Sahel is a semi-arid band between around 10ºN and 20ºN and extending from the coasts of Senegal to the Red Sea. The region is a well known for its quite distinct precipitation regime with an extensive dry season (Nicholson, 1995), which presents a strong impact on socio-economic life with heavy crops in the context of severe droughts.

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The later led in the past to recognized humanitarian crisis as important migration of peoples or deaths due to famine.
One of the principal characteristics of this area is the strong space-time variability of rainfall on various time scales, i.e. intra-seasonal, inter-annual and decadal scales (e.g. Moron, 1994; Nicholson 1998; Sultan and Janicot, 2003). Thus, the community life at the local scale is largely dependent to the climate and its change, as the strong majority of socio-economic activities are mainly related to the rainwater agriculture.

The development of adaptation policies in the perspective of climate variability and change requires an accurate spatio-temporal resolution to develop and manage risk assessment studies at the local scale, in using state-of-the-art global climate models (GCMs) and/or downscaling methods. Prior to the establishment of future climate, an extensive assessment of GCMs is necessary in using relevant temporal resolution to characterize the climate regime, especially the precipitation one in term of intensity, duration and frequency of rainfall events. This is particularly true for the monsoon over western Africa in which small number of event are responsible for the major part of the precipitation amount, through organized mesoscale convective systems as well as interaction with the ITCZ (Inter-Tropical Convergence Zone; Sultan and Janicot, 2003, Sultan *et al*., 2003). These systems by nature have their origin at the regional or local scale with strong feedbacks within land surface conditions (i.e. soil and landscape, e.g. Zeng *et al.*, 1999). Hence, they are inherently difficult to accurately simulate by coarse-scale GCMs. However, one criterion for selecting GCMs to construct regional climate scenarios involves the validity of the model, which is evaluated by examining the GCM's ability to simulate present-day and past climates, both globally and for regional areas of interest (e.g. IPCC-TGCIA; see for western Africa recent results of Hoerling *et al*., 2006).

In that context, the objective of the present study is to evaluate three different coupled GCMs on their ability to simulate climate indices of precipitation and their spatial variability over western Africa in comparison with observed current climatology (over the period 1961-1990). As the need of daily data to calculate wet days, intensity per wet days, dry days and extremes of precipitation, this set of GCMs was used as they were the only model outputs available at this temporal resolution at the beginning of the project in 2002. The validation in using daily scale information allows to evaluate the simulated monsoon regime in terms of intensity, duration and frequency of precipitation events during the wet season (in general appearing between April to October according to the considered area). Also, two sets of reanalyses (NCEP and ECMWF-ERA40, Kistler *et al.*, 2001, and Kållberg, 1997, respectively) products have been compared with GCMs runs as these datasets are regularly used for models validation. The evaluation of these reanalyses will help to assess the relative confidence of these products over the Sahelian area, used as reference for the baseline climatology. Finally, this evaluation of climate models performance and reanalysis over this region will complete numerous studies most based on seasonal assessment from monthly mean values (Kamga *et al.*, 2005; Kamga and Buscarlet, 2006; Hoerling *et al*., 2006).

The considered models and data used are described in the next section. The methodology used for the evaluation of models performance is presented in section 3. The results are presented and discussed in section 4. Discussion and main conclusion are outlined in section 5.

2. DATA

This section describes the three types of data used in this study, i.e. climate models, reanalyses and observed data. All the dataset correspond to the daily precipitation information covering the recent three decades 1961-1990. This time-window is regularly used as a baseline to validate the current climate simulated by climate models, as well as to construct climate change anomalies in the future from this reference period. All precipitation data were considered for April to October months.

2.1. Climate models

Data from three coupled GCMs (Table 1) were obtained both from the web site of the Canadian Climate Impacts Scenarios project of Environment Canada (recently renamed Climate Change Scenarios Network, http://www.ccsn.ca) for the Canadian GCM and from the modelling centre for the United Kingdom and the German models.

Table 1. GCM used in the study, namely CGCM2 (Flato *et al.*, 2000), HadCM3 (Gordon *et al*., 2000) and ECHAM4 (Roeckner *et al.*, 1996).

Modeling centre	Version	Resolution (lat. x long.)
Canadian Centre for Climate Modelling and Analysis (Canada)	CGCM2	3.7°x3.7°
Hadley Centre for Climate Prediction and Research (United Kingdom)	HadCM3	2.5ºx3.75º
Max Planck Institut für Meteorologie (Germany)	ECHAM4	2.8ºx2.8º

The current-climate simulations for each model run correspond to transient experiments that incorporated historic equivalent CO_2 and sulphate aerosols both reconstructed from observed data. These runs at the time of the beginning of this study represented the latest available GCM versions from the various modelling centres and were incorporated into the IPCC Third Assessment Report (IPCC, 2001). All runs correspond to the first member of the ensemble runs using the SRES A2 emission scenarios (see Nakinocevic *et al.*, 2000) to provide climate change simulations.

2.2. Reanalysis Products

Reanalyses from the National Centre of Environmental Prediction (NCEP, e.g. Kalnay *et al*., 1996) were used on a daily scale. The precipitation variable is extracted from the regular latitude-longitude resolution of 2.5º × 2.5º.

The European Centre for Medium-Arrange Weather Forecasts (ECMWF-ERA40; e.g. Kållberg, 1997, and Kållberg *et al*., 2004) reanalyses data were also used. The reanalysed products were available at a resolution of 2.5º X 2.5º degrees every 6 hours, and are identical to those of NCEP in terms of grid resolution, and pre-processing procedure.

2.3. Observed Data

The observation data considered here were provided by the regional research centre Agrhymet (http://www.agrhymet.ne) which collect and archive national data from each country of CILSS institution. The data base incorporate 244 observed stations (located in Figure. 1), in which a quality control procedure has been made over the entire period 1961-

1990. In each observed series, more than 80% of daily precipitation values are taken in to account for a given year (season or month), in order to be considered in the computed climatology of the indices of precipitation.

Table 2. Precipitation indices used in the study in considering intensity, duration and frequency of wet/dry sequences.

Indices	Definition
Prcp1 (%)	Number of days with precipitation ≥ 1 mm
SDII (mm/day)	Simple daily precipitation index
CDD (day)	Maximum length of consecutive dry day with precipitation < 1mm
R3days (mm)	Maximum of cumulated precipitation over 3 days consecutive days
Prec90p (mm/day)	90th percentile of daily precipitation
MOY (mm/day)	Mean of daily rainfall
STD (mm/day)	Standard deviation of daily rainfall

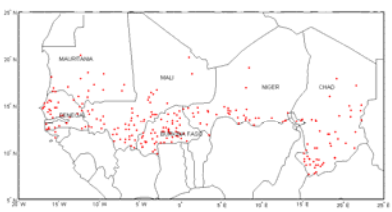

Figure 1. CILSS-Agrhymet observed stations considered in this study.

3. METHODOLOGY

3.1. Diagnostic variables of precipitation

From the climate indices used in various studies to characterize extreme and variability of basic variables as precipitation (Klein and Können, 2003; Vincent and Mekis, 2006; see also the European STARDEX project: http://www.cru.uea.ac.uk/cru/projects/stardex/), five indices have been identified to assess frequency, intensity and extremes of wet days (Table 2). Mean conditions and intra-seasonal variability of precipitation have been also included in the analysis (see Table 2). All indices are computed over the entire period from April to October months, and were averaged over the period 1961-1990.

3.2. Gridding Procedure and Study Area

In this study, a kriging procedure has been used for the spatialization of available climate records shown in Figure. 1, according to each model/reanalyse grid. This is based on former theoretical works (Deutsch and Journel, 1992 ; Journel & Huijbregts, 1992; Kitanidis, 1997; Marcotte, D. 1991), and uses the EasyKrig 3.0 tool (as developed by Dr. Dezhang Chu from Woods Hole Oceanographic Institution, United States). The ordinary kriging was considered with a grid adjustment for each model/reanalyse. The results were evaluated and validated using variance map and statistical tests, with a cross-validation procedure (results not shown here).

The study area encompasses the continental region of Sahel between the latitudes 10 to 20°N and the longitudes 25°W to 25°E (see Figure. 1). This region is large enough for GCM and reanalysis representation of sahelian precipitation, from wet areas near the Guinean coastlines in the South to dry or arid region of Sahara in the North.

From the krigging values of indices listed in Table 2, maps are presented in section 4 from observed data as well as differences between GCMs/reanalysis and observed precipitation indices. All indices are interpolated into the GCM/reanalysis grid in using the corresponding original resolution of each model given in Table 1.

3.3. Statistical Criteria

The models/reanalyses performance are evaluated using three statistical parameters mean bias error (MBE), the mean absolute error (MAE) and the mean normalized differences (ND) defined respectively as follows for each grid point:

$$MBE = \left\langle \overline{M(t)}_{i,j} - \overline{O(t)}_{i,j} \right\rangle$$

$$MAE = \left\langle \left| \overline{M(t)}_{i,j} - \overline{O(t)}_{i,j} \right| \right\rangle$$

$$ND = \left\langle \left(\frac{\overline{M(t)} - \overline{O(t)}}{\sigma(O(t))} \right)_{i,j} \right\rangle$$

where t refers to the time and varies between 1 and 30 (for 30 years); <> represents the spatial average over the entire grid; i, j represent the subscripts associated to each

grid point; M refers to Model and O to Observation; and σ refers to the temporal standard deviation from observed data.
These statistical criteria are appropriate to quantify errors in terms of a systematic over/under estimation of observed indices (MBE). They are also useful to highlight the amplitude of mean error (MAE) and the error over a long-term mean (i.e. ND, in dividing the MBE by the climatological standard deviation, which is the mean bias obtained when a series is replaced by its long-term mean).

4. RESULTS

4.1. Spatial comparison with kriging indices

As shown in Figure 2, GCMs and reanalyses under-estimate systematically by about a factor 2, the mean seasonal precipitations in southern Sahel which corresponds to the wettest area during the monsoon period. In the arid regions of Sahara, GCMs badly reproduce the decrease of rainfall from South to North and West to East. The intra-seasonal variability (shown in Figure 3) is systematically under-estimated in the southern Sahel by GCMs and reanalyses, especially by the HadCM3 model and ECMWF reanalyses. In the other regions, the difference between GCMs and observations is less important with weak over-estimation of variability in northern areas.

The frequency of wet days (shown in Figure 4) is over-estimated in the central zone and the South-East for the three GCMs. In particular, HadCM3 over-estimates the observations by a factor 2, whereas ECHAM4 model tends to over-estimate the observations in the southwestern and southern central regions. Despite a weak over-estimation over sub-saharian zones, the GCMs simulate relatively well the wet days in northern regions, especially the ECHAM4 model in the North-East.

The spatial distribution of mean seasonal precipitations intensity (shown in Figure 5) is generally badly simulated by the models despite relative accurate values over the most rainy areas in the South, except for the ECMWF reanalyses and for the model ECHAM 4 which largely under-estimate the intensity of precipitation during wet days. Futhermore, the set of GCMs and reanalyses do not reproduce adequately the decrease of precipitation intensity from West to East and from South to North. Hence, the errors in the simulation of the precipitation regime by GCMs/reanalyses are not only linked to the frequency of wet days but also linked to a problem to reproduce the intensity.

The comparison between simulated and observed maximum of consecutive dry days is shown in Figure 6. This confirms the poor capacity to simulate the lowest dry sequences in southern Sahel. However, in the central Sahel and northern semi-arid zone, the simulated CDD is largely over-estimated for the reanalyses and under-estimated for the CGCM2 and HadCM3 models. Only ECHAM4 model simulates relatively well the dry sequences in North-East and North-West, despite an under-estimation in northern central zones. The dry sequences simulated by the models in Sahel reveal some strong biases in sub-saharian zones, with a systematic over-representation of ITCZ structure and deepening over the northern areas of western Africa, as revealed in previous works (e.g. Kamga and Buscarlet, 2006).

The maximum of precipitations cumulated over three consecutive days (shown in Figure 7) is generally well reproduced by the set of reanalyses by comparison with GCMs. The overall GCMs under-estimate this amount of precipitation in southern areas. However, the CGCM2 model over-estimates this quantity by a factor two or three. The simulated distribution of this indice corresponds generally to that of SDII, suggesting some systematic biases in the simulated duration of intense wet days.

Finally, the simulated extreme of precipitation represented by the 90^{th} percentile (shown in Figure 8) reveals more often an under-estimation in particular in South, West and North. HadCM3 model seems to under-estimate mostly this indice. Except for southern regions, the overall GCMs and reanalyses seem to be unable to adequately simulate the number of days to exceeding the 90^{th} of the reference period (not shown).

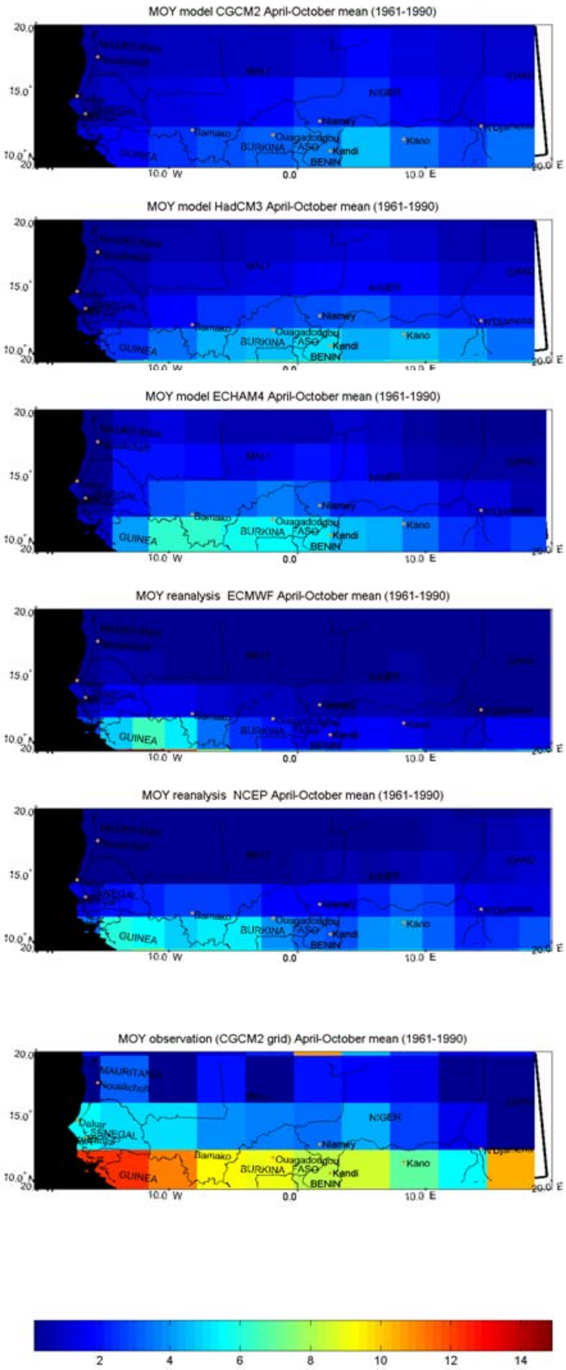

Figure 2. Daily mean precipitation [MOY] (in mm/day) between April and October and over the period 1961-1990. From up to down the maps of MOY associated to the three models (CGCM2, HadCM3 and ECHAM4) and the two sets of reanalyses (ECWMF and NCEP) are shown. The bottom map represents the kriged observation data interpolated to correspond to CGCM2 model grid.

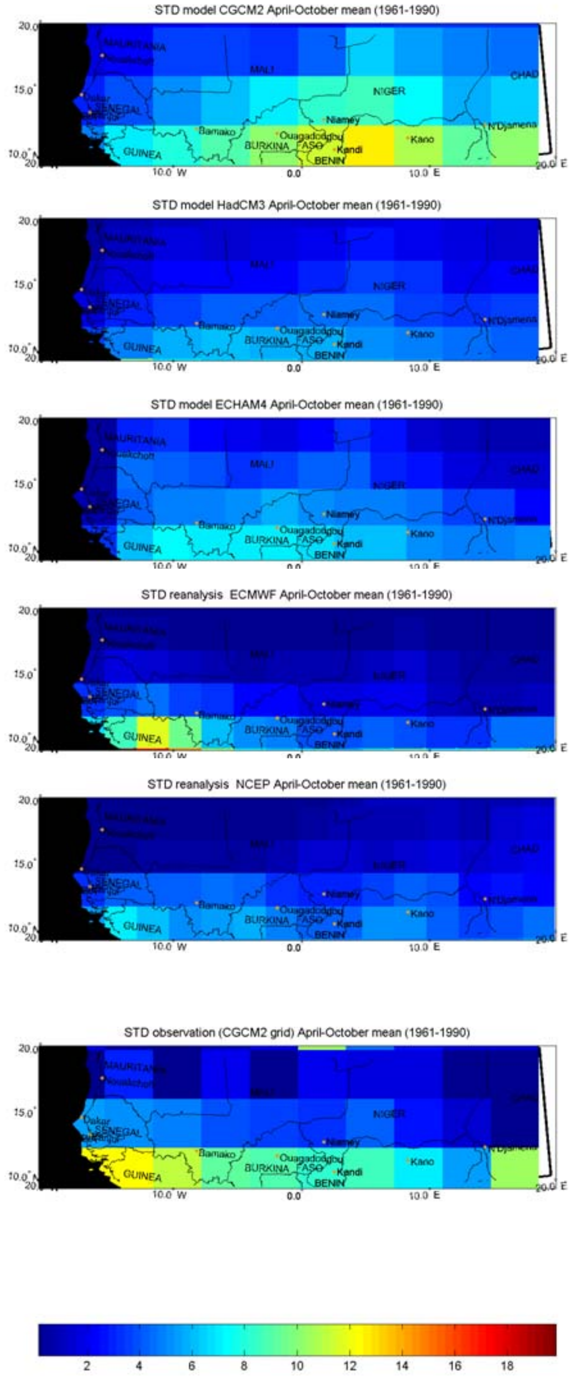

Figure 3. Same as Figure 2 for the intra-seasonal standard deviation simple (in mm/day).

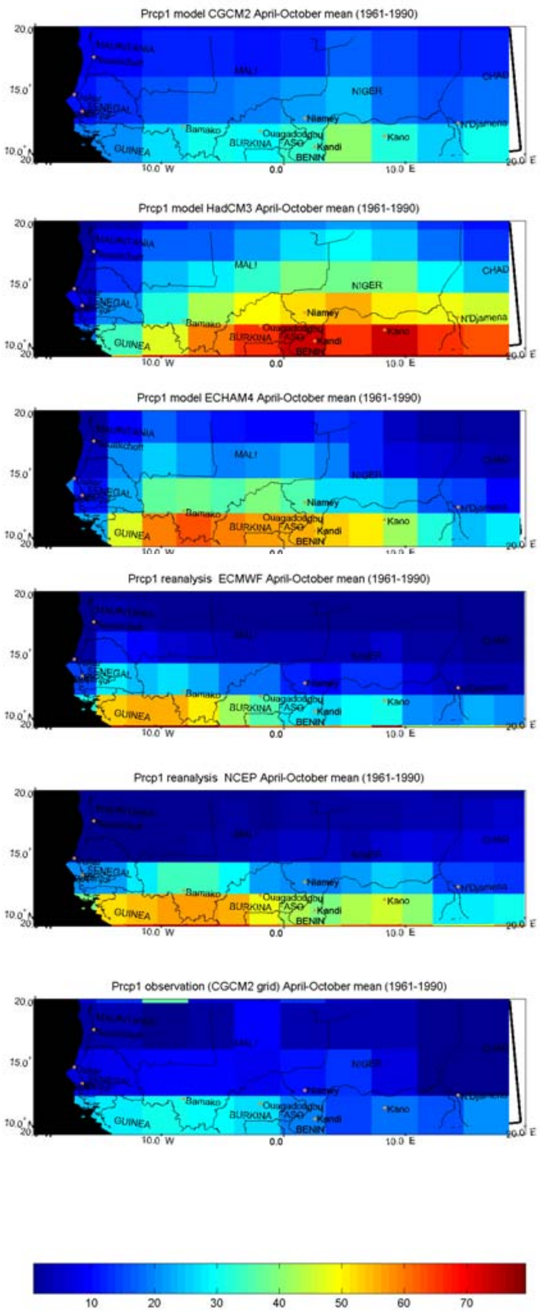

Figure 4. Same as Figure 3 but for the frequency of day with precipitation Prcp1 (%).

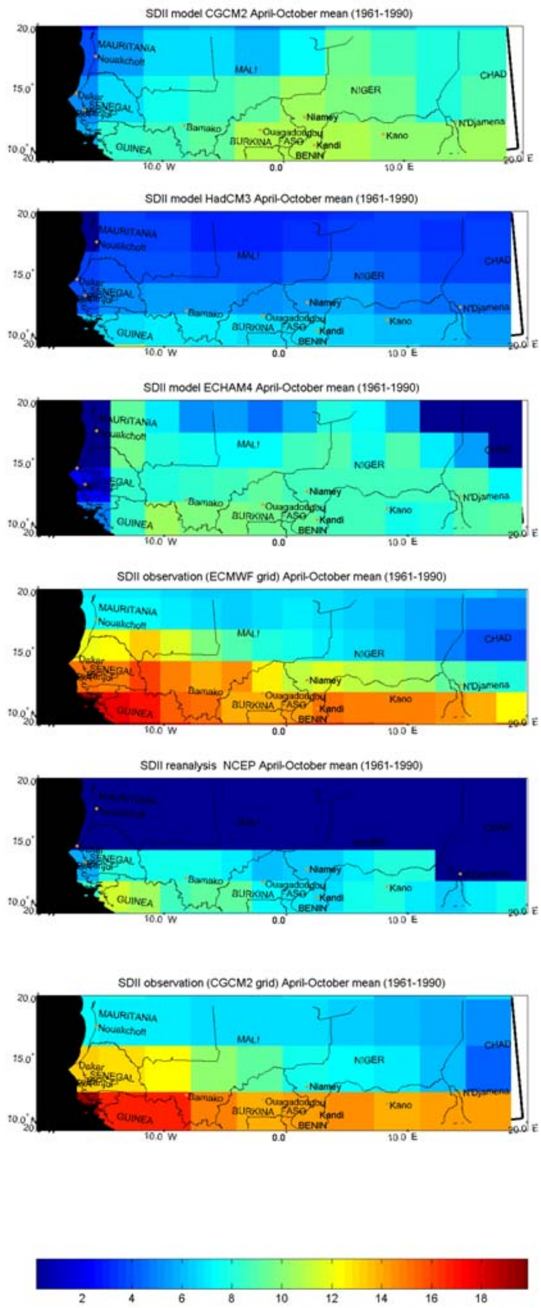

Figure 5. Same as Figure 2 for the simple daily precipitation index SDII (in mm/day).

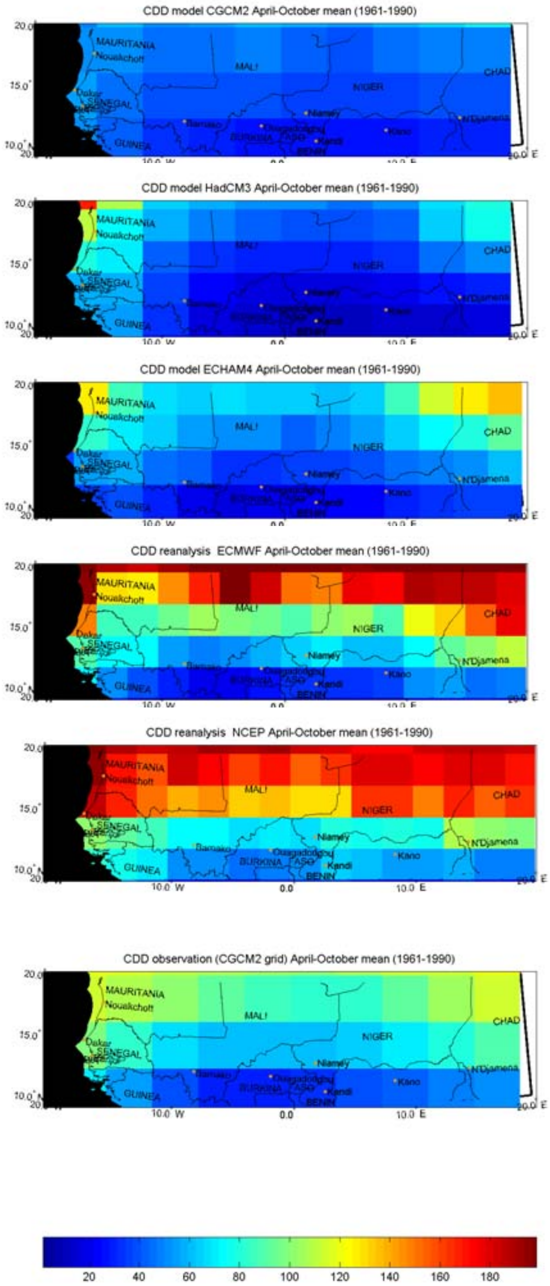

Figure 6. Same as Figure 2 for consecutive dry days CDD (in days).

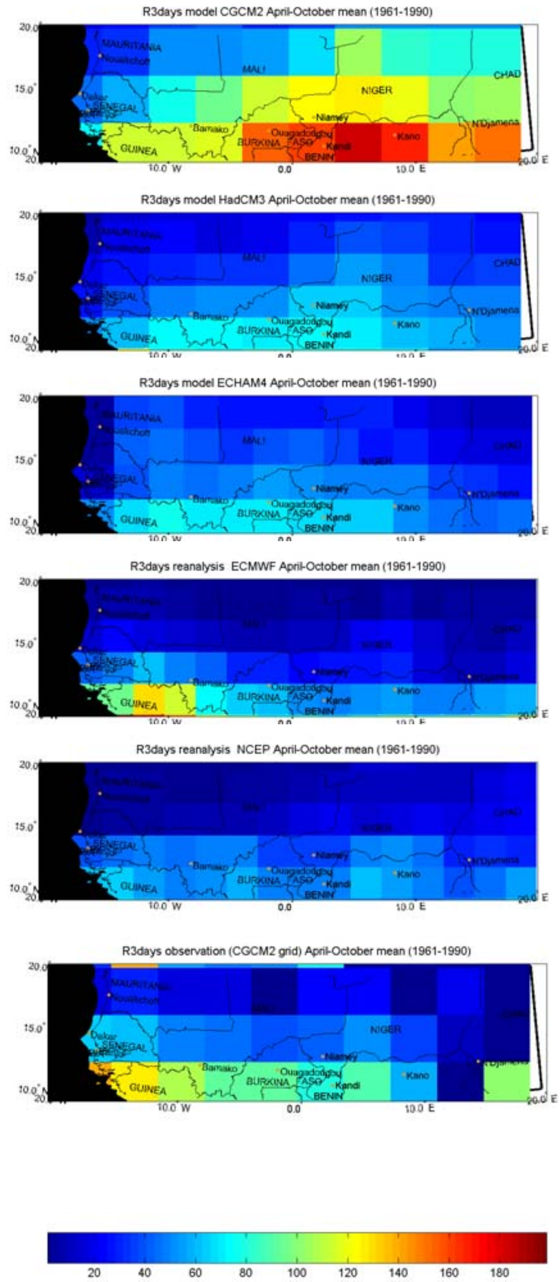

Figure 7. Same as Figure 2 Maximum of cumulated precipitation over 3 days consecutive days R3days (in mm)

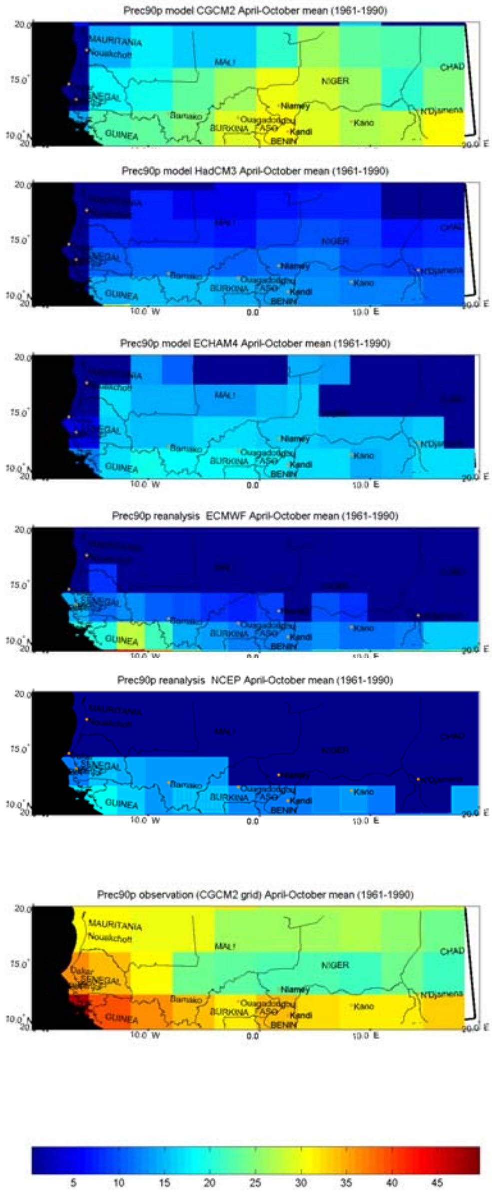

Figure 8. Same as Figure 2 for 90th percentile of daily precipitation Prec90p (mm/day)

4.2. Spatial mean of statistical criteria

Figures 9, 10 and 11 show respectively the GCMs/reanalyses MBE, MAE and ND, for each considered indice over the overall Sahel window i.e. (10°N-20°N, 25°W, 25°E).

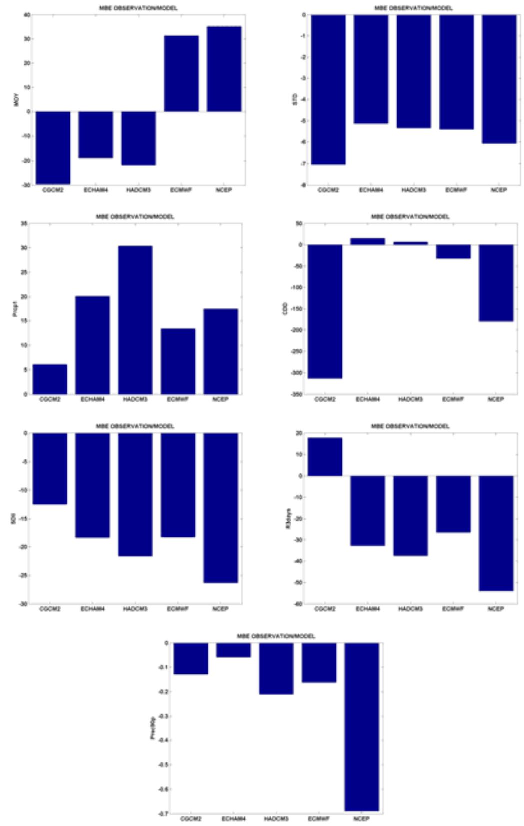

Figure 9. Mean spatial MBE values for each indice from GCMs/reanalyses over April-October and 1961-1990. For each indice (names given in y-axis), MBE is given for CGCM2, ECHAM4, HadCM3, ECMWF and NCEP, respectively, from left to right.

Over all the sahelian area, the mean biases of inter-seasonal variability are almost the same between GCMs and reanalyses, with an under-estimation about 5-7 mm/day. A systematic under-estimation of the mean precipitation appears from the GCMs simulated values (between 10 to 20 mm/day), whereas the reanalyses over-estimate the mean rainfall. CGCM2 displays the highest bias for mean precipitation, whereas NCEP the most important bias in standard deviation. Furthermore, large differences exist in mean bias of wet days between the models, in spite of all models and reanalyses over-estimate this indice. This latter varies between 5 and 30% with the weakest bias for the CGCM2 model and the highest for the HadCM3 one. Biases related to maximum consecutive dry days are quite different between models and reanalyses, with a strong under-estimation by 30 days with the CGCM2 model. The bias on precipitation intensity varies from a ratio of 1 to 2, with a systematic under-estimation between 4 to 8 mm/day. The maximum of precipitation amount cumulated over three days reveals an over-estimation for CGCM2 of about 20 mm, whereas all other GCMs and reanalyses display an under-estimation of 20 to 50 mm/day. The overall GCMs and reanalyses under-estimate systematically the extremes precipitation by 12 to 25 mm/day.

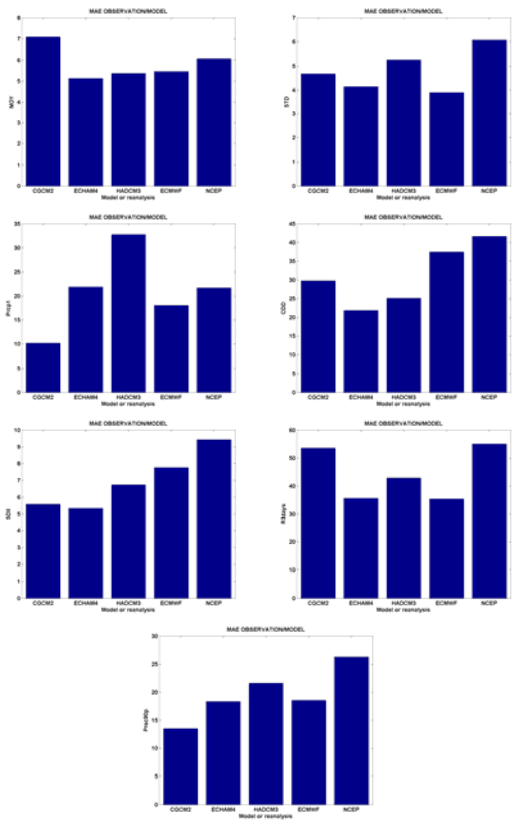

Figure 10. Same as Figure 9 but for the mean spatial MAE.

The mean absolute error (shown in Figure 10) allows to complete that of MBE. As illustrated for the mean precipitation, the MAE is similar in absolute amount to that of related MBE suggesting a systematic negative bias for GCMs and positive one for reanalyses. The same similitude remains valid for standard deviation. MAE values for Prcp1 are also similar in magnitude to the corresponding MBE, and conserve the differences between GCMs/reanalyses. Thus the over-estimation of wet days is quite common over the major part of the sahelian region, as suggested in Figure 4. For the CDD and SDII, the highest values of MAE come from the reanalyses whereas ECHAM4 displays the lowest error. For the R3days and Prec90p the distribution of MAE values is more heterogeneous between models and reanalyses, especially from NCEP values which suggest the strongest absolute values for extremes of precipitation.

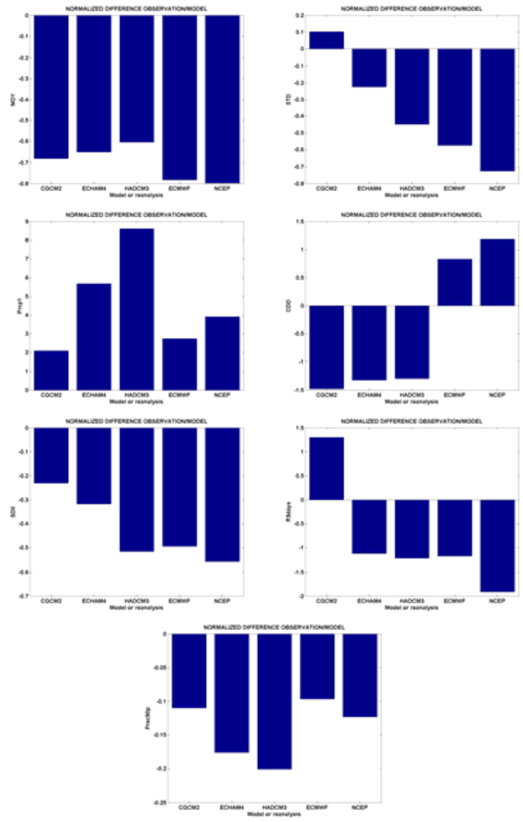

Figure 11. Same as Figure 9 but for the mean spatial ND (normalized values).

The mean normalized differences between models/reanalyses and observation are shown in Figure 11. The main interest of the normalization is to allow a comparison between all indices. This allows to evaluate the robustness of each simulated indice between models and reanalyses. This suggests that the highest relative errors appear for Prcp1 and CDD with respect to other indices. CGCM2 performs better for Prcp1 indice whereas the other models/reanalysis display nearly the same results for other indices. The inter-seasonal variability and the mean precipitation are also better reproduced by GCMs.

5. DISCUSSION AND CONCLUSION

The analysis of GCMs and reanalyses performance compared to observed 1961-1990 climatology over the Sahelian wet season reveals:

- A various performance according to the considered model/reanalyse as well as to the considered indices and regions;
- The biases in the simulated mean precipitation are related to strong difficulty

in GCMs to accurately simulate the frequency, intensity and duration of wet days or dry spells;

- The highest errors from simulated values are revealed in the frequency of daily precipitation, and in the maximum of consecutive dry days. A systematic over-estimation in the simulated values of wet days appear in the semi-arid areas of Sahel;
- The reanalyses products have more often the same biases as those from the GCMs runs for the majority of extreme indices;
- A strong limitation of the simulated precipitation regime by GCMs is revealed over the Sahel. This can be linked directly and indirectly to the limitation of model's physics and sub-grid scale parameterization to correctly describe the complexity of convective systems, appearing over the region and responsible for the major characteristics of the wet season.

According to the above considerations, GCMs appear to be limited for their application in constructing climate scenarios for this region. The precipitation regime over the Sahel, in which periodic severe human and environmental impacts due to strong climate variability of drought or flood, requires alternative methods as downscaling techniques (both dynamical and statistical ones) in order to increase our confidence in the anticipated climate change, as well as to construct reliable climate change scenarios at the regional/local scale. In particular, statistical downscaling methods can constitute an alternative method for climate changes information requisite at the local scale. These methods are computationally inexpensive with respect to regional climate models and they can be used to provide site-specific information, which can be critical for many climate change impact studies in Sahel with limited resources. A work is underway with two statistical downscaling methods and promising results have been recently obtained to improve the frequency, intensity and duration of wet/dry spells at the local scale.

Furthermore, in order to response to population needs in Sahel, the development of new climate indices for their use in climate change information, i.e. related to the quality of the monsoon season with on-set/off-set and length of the wet period, is also planned.

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