Climate Change Signals Over Senegal River Basin Using Regional Climate Models of the CORDEX Africa Simulations

Mamadou Lamine Mbaye[1](✉), Samo Diatta[1],
and Amadou Thierno Gaye[2]

[1] Laboratoire d'Océanographie,
des Sciences de l'Environnement et du Climat (LOSEC),
Université Assane SECK de Ziguinchor, BP 523, Ziguinchor, Sénégal
`mlmbaye@univ-zig.sn`
[2] Laboratoire Physique de l'Atmosphère et de L'Océan (LPAO),
ESP/UCAD/Sénégal, Dakar, Sénégal

Abstract. This study provides an overview of the impact of a statistical bias correction based on histogram equalization functions on a set of high resolution climate simulations over the Senegal River Basin. Regarding the future changes of extreme precipitation (greater than 50 mm), the models diverge in predicting heavy rainfall events in the majority of the basin. However, an increase of extreme precipitation is found around the Guinean Highlands. The results show also an increase of dry day's length and a decrease of wet days spells by all the RCMs, except one model that shows an opposite change of these climate indices. The bias correction affects mainly the magnitude of the climate change signals of extreme precipitation. Changes under the Representative Concentration Pathways (RCP8.5) are the most pronounced with uncorrected data. Bias corrected RCMs data are potentially useful for climate change impact studies over the Senegal River Basin. This study highlights a convergence of all RCMs (except for RCA RCM) in projecting a decrease of wet days and an increase of dry days over the Senegal River Basin.

Keywords: Climate change · Bias correction · Signal · Regional climate model
Senegal Basin

1 Introduction

Climate change over rural areas has led to considerable impacts on critical sectors such as water resources, agriculture, health, etc. Due to its weak capabilities, Africa is highly affected by these impacts, and this is likely to be exacerbated in the future by extreme events (such as flood, drought) and the high population growth which increases its exposure and vulnerability. Moreover, the changes in extreme precipitation and temperature are predicted by many global climate models as a response to greenhouse gas increase and such changes will have significant environmental and social impacts [1]. The well-known droughts during the three last decades of the 20th century over West Africa were the most severe consequences ever seen in Africa. Nowadays, climate and

C. M. F. Kebe et al. (Eds.): InterSol 2018, LNICST 249, pp. 123–132, 2018.
https://doi.org/10.1007/978-3-319-98878-8_12

hydrological models are the most powerful tools available at our level to address the issues of climate change on water resources. Among these climate models, GCMs output are not suitable for impact studies due to their coarse resolution and systematic biases [2]. Therefore multiple efforts in improving the quality of climate models output made by the international scientific community has come to an international project known as the COordinated Regional climate Downscaling Experiment [3]. The CORDEX purpose is to provide higher regional climate simulations for climate change impact studies and decision making at the regional level [4]. The finer spatial resolution of RCMs when compared to GCMs can be an added value while simulating regional climate features such as precipitation over mountainous areas [5]. However, it is pointed out that RCMs output are associated with systematic biases that can affect hydrological simulations [6]. Previous studies over West Africa, have shown an increase in the frequency of extreme rainfall events from the end of 20th century to early 21st century over the Sahel by using observed stations data [7]. In addition, a probable intensification of droughts events is found by [8] through an increase of dry days and the frequency of their occurrences. [9] by analyzing trends in extreme rainfall indices over Senegal from 1950 to 2007, suggested that modest to significant increases in daily wet days intensity. Projected changes of four RCMs indicated a decline in mean precipitation except for one RCM over one region in Senegal [10]. Furthermore, [11, 12] found that despite the projected decreases in total rainfall, the proportion of total annual rainfall that falls in heavy events tends towards increases in the ensemble projections. Moreover, an assessment of plausible regional trends associated to the return period, from the hazard maps of annual mean of daily rainfall by [13], showed a general rise, owing to an increase in the mean and the variability of extreme precipitation over the Senegal River basin. The future evolution of extreme precipitation dwell unclear at the basin scale where more detail information are needed by water resources managers and users. Hence, to our knowledge there is a lack studies and understanding that account for the removal of RCMs biases and the effect of the statistical bias correction on the climate change signals of extreme precipitation at the basin scale. For this reason, post processing of climate model output known as bias correction is often used for bias removal. However, bias correction cannot improve the misrepresentation of physical processes and transient response to greenhouse gas emissions [14]. In recent impact studies, quantile mapping or histogram equalization methodology is commonly used due to its skills, effectiveness and less parameters to fit, and also because it improves both mean and variance of precipitation fields (as seen in [14–18]). These authors have modified/used the methodology developed by [19] that is also applied in the present study. This study aims to assess the potential changes of climate change signals of extreme precipitation at the basin scale by using bias corrected data and uncorrected data from CORDEX RCMs.

The paper is structured as follows. The data and the methods are briefly given in Sect. 2. Section 3 presents the results of the projections of precipitation characteristics. The discussion of the results is detailed in Sect. 4. Finally, Sect. 5 delivers the conclusion.

2 Data and Methods

2.1 Senegal River Basin

The Senegal River Basin (SRB) is situated in West Africa (Fig. 1). The basin's catchment is about 300,000 km^2 and it is shared by four countries such as Guinea, Mali, Mauritania and Senegal [20]. The basin is subject to a large south–north rainfall gradient with maximum in the south (up to 1800 mm/year) and minimum in the north (150 mm/year) as like most West African countries. In addition, the northern basin (sahelian part) has the hottest temperatures.

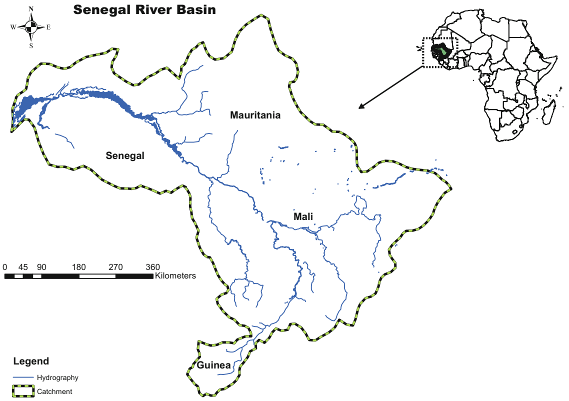

Fig. 1. Senegal River Basin

2.2 Data

Rainfall simulations from five regional climate models (REMO, HIRHAM5, RACMO22T, CCLM4, and RCA4) that are involved in the COordinated Regional climate Downscaling Experiment [3] under the Representative Concentration Pathways (RCPs 4.5 and 8.5) are analyzed. Some characteristics of the models are described briefly in Table 1. Additionally, gridded precipitation data from the EMBRACE forcing data based on ERA-interim known as WFDEI [21] are used for observational datasets. Due to the well-known biases of RCMs output, a statistical bias correction is applied to correct models biases following the method of [19]. The WFDEI data are used to bias correct RCMs simulations during the training period (1979–2005) where transfer functions are derived (details in [22]).

2.3 Bias Correction

The bias correction is based on fitted histogram equalization where the corrected variable is a function of the modeled counterpart ($V_{cor} = F(V_{mod})$). The statistical bias correction technique is described in detail in [19], and the method is widely used in several studies [14–16, 18, 22], etc. Therefore, we give only a short summary of the method as follows. Transfer functions (TFs) of daily rainfall data are generated. To obtain the TFs, observed and corresponding simulated time series of the same length are sorted according to their magnitude, from smallest to largest. A transfer function maps the cumulative probability distribution function of the modeled data onto that of the observed. The bias correction transfer functions are derived for the training period 1979–2005 between RCMs and WFDEI data and applied to 1971–2000 for the historical and to 2071–2100 RCMs simulations for both scenarios.

2.3.1 Precipitation Bias Correction

The following transfer functions (TFs) were used:

$$P_{cor} = a + bP \tag{1}$$

$$P_{cor} = (a + bP)\left(1 - e^{(-(P-P_0)/\tau)}\right) \tag{2}$$

Where P_{cor} represents the bias corrected precipitation, P is a given value to be corrected and, a, b, P_0 and τ are fit parameters. In the linear Eq. (1), the coefficients a, and b are respectively additive and multiplicative correction factors. P_0 is the value of precipitation below which modeled precipitation is set to zero. Equation (2) is composed by an exponential that tends to a linear asymptote (a + bP); τ is the rate at which the asymptote is approached and P_0 is the dry day correction term. For high intensities the TF of Eq. (2) tends to the linear term as Eq. (1), and it presents a systematic change of slope at the lowest intensities [18].

Table 1. Some characteristics of the RCMs

	MPI-REMO	DMI-HIRHAM5	CLMcom-CCM4-8-17	KNMI-RACMO22T	SMHI-RCA4
Institution	Climate Service Center	Danish Meteorological Institute	Climate Limited_area Modelling Community (CLM-Community)	Royal Netherlands Meteorological Institute	Swedish Meteorological and Hydrological Institute, Rossby Centre
Short name	REMO	HIRHAM5	CCLM4	RACMO22T	RCA4
Driving model	MPI-ESM-LR	ICHEC-EC-EARTH	MPI-M-MPI-ESM-LR	ICHEC-EC-EARTH	NOAA-GFDL-GFDL-ES2 M
Resolution/projection	0.44° Rotated pole	0.44° Rotated pole	0.44° Rotated pole	0.44° Rotated pole	0.44° Rotated pole
Advection scheme	semi-lagrangien	semi-lagrangien	Fith order upwind [23]	semi-lagrangien	eulerian
Convection scheme	[24]	[24]	[24]	[24]	[25, 26]
Vertical coordinates/levels	Hybrid/27	Hybrid3.1	Terrain following/3.5	Hybrid/40	Hybrid/40
References	www.remo-rcm.de	www.dmi.dk/dmi/tr06-17	www.clm-community.eu	http://www.knmi.nl/research/regional_climate/models/racmo.html	http://www.smhi.se/en/research/research-departments/climate-research-rossby-centre2-552/rossby-centre-regional-atmospheric-model-rca4-1.16562

2.4 Simulations Analyses

The following climate indices are used to assess the climate change signals: the maximum number of consecutive wet days (cwd), maximum number of consecutive dry days (cdd). A day is considered as wet/dry when the precipitation is greater/less than 1 mm/day. Additionally, days where rainfall is higher than 50 mm is computed as extreme rainfall events in JAS season. The changes represent the difference between the scenario period (2071–2100) and the reference period (1971–2000).

3 Projections of Precipitation Characteristics

The changes in the number of extreme rainfall days are displayed in Fig. 2. Uncorrected REMO and RACMO22T output show a decreasing tendency of extreme rainfall events with RCP8.5 (−35 days) particularly in the eastern basin for RACMO22T and in the majority of basin for REMO. However, for these same models and scenario, the bias correction seems to alter the climate signal for RACMO22T; as for REMO the bias correction decreases the signal. With RCP4.5, the changes are similar to those found with RCP8.5 for RACMO22T. For REMO, the north-western part of the basin depicts the highest changes with RCP4.5. Furthermore, the southern basin exhibits an increase of extreme rainfall in all data and scenarios for REMO and RACMO22T. For HIRHAM5, it is found a clear increasing tendency of heavy precipitation for both datasets and scenarios (up to 35 days in the southern basin). As for RCA4, corrected and uncorrected data show identical spatial patterns with RCP4.5 where the Guinean Highlands depict a decrease of extreme precipitation by contrast above 12°N, slight increase (5 to 10 days) is found in the majority of the basin. In case of RCP8.5, both RCA4 simulations have similar spatial patterns where in some parts show a slight increase and others show a decrease. In addition, the basin is likely to experience generally an increase of heavy rainfall events with RCP4.5 (raw and corrected RCA4 data). As with RCP8.5, both CCLM4 simulations show an increase below 13°N; however, above this latitude, decreased high rainfall events seem to dominate the changes that are more pronounced with uncorrected data.

The changes of the maximum consecutive dry days are displayed in Fig. 3. Considerable increases of dry days (up to 60 days particularly in the northern basin) are found in REMO, HIRHAM5, CCLM4, and RACMO22T in both scenarios. However, this later model shows slight decrease of dry day length in the south-eastern basin. Moreover, RCA4 model shows considerable decrease of cdd to more than 20 days in the majority of the basin, except around the mountainous areas where a slight increase of cdd is found. For all models, both simulations show similar spatial patterns.

Figure 4 shows the changes in the consecutive wet days. All the models except RCA4, project a general decline of wet days (up to more than 20 days). RCA4 model exhibits an increased pattern of wet days length. RACMO22T model also show slight

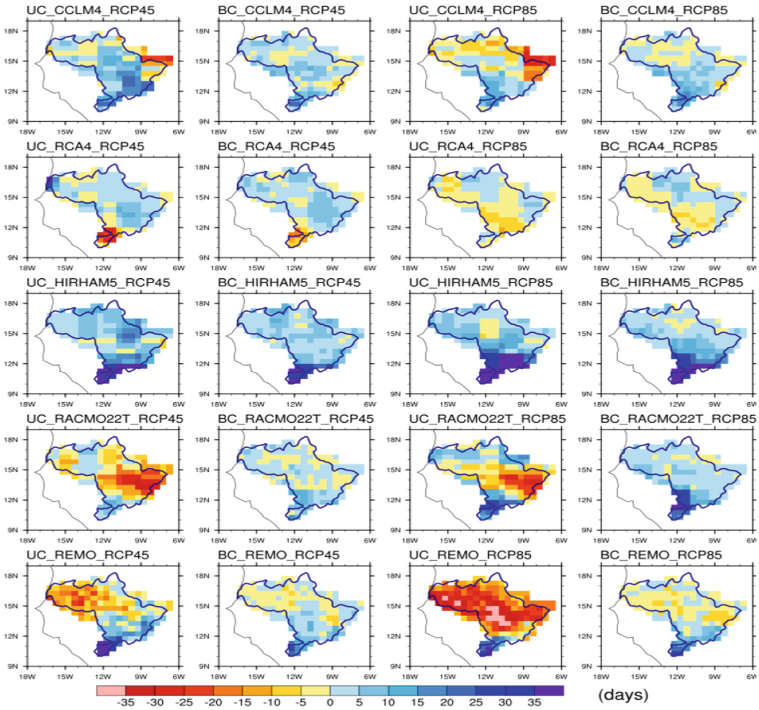

Fig. 2. Changes in the number of daily rainfall greater than 50 mm [UC: uncorrected, BC: bias corrected]

increase in the southern basin. These findings are consistent with above results for the dry days spells. Bias corrected and uncorrected data show similar spatial pattern even though some differences exist in the magnitude of the projected signals.

4 Discussion

The projected changes of extreme precipitation (Fig. 2), RACMO22T shows a decrease particularly in some localized parts of the basin and a possible alteration of the climate signal due to bias correction. This finding shows the limitation of the correction and its impact on the climate change signal as suggested by [15]. As for REMO, the decreased extreme rainfall is also marked up by a reduced bias corrected signal.

However, heavy rainfall is projected in the wettest part of SRB (e.g. Guinean Highlands) that benefit to orographic precipitation; as well as CCLM4 that depicts also similar findings in this part of the basin. Additionally, it is only with HIRHAM5 that the basin is likely to experience a very noticeable increase of extreme rainfall. The differences between models are mainly due their physical parameterizations.

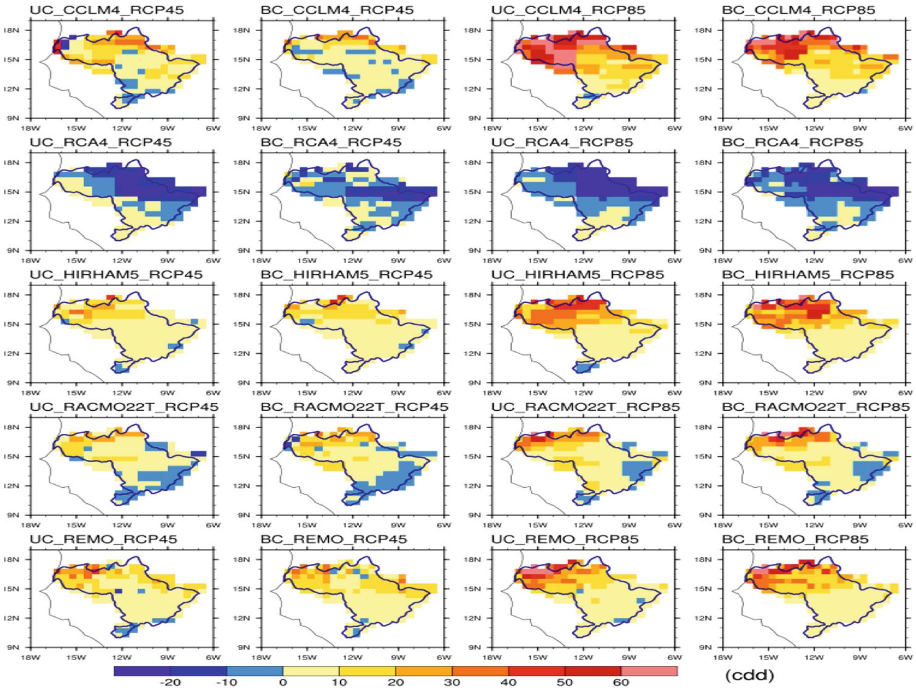

Fig. 3. Changes in the consecutive dry day [UC: uncorrected, BC: bias corrected]

The changes of cdd and cwd as displayed in Figs. 3 and 4, respectively, show considerable increase of dry days and decrease of wet days by all models, except, RCA4 which shows increased wet days. This increase of dry days spells will lead to a drying of the basin that is likely to be more acute in the north. These RCMs divergence is mainly due to the convection scheme used within the models as it was suggested by [4].

Moreover, there is a consistency between these two climate indices in all models; this means that while cdd increases, cwd decreases. The drying of the basin as projected in most of the RCMs can be due to the results of low rainfall intensity and low high rainfall events. This drying is more pronounced with RCP8.5 than with RCP4.5 suggesting the influence of the chosen radiative forcing. In case of the impact of the bias correction, it affects mainly the magnitude of the signals even though some alterations may occur in localized parts of the basin.

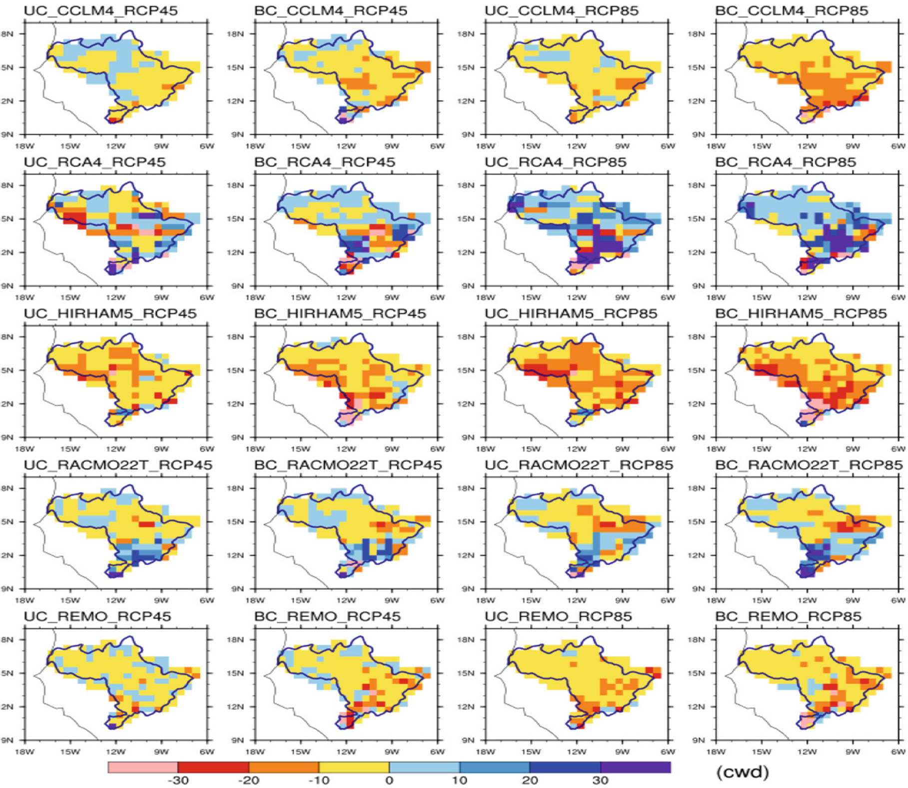

Fig. 4. Changes in the consecutive wet days [UC: uncorrected, BC: bias corrected]

5 Conclusion

In this study, an analysis of the implicit effect of statistical bias correction of five RCMs output on extreme precipitation over the Senegal River Basin was provided. During the present day climate (not shown here), the applied bias correction technique shows generally considerable added value over SRB by successfully removing the RCMs biases during the evaluation part. With respect to the projected climate change signals on extreme precipitation uncorrected and bias corrected data depict substantial changes by the end of 21st century. Divergence was found between models in predicting extreme precipitation over the basin where some models project a decrease and others show an increase. Moreover, the basin may experience substantial drying due to increased number of dry days and decrease of wet spells by four RCMs by contrast to RCA4 which shows more rainfall events. The differences between models output changes were mainly due their different convection scheme. The northern basin is subject to the more pronounced drying. As regard to the radiative forcing, the extreme scenario (RCP8.5) exhibits the higher changes. However, with the most troublesome variable which is precipitation in climate modeling over West Africa, the bias correction may change the signal in specific areas. The main findings of this work is a drying of the basin due to a likely decrease of wet days and an increase of dry days as it is projected by all RCMs (except for the RCA RCM). Therefore the projected changes over the SRB have to be carefully interpreted due to the various sources of uncertainties that are associated, especially those arising from the choice of the bias correction methodology, the various RCM models and their driving GCMs. To reduce these uncertainties, it would be desirable to conduct analogous analyses with more different RCMs output, different bias correction techniques which would enable uncertainty analyses in future investigations.

Acknowledgments. We thank the Laboratoire Physique de l'Atmosphère et de l'Océan (LPAO/ESP/UCAD/SENEGAL) and the Laboratoire d'Océanographie, des Sciences de l'Environnement et du Climat (LOSEC/UFR ST/Physics Department/UASZ/SENEGAL) where this work has been done. Many thanks to Stefan Hagemann, Andreas Haensler, Tobias Stacke and Christopher Moseley for their supports during our stay in Hamburg (Germany).

References

1. Vizy, E.K., Cook, K.H.: Mid-twenty-first-century changes in extreme events over Northern and Tropical Africa. J. Clim. **25**, 5748–5767 (2012)
2. Hagemann, S., et al.: Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth Syst. Dynam. **4**, 129–144 (2013). https://doi.org/10.5194/esd-4-129
3. Giorgi, F., Jones, C., Asrar, G.: Addressing climate information needs at the regional level: the CORDEX framework. World. Meteorol. Org. Bull. **58**, 175–183 (2009)
4. Klutse, N.A.B., Sylla, M.B., Diallo, I., et al.: Daily characteristics of West African summer monsoon precipitation in CORDEX simulations. Theor. Appl. Climatol. **123**, 369 (2016). https://doi.org/10.1007/s00704-014-1352-3
5. Haensler, A., Hagemann, S., Jacob, D.: The role of simulation setup in a long-term high resolution climate change projection for southern African region. Theor. Appl. Climatol. **106**, 153–169 (2011). https://doi.org/10.1007/s00704-011-0420-1
6. van Roosmalen, L., Sonnenborg, T.O., Jensen, K.H., Christensen, J.H.: Comparison of hydrological simulations of climate change using perturbation of observations and distribution-based scaling. Vadose Zone J. **10**(1), 136–150 (2011). https://doi.org/10.2136/vzj2010.0112
7. Ly, M., Traore, S.B., Alhassane, A., Sarr, B.: Evolution of some observed climate extremes in the West African Sahel. Weather Clim. Extremes **1**, 19–25 (2013). https://doi.org/10.1016/j.wace.2013.07.005
8. Faramarzi, M., et al.: Modeling impacts of climate change on freshwater availability in Africa. J. Hydrol. **480**, 85–101 (2013)
9. Sarr, M.A., Zorome, M., Seidou, O., Bryant, C.R., Gachon, P.: Recent trends in selected extreme precipitation indices in Senegal – a change-point approach. J. Hydrol. **505**, 326–333 (2013)
10. Sarr, M., Seidou, O., Tramblay, Y., El Adlouni, S.: Comparison of downscaling methods for mean and extreme precipitation in Senegal. J. Hydrol. Reg. Stud. **4**, 369–385 (2015)
11. McSweeney, C., New, M., Lizcano, G.: UNDP Climate Change Country Profiles: Senegal (2010a). http://country-profiles.geog.ox.ac.uk/. Accessed 24 Feb 2018

12. McSweeney, C., New, M., Lizcano, G., Lu, X.: The UNDP climate change country profiles improving the accessibility of observed and projected climate information for studies of climate change in developing countries. Bull. Am. Meteor. Soc. **91**, 157–166 (2010)
13. Giraldo Osorio, J.D., García Galiano, S.G.: Building hazard maps of extreme daily rainy events from PDF ensemble, via REA method, on Senegal River Basin. Hydrol. Earth Syst. Sci. **15**, 3605–3615 (2011). https://doi.org/10.5194/hess-15-3605-2011
14. Haerter, J.O., Hagemann, S., Moseley, C., Piani, C.: Climate model bias correction and the role of timescales. Hydrol. Earth Syst. Sci. **15**, 1065–1079 (2011). www.hydrol-earth-syst-sci.net/15/1065/2011/, http://doi.org/10.5194/hess-15-1065
15. Hagemann, S., Chen, C., Haerter, J.O., Heinke, J., Gerten, D., Piani, C.: Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. J. Hydrometeor **12**, 556–578 (2011). https://doi.org/10.1175/2011JHM1336.1
16. Schoetter, R., Hoffmann, P., Rechid, D., Schlünzen, K.H.: Evaluation and bias correction of regional climate model results using model evaluation measures. J. Appl. Meteor. Climatol. **51**, 1670–1684 (2012). https://doi.org/10.1175/JAMC-D-11-0161.1
17. Chen, C., Haerter, J.O., Hagemann, S., Piani, C.: On the contribution of statistical bias correction to the uncertainty in the projected hydrological cycle. Geophys. Res. Letters **38**, L20403 (2011)
18. Dosio, A., Paruolo, P.: Bias correction of the ENSEMBLES high-resolution climate change projections for use by impact models: evaluation on the present climate. J. Geophys. Res. **116**, D16106 (2011). https://doi.org/10.1029/2011JD015934
19. Piani, C., et al.: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. J. Hydrol. **395**, 199–215 (2010). https://doi.org/10.1016/j.jhydrol.2010.10.024
20. OMVS: Sdage du fleuve Sénégal, rapport de phase 1: etat des lieux et diagnostic. version finale Decembre, 457 pp. (2009)
21. Weedon, G.P., Balsamo, G., Bellouin, N., Gomes, S., Best, M.J., Viterbo, P.: The WFDEI meteorological forcing data set: WATCH forcing data methodology applied to ERA-Interim reanalysis data. Water Resour. Res. **50**, 7505–7514 (2014). https://doi.org/10.1002/2014WR015638
22. Mbaye, M.L., Haensler, A., Hagemann, S., Gaye, A.T., Moseley, C., Afouda, A.: Impact of statistical bias correction on the projected climate change signals of the regional climate model REMO over the Senegal River Basin. Int. J. Climatol. **36**, 2035–2049 (2016). https://doi.org/10.1002/joc.4478
23. Baldauf, M.: Stability analysis for linear discretisations of the advection equation with Runge-Kutta time integration. J. Comput. Phys. **227** (2008). https://doi.org/10.1016/j.jcp.2008.03.025
24. Tiedtke, M.: A comprehensive mass flux scheme for cumulus parameterization in large-scale models. Mon. Weather Rev. **117**, 1779–1800 (1989)
25. Kain, J.S., Fritsch, J.M.: A one-dimensional entraining/detraining plume model and its application in convective parameterization. J. Atmos. Sci. **47**, 2784–2802 (1990)
26. Kain, J.S., Fritsch, J.M.: Convective parameterization for Mesoscale models: the Kain-Fritsch scheme. In: Emanuel, K.A., Raymond, D.J. (eds.) The Representation of Cumulus Convection in Numerical Models. MM, pp. 165–170. American Meteorological Society, Boston, MA (1993). https://doi.org/10.1007/978-1-935704-13-3_16