ASSESSMENT OF CLIMATE CHANGE IMPACT ON WATER RESOURCES IN THE SENEGAL RIVER BASIN AT BAKEL

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Assessment of climate change impact on water resources in the Senegal River basin at Bakel
List of Abbreviations and Acronyms

AEJ: African Easterly Jet
AEW: African Easterly Wave
CanESM: Canadian Earth System Model
CDD: Consecutive Dry Days
CDF: Cumulative Distribution Function
CMIP: Coupled Model Intercomparison Project
CORDEX: COordinated Regional Downscaling EXperiment
CRCM5: Canadian Regional Climate Model
CRU: Climate Research Unit
CSIRO-Mk2: Commonwealth Scientific and Industrial Research Organisation Mark 2b
CV: Coefficient of Variation
CWD: Consecutive Wet Days
BC: Bias correction
DKRZ: Deutsches Klimarechenzentrum
ECHAM: Atmospheric General Circulation Model
EC-EARTH: European Earth System Model
ENDA-TM: Environnement et Développement du Tiers Monde
ERA: European Reanalysis
ET: Evapotranspiration
GCM: Global Circulation Model
GLUE: Generalized Liberalized Uncertainty Estimation
GPCC: Global Precipitation Climatology Center
HadCM3: Hadley Centre Coupled Model, version 3
HBV: Hydrologiska Byråns Vattenbalansavdelning
HD: Hydrological Discharge model
IPCC: Intergovernmental Panel on Climate Change
LSP2: Land Surface Parameters, version 2
LSS: Land Surface Scheme
MCS: Mesoscale Convective Systems
ModHyPMA: Modèle Hydrologique basé sur le Principe de Moindre Action
MPI-ESM-LR: Max Planck Institute for Meteorology Earth-System Model Lower Resolution
MPI-HM: Max Planck Institute for Meteorology Hydrology Model
NCAR-PCM: National Centre for Atmospheric Research Parallel Climate Model
NDD: Number of Dry Days
NSE: Nash Sutcliffe Efficiency
OMVS: Organisation pour la Mise en Valeur du fleuve Senegal
PBIAS: Percent Bias
PDF: Probability Distribution Function
PET: Potential Evapotranspiration
RCM: Regional Climate Model
RCP: Representative Concentration Pathway
REMO: Regional Model
SHL: Sahelian Heat Low
SL: Simplified Land
SRB: Senegal River Basin
SST: Sea Surface Temperature
TF: Transfer Function
THY: Terrestrial HYdrology
TS: Time Series
UC: UnCorrected
UN: United Nations
UNFCC: United Nations Framework Convention on Climate Change
USB: Upper Senegal Basin
WA: West Africa
WAM: West African Monsoon
WASCAL: West Africa Science Service Centre and Adapted Land Use
WATCH: Water and global Change
WFDEI: WATCH Forcing Data based on ERA-Interim
Abstract
In this study we assess the impact of climate change on water resources by using uncorrected and bias corrected data from the regional climate model REMO simulations over the Senegal River Basin (SRB). Both simulations were used as input of the Max Planck Institute for Meteorology – Hydrological Model (MPI-HM) over the Upper Senegal Basin (USB).

Applying the bias correction simulations of present day climate (1971-2000) substantially improved for both temporal and spatial variations of the analyzed climate parameters (precipitation, temperature) when compared to interpolated gridded observations and station data. Additionally, the bias corrected input give better representation of the mean river flow, the low flows (10th percentile) and the high flows (90th percentile) at the outlet of the USB.

For the future, the regional climate model projections for precipitation show a general decrease by the end of 21st century (2071-2100) for both scenarios (Representative Concentration Pathways RCP4.5 and RCP8.5) and datasets in the majority of the basin, except the Guinean highlands where a slight increase is found. In case of the potential changes of the maximum consecutive number of dry days and wet days, the northern basin is likely to face the most pronounced increase of dry days and decrease of wet days, although a slight increase of heavy rainfall is found with similar spatial patterns in both data. Higher decadal variability of the maximum 5-day precipitation with the uncorrected data in RCP8.5 is projected, while uncorrected and bias corrected data depict similar temporal variability for extremely wet days. Furthermore, a general temperature increase is projected over the entire basin for both scenarios, but more pronounced under the RCP8.5 scenario. Warm night’s percent is found to be higher than warm day’s percent. As for the potential changes of the basin’s hydrology, a general decrease of river discharge, runoff, actual evapotranspiration, soil moisture is found under RCP4.5 and RCP8.5 in all simulations. The decrease is higher under RCP8.5 with uncorrected data in the northern basin. However, there are some localized increases of runoff in some parts of the basin (e.g. Guinean Highlands). Furthermore, the available water resources are projected to substantially decrease by more than -50% in the majority of the basin for all data, except the southern basin in Guinea where no change is projected.

The impact of the bias correction on the projected climate change signal, affects mainly the magnitude of the signal rather than its direction of change although some modifications may occur in particular months and localities.

Keywords: Climate change signal, impact, bias correction, regional climate model, water resources, Senegal River Basin
Résumé
Dans cette étude, l'impact du changement climatique sur les ressources en eau du bassin du fleuve Sénégal a été évalué en utilisant des données corrigées et non corrigées des simulations du modèle régional climatique REMO. Les deux types de simulations ont été utilisés comme entrée du modèle hydrologique de l'Institut Max Planck pour la Météorologie dans le Haut bassin du fleuve Sénégal. Les simulations corrigées sur le climat passé (1971-2000) ont nettement amélioré les variations temporelle et spatiale des précipitations et des températures par rapport aux observations. Ces données corrigées ont permis aussi d'obtenir une meilleure représentation du régime d'écoulement du fleuve à l’exutoire du bassin. Les projections du modèle régional montrent une baisse générale des précipitations à la fin du 21ème siècle (2071-2100) pour les deux scénarios (RCP4.5 et RCP8.5) et pour toutes les données dans la majeure partie du bassin, à l'exception de la partie guinéenne où une légère augmentation est projetée. Dans le cas des changements potentiels du nombre maximal consécutif de jours secs et de jours humides, le nord du bassin est susceptible de faire face à l'augmentation la plus prononcée de jours secs et à la diminution de jours pluvieux, bien qu’une légère augmentation des pluies extrêmes soit prévue avec des tendances spatiales similaires entre les deux types de données. Une forte variabilité décennale du total de 5 jours de précipitations avec les données non corrigées avec le scenario RCP8.5 est trouvée. En outre, les données non corrigées et corrigées présentent une variabilité décennale similaire pour les jours extrêmement humides. De plus, une augmentation générale de la température est projetée sur l'ensemble du bassin pour les deux scénarios, mais elle est plus prononcée dans le scénario extrême RCP8.5. Le pourcentage des nuits chaudes est plus élevé que celui des journées chaudes. En ce qui concerne les changements potentiels de l'hydrologie du bassin, une diminution générale des écoulements, de l'évapotranspiration réelle et de l'humidité du sol est prévue avec les deux scenarios dans toutes les simulations. La diminution est plus élevée dans les données non corrigées avec le scenario RCP8.5 au nord du bassin. La disponibilité des resources en eau pourrait diminuer de plus de 50% dans la majeure partie du bassin, à l'exception de la zone sud ou aucun changement notoire n’est constaté.

L'impact de la méthode de correction des biais sur le signal climatique projeté, affecte principalement l’amplitude du signal plutôt que son sens de changement bien qu’une modification soit possible de se produire au cours de certains mois et à des localités particulières.

Mots clés: changement climatique, impact, correction de biais, modèle régional climatique, ressources en eau, bassin du fleuve Sénégal
Chapter 1

1. General introduction

Water management planners are facing considerable uncertainties related with the future availability of water resources and extreme events (such as floods and droughts) worldwide. In addition, climate change and its potential impacts on the hydrological system are increasingly contributing to these uncertainties. The general increase of surface air temperature strengthens the hydrological cycle due to increased evaporation which in turn leads to more atmospheric water vapour. Long-term observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates et al., 2008). Several studies on climate change impact have shown that water resources are impacted in all investigated areas (Gosain et al., 2006; Chen et al., 2011, Grillakis et al., 2011; Ibrahim et al., 2012; Arnell and Gosling 2013; Hagemann et al., 2013, etc). These changes have effects on critical sectors such as water resources, agriculture, energy, health, biodiversity, among others in many regions around the world particularly in Africa. Africa as a whole is one of the most vulnerable continents due to its high exposure and low adaptive capacity (IPCC-PART B, 2014). The decreasing rainfall and devastating droughts in the Sahel region (West Africa) during the last three decades of the 20th century are among the largest climate changes anywhere (Bates et al., 2008). Impact studies over WA have shown that water resources are significantly impacted by climate change (Ardoin-Bardin et al., 2009; Karambiri et al., 2011; McCartney et al., 2012; Ruelland et al., 2012; Faramarzi et al., 2013; Mahe et al., 2013; Aich et al., 2013, etc). Furthermore, the recurrence of droughts in West Africa, has led to a significant decline of water flows in many West African river basins (e.g. Gambia, Oueme, Upper Niger, Senegal, etc). Rivers constitute the main water resource for drinking, irrigation, and industrial purposes in inland areas (Mouri et al., 2011b). For much of Africa, knowledge about recent climate change is limited, due to weak climate monitoring, and gaps in coverage that continue to exist (IPCC-PART A, 2014). Additionally, 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 (Ly et al., 2013) and the agroclimatic risks and negative impacts due to these events is less uncertain (Salack et al., 2015). These impacts, may likely be exacerbated in the future by extreme events (such as flood, drought) and the high population growth (IPCC-PART-B, 2014). The changes in extreme precipitation and temperatures are predicted by many global
climate models (GCMs) as a response to the increase in greenhouse gases (Vizy and Cook, 2012; Sillmann et al., 2013b).

This introductory Chapter is organized as follows: Section 1.1 gives a short overview about climate change impacts over Africa; the background and the problem statement of the study are given in Section 1.2 and Section 1.3, respectively. Section 1.4 details the research questions, followed by the hypotheses in Section 1.5. The objectives are given in Section 1.6. Moreover, the organization of the thesis ends this General Introduction.

1.1 Climate change impacts over Africa

The terms of climate change refers in general to any persistent variation of the climate state over a long term period (several decades). In the literature, two definitions are commonly used which are the UNFCCC (UN, 1992) and the IPCC (2007).

According to the UNFCCC, climate change is “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

The IPCC defines climate change as a statistically significant variation in the mean state of the climate or its variability, persisting for an extended period (typically decades or longer).

Climate change, as defined here, may be caused by natural internal processes or external forcings or by persistent anthropogenic changes in the composition of the atmosphere or land use.

Several studies over the region have shown that river discharge variations are highly affected by rainfall fluctuations. Descroix et al. (2009) have found a decrease of annual river discharge over the Sudanian areas due to the strong decline of rainfall in late 20th century. However, these later authors found also an increased runoff despite the decreased rainfall in the Sirba basin (Burkina Faso/Niger); this situation is so called the “Sahelian paradox”. This situation was mainly due to the land cover degradation. Moreover, Ruelland et al. (2012) found a considerable decrease of rainfall and continuing increase of potential evapotranspiration that is likely to reduce runoff in the Bani catchment towards the 21st century. A probable intensification of droughts events is expected for the period 2020-2040 by Faramazi et al. (2013) through an increase of dry days and the frequency of their occurrences. It has been found that the changes in river discharge are almost twice than those in precipitation over four large African river basins (Limpopo, Niger, Ubangi, and Upper
Blue Nile) (Aich et al. 2014). A comparison of lot a studies by several time slices has revealed that the impacts of climate change are more pronounced in the late 21st century by the rising green houses gases concentrations (Roudier et al. 2014). The changes are highly heterogeneous over the region where some parts depict increased runoff and others show decreased runoff. Around the Fouta Djalon Mountains and the inner delta of Niger River strong decline of streamflows was projected by Paturel et al. (2007). Furthermore, over Burkina Faso Ibrahim et al. (2014) have found an increase of heavy rainfall events that are greater than 50 mm towards the mid-century. These above changes have also considerable impacts in the Senegal River Basin.

1.2 Background

As far as the Senegal River Basin (SRB) was concerned by the above mentioned extreme climate, its annual average flow at Bakel (reference station) fell from 1,374 m³/sec over the period 1903-1950 to 597m³/sec over the period 1951-2002, and from an average of 840m³/sec in the period 1950-1972 to only 419m³/sec in the period 1973-2002 (ENDA-TM, 2007). That hydrological drought has reduced rainfed agriculture, decreased the seasonal flooding of wetlands, limited economic development, and in the overall, enhanced poverty (Oyebande and Odunuga, 2010). Such water shortage has obviously affected the main activities in the basin (agriculture, fishery, hydropower generation, etc).

A series of studies has already been carried out over WA where the Senegal River basin is situated in order to analyze the ability of models to simulate region’s climate, but also to quantify projected climate changes and to identify potential climate change impacts. Ardo-Bardin et al. (2009) evaluated the ability to reproduce the climate of the region of four Global Circulation Models (CSIRO-Mk2, ECHAM4, HadCM3 and NCAR-PCM) used in the Third Assessment Report of the IPCC, and they found that all four models failed to reproduce the rainfall volumes in the Sahelian zone, and the seasonal dynamics of rainfall in the Guinean zones. In a subsequent study, Bodian (2011) found a divergence of projected streamflows in upstream sub-basins when using the same GCMs’ projection data as input for a hydrological model. This divergence was mainly addressed to the coarse resolution of the GCMs unable to correctly represent the local processes. Projected increase in dry spell length by 2050 was highlighted by Karambiri et al. (2010), and Osorio and Galiano (2012) by analyzing regional climate models (RCMs).

1.3 Problem Statement

In its efforts to improve the quality of RCMs output, the international scientific community has developed the COordinated Regional climate Downscaling Experiment (CORDEX,
The purpose of CORDEX is to provide higher regional climate simulations for climate change impact studies and decision making at the regional level (Klutse et al. 2015). The finer spatial resolution of RCMs can be an added value while simulating regional climate features such as precipitation over mountainous areas (Haensler et al., 2011), extreme events, and regional scale climate anomalies (Fowler et al. 2007). Nevertheless, RCMs’ outputs are also associated with biases that can affect hydrological simulations (Roosmalen et al. 2011).

The RCMs biases were found by Gbobaniyi et al. (2014) after the analysis of 10 RCMs of the CORDEX project which vary substantially from model to model over West Africa. According to Klutse et al. (2015) RCMs differences in biases are associated with the convective scheme employed. To overcome the well known biases in GCMs/RCMs output, statistical post-processing of climate output commonly known as bias correction is often used in impact studies. Statistical bias correction methodologies act on model output so the statistical properties of the corrected data match those of the observation (Haerter et al., 2011). However, bias correction cannot correct for incorrect representation of dynamical and/or physical processes as suggested by these later authors. A review on several bias correction techniques is available in Teutschbein and Seibert (2010).

The delta change method which consists of perturbing an observed data set with absolute or relative change factors derived from the comparison of RCM data for the current climate and a projected scenario climate (Hay et al. 2000), is widely used in many climate change impact studies (Roosmalen et al. 2011; Akhtar et al., 2008; Robler 2011; etc). In addition, others used quantile mapping or histogram equalization, by fitting probability density function or cumulative distribution function to the modelled and observed data (e.g. Piani et al. 2010a, b; Schoetter et al. 2012; etc). Chen et al. (2011), and Haerter et al. (2011), have modified the methodology developed by Piani et al. (2010b). This later methodology has been applied also by Hagemann et al. (2011) and Dosio and Paruolo (2011). Due to its skills and less parameters to fit, the widely used methodology of Piani et al. (2010b) is also applied in the current study on the simulations (historical and scenario) of the regional climate model REMO. Inversely, taking into account the concern of the potential alteration of climate change signal due to bias correction (Hagemann et al., 2011), both uncorrected and bias corrected data from the regional climate model REMO are used to drive the Max Planck Institute for Meteorology -Hydrological model (MPI-HM). Moreover, the future evolution of extreme precipitation and temperatures at the basin scale are still unclear, and there is a lack of understanding on the impact of statistical bias correction on extreme climate at the basin scale; because detailed informations are needed by water resources managers and users.
Then, in this study we attempt to address the issue of bias correction effect on precipitation and temperature changes over the Senegal River Basin on one hand, and to investigate the seasonal changes on hydrological variables (such as soil moisture, evapotranspiration, river discharge and runoff), extreme streamflow and water availability changes over Upper Senegal Basin (USB) in the other hand. Thus, the better understanding of potential future changes in the spatial and temporal variability of the hydrological cycle is fundamental to inform local societies and water resources managers in order to increase awareness and to support the development of adaptation strategies, and also agricultural productivity which accounts for more than 80% of the water withdraws in the basin (Oyebande and Odunuga 2010). These above challenges are the main reasons of the scientific questions that have been raised in this study as detailed in the following Section.

1.4 Research Questions

The essential questions that have motivated this study are the following:

➢ What is the effect of bias correction on REMO output and does bias correction modify the climate change signals (for precipitation and temperature)?

In this above question, the added value of bias correction is investigated in order to see if the corrected data are able to represent correctly the present day climate. Additionally, the potential changes of precipitation and temperature, and the effect of statistical bias correction on the projected climate change signals are also examined systematically.

➢ How the basin’s hydrology varies temporally and spatially and does the bias corrected input allow reproducing well the river regimes?

The aim of this second question is to better understand the temporal and spatial variability of hydrological variables such as runoff, evapotranspiration, soil moisture over the Upper Senegal Basin which generates more than 80% of flows of the Senegal River. As like the first question, a great interest is given to the ability of bias corrected input to well reproduce the river regimes.

➢ What are the projected hydrological indicators changes (evapotranspiration, river discharge, runoff, soil moisture)? And also how climate change may affect the availability of water resources of the basin?

In this third and last question, a focus is given to the annual cycle and seasonal changes of above variables because to our knowledge no study has addressed these changes over the Upper Senegal Basin, as well as the potential changes of available water resources. Furthermore, the interannual variability of river discharge and precipitation is investigated towards the end of 21st century.
To attempt to give answers to these scientific questions, the following hypotheses are adopted in Section 1.5.

1.5 Hypotheses

- **Bias correction will improve well the present day climate**
  
  In this first hypothesis, we assume that the bias correction will improve well both temporal and spatial variations of precipitation and temperature during the present day climate (historical period) when compared to observed data.

- **Temperature and precipitation will change considerably**
  
  In the future, the most common indicators of climate change such as precipitation and temperature will change substantially over the basin in the coming decades particularly in late century.

- **Well reproduction of river regimes with corrected input**
  
  The bias corrected data which are used as climate forcing data of the hydrological model, will reproduce well the river regimes (low and high flows) during the historical period. In other words, the bias corrected has an added value in simulating the river flows in the past.

- **Water resources will be highly affected by climate change**
  
  In this last hypothesis, climate change will impact highly the water resources of the basin in the future. Furthermore, actual evapotranspiration, soil moisture and runoff will be affected by the change of the basin’s climate.

1.6 Objectives

The main objective of this study is to assess the effects of climate change on water resources in the Senegal River Basin.

In order to achieve the main objective of the study, the following specific objectives will be adopted:

- To bias correct and evaluate the REMO regional climate model output to simulate the present day climate and to assess the potential changes in temperature, precipitation, potential evapotranspiration by the end of 21st century under the new IPCC Representative Concentration Pathways scenarios (4.5 and 8.5);

- To evaluate the ability of the MPI-HM in reproducing past river flow regimes by using uncorrected and bias corrected input;

- To assess the potential changes of river discharge, runoff, soil moisture, actual evapotranspiration and available water resources;
1.7 Thesis structure
A part from this first Chapter that states the general introduction which details the context of the whole study and some definitions and literature review on climate change impacts over Africa, the thesis is composed by four subsequent scientific chapters (2-5). Some inevitable repetitions may occur because some chapters (3-5) were designed to be potential papers themselves. The last Chapter summarizes the main findings and conclusions, and gives further research lines as outlook. The references of all chapters are gathered together into a single reference list at the end of the thesis.

The following Chapter deals with the data and the methods used in the whole study. A description of the hydro-climate characteristics of the study area by using observational datasets and from literature review is given. A full detail of all data (observations and climate simulations) used in the present study is provided. Moreover, the statistical bias correction of climate model output and the hydrological modeling methodologies are also described.

The third chapter gives clarification about the performance of the regional climate model REMO over the Senegal River Basin. This was done mainly by comparison to observational datasets for both spatial and temporal variability.

The questions whether there is an added value of bias correction and its potential impact on the future climate change signals are tackled in Chapter 4. Additionally, the results and discussions during the present day climate and the climate change projections are also presented.

Chapter 5 assesses the potential impact of climate change on water resources over the Upper Senegal Basin. It aims of providing answers of the suitability of using bias corrected input for hydrological impact studies and how climate change may affect the future water resources availability.

Chapter 6 summarizes the findings of the thesis with respect to the objectives mentioned above. Furthermore, it presents an outlook for future research in the fields on climate change impacts over the Senegal River Basin.
Chapter 2

2. Data and Methodology

2.1 Introduction

In this chapter, detailed description of the data used during the current study is given. The data are composed mainly by stations data, gridded observational datasets, and regional climate simulations data. The characterization of the hydro-climate conditions of the basin is done by using the observed stations and the documented literature. Furthermore the bias correction technique used to correct REMO output is described as well as the hydrological model used to study the impact of climate change on water resources in the Upper Senegal Basin.

The Chapter is organized mainly into four Sections: Section 2.1 describes the Senegal River Basin; the details of all datasets used are given in Section 2.2. This later Section is followed by the methodology’s Section. A brief summary and conclusions Section ends the Chapter.

2.2 Senegal River Basin

The Senegal River Basin is the second largest river basin in West Africa (Figure 1). From its source in Guinea it flows through the western Sahel region in Mali, Mauritania and Senegal; its catchment is about 300,000 km² and it has a length of 1,800 km (OMVS, 2009). The three main tributaries (Bafing, Bakoye and Faleme) ensure over 80 % of the Senegal River’s flow. The Bafing transfers half of the flow; mainly for this reason that the Manantali dam (water storage capacity of 11.5 billion m³) was built on its course, while the Diama dam is located 23 km from Saint Louis near the River mouth in the delta (Diene, 2012). The Diama dam was built in order to block seawater intrusion. It has created favourable conditions for irrigation and double cropping in its upstream water body. The Manantali dam was constructed mainly for hydro power generation and to attenuate extreme floods. The regulation of river flows at Manantali has somewhat changed the natural flow regime of the river. These human activities have considerably affected the quantity and the quality of water, and also disturbed the natural ecosystems of the delta. As underlined by Giosan et al. (2014) river engineering is among of the main causes of delta loss. For the hydrological modeling, we focus in the upper Senegal basin (USB) due to the backwater effects from Diama’s dam and the lot of anthropogenic activities which denaturalize the natural river flow in downstream.

The basin is subject to a large north–south precipitation gradient ranging from 150 mm/year in the north to more than 1650 mm/year in the south (Figure 2.2a).
Its temperatures vary from 22 °C in the south to more 31°C in the north (Figure 2.2b).
The predominantly natural vegetation of the region follows this rainfall gradient, ranging from semi-arid savannah in the north to sub-humid forest in the south (Stisen et al., 2008).
The annual mean of river discharge at Bakel as plotted in Figure 2.3 shows that the decade 1960-1961 has the higher river discharge (up to 1050 m³/s), then it decreases drastically from the years 70s to the year 1990. The most severe decline of discharge (until 200 m³/s) occurs in the period 1980-1990. From this later period to 2010, it increases slightly (up to 750 m³/s).
Figure 2.2: Annual mean of precipitation (a) and temperature (b) at stations over SRB
This suggests also the decadal variability of streamflow as precipitation over West Africa. This decline of river flow is consistent with the well known meteorological drought since the 70s over the Sahel region.

The standardized precipitation and discharge indexes presented in Figure 2.4 at Bakel show their decrease since the years 70s to more than -100%. Then, slight increases are noticed after the year 1995 to 2010 even though there are some particular years where they decrease.

The decrease of streamflow follows the decrease of precipitation; this shows how river discharge is highly dependent on rainfall over this semi-arid region. Before the years 70s, wetter years were found, and the droughts seem to be recovered after 2000.
Furthermore, the Senegal River and its tributaries Bafing and Bakoye pass through Precambrian sandstone deposits, lower Cambrian schisto-dolomitic deposits and Palaeozoic metamorphic rocks that are mainly composed of schists and quartzites from a volcano-sedimentary complex and granites (Michel, 1973). From Bakel to the mouth, the Senegal River is bordered by Holocene fluvio-deltaic deposits composed of fine sands, silts and clays, surrounded by stabilized so-called red dunes (Michel et al., 1993). Of the gauging stations along its course the station Bakel provides discharge measurements since 1904. At this station 81% of the total catchment is drained so that it is largely used in the literature as the reference station for discharge estimates. High flows occur from August to October and suspended matter discharge, probably, peaks earlier and surface runoff has a suspended matter concentration of ~1g L\(^{-1}\) and is responsible for 50-80% of the riverine suspended load via slope erosion (Kattan et al., 1987). In the river bed this suspended load is diluted by subsurface and groundwater discharge (Kattan et al., 1987). In contrast to the discharge minimum in the early 1970s which was due to severe droughts, this recent drop is due to increased irrigation and the dam construction (Hubert et al., 2007; Rasmussen et al., 1999). Human impact has increased considerably since the 1970s when irrigated areas were created since the natural flooding of the banks ceased due to droughts (Rasmussen et al., 1999). The natural flood receding agriculture has been replaced by irrigation which is more costly also as fertilizers are required to maintain the yield (Rasmussen et al., 1999).

Figure 2.5 displays the seasonal cycles of precipitation during the following decades (1960-1969, 1970-1979, 1980-1989, 1990-1999, and 2000-2009) at 10 stations over the SRB. A high variability in term of magnitude is noticed within the same station and from station to another. The upstream stations (e.g. Kenieba, Kita, Kidira, etc) have the maxima of rainfall (up to 12 mm/day). The minima of rainfall are found in downstream stations (e.g. Saint Louis, Podor, etc).
This situation confirms the well known south-north gradient of rainfall in West Africa with maxima in the southern basin where there are more moisture and forest. The precipitation varies from a decade to another and it decreases generally from the first decade (1960-1969) to the last decade (2000-2009).

Furthermore, the number of JAS (July August September) dry days is presented in Figure 2.6. As like the gradient of rainfall, there is a high gradient between the north (drier) and the south
The number of dry days in the southern basin is around 20 days and it increases northward up to 70 days in the northern basin. This means that, there are approximately 20 days where rainfall is greater than 1mm in this main rainy season period in the northern basin. As most parts of the basin are within the Sahel, precipitation is somehow influenced by limited moisture in this dry and hot region. The moisture originated from moisture advected by the atmosphere mainly transported by mesoscale and large dynamical processes such African Easterly Jet (AEJ), African Easterly Waves (AEW), and the monsoonal flow (Messager et al., 2006). The limited available moisture influences the local evaporation that is found to be the origin of about 27% of the precipitation over West Africa (Gong and Eltahir 1996). These dry days are within the period when the Sahel experiences its severe droughts of the 20th century which was a result of the cooling of the North Atlantic relative to the South Atlantic (Giannini et al., 2013).

Moreover, the seasonal cycles of river discharge at some stations from 1984 to 2009 is displayed in figure 2.7. The lower streamflows are found at stations within the Faleme tributary (Fadougou, Gourbassi and Kidira) where the maximum is reached at the outlet Kidira (400 m³/s), Bafing Makana station in the Bafing tributary has an intermediate flow of 800 m³/s. The stations situated in the Senegal sub-basin such as Kayes, Matam and Bakel depict the highest river flows with maxima (up to 1750 m³/s) reached at stations after the confluence (Bakel and Matam).
2.3 Data
The choice of climate simulations does not depend only to the raised scientific question but to the availability of data and the capacity to process them with the scope of the project (Murth et al., 2013). Limited stations data were available in the whole basin; for this reason a good coverage of re-analysis data were used as an alternative dataset. Climate scenarios were obtained from the regional climate model REMO in the framework of CORDEX.

2.3.1 Observational data

2.3.1a Stations data
Daily rainfall and temperature data from eleven stations available for the period 1961 to 2010 were obtained from the National Meteorology Agencies of the riparian countries (Senegal, Mali, Mauritania, and Guinea) of the basin (Figure 2.1). This long period concerns generally the stations localized in the Senegalese part of the basin. All the others station have many missing data. Then, in some analyzed cases, specific periods (e.g. 1981-1990, 1979-2005, 1960-2009) and stations are used depending on the spatial coverage of the stations over the basin, the period without/or with less missing values and the needed information to show. The stations from Senegal were already been corrected by Salack (2013) and the few other stations were control by statistics (e.g. regression, correlation, double mass curve, etc); but here we don’t present this quality control of data. Furthermore, observed river discharge data at Bakel, Matam, Kayes, Dakkasaidou, Bafing Makana and Sokotoro data were used during the evaluation of hydrological simulations.
2.3.1b Water and Global Change forcing data

The Water and Global Change (WATCH) forcing data methodology applied to ERA-interim reanalysis data (Dee et al., 2011) known as WFDEI based on the work of Weedon et al. 2014, available at half-degree (0.5°) resolution and covers the period 1979-2012 were used in this study to evaluate and bias correct regional climate output. The WFDEI data are designed as climate forcing data for land surface and hydrological models where good quality of climate observations is not available. They are derived from the surface variables of ERA-interim reanalysis and were monthly corrected by Climate Research Unit (CRU) data (TS3.1/TS3.101/TS3.21) (Haris et al., 2013) and GPCC (versions: v5/v6) (Schneider et al. 2013). The details on the correction of the data can be found in Weedon et al. (2011). The variables used in this study are precipitation, minimum, maximum and mean temperature, surface pressure, and wind speed, specific humidity, and radiations. These data were used due to its spatial coverage when compared to REMO output and also the sparse stations data and they have also the same spatial grid as the Max Planck Institute for Meteorology-Hydrological Model which is used in the hydrological modeling part (Chapter 5).

2.3.2 Regional Climate Model REMO data

Daily data from a set of simulations (historical and scenario) conducted with the regional climate model REMO (Jacob and Podzun, 1997; Jacob et al. 2001) are used. REMO is a three-dimensional, hydrostatic atmospheric circulation model which solves the discretized primitive equations of atmospheric motion. The REMO simulations are driven mainly with data from the global climate model MPI-ESM-LR (Stevens et al., 2013) following the newly developed RCP4.5 and RCP8.5 Representative Concentration Pathways of the latest IPCC report. RCP 4.5 is a scenario that stabilizes radiative forcing at 4.5 W/m² in the year 2100 without ever exceeding that value. This later scenario is chosen because it represents somewhat the medium-low RCP and it reflects also the situation in our region. As for the increasing greenhouse gas emissions RCP8.5 over time, its choice is based in the fact that it reflects the impact of the largest potential climate change. The radiations used here were driven by EC-EARTHT. REMO has a rotated spherical grid with Arakawa-C-grid for horizontal discretization in which all variables, except the wind components, are defined in the centre of the respective grid box, the grid box centres are defined on a rotated latitude-longitude coordinate system; the vertical variations of the prognostic variables (except surface pressure) are represented by a hybrid vertical coordinate system (Elizalde et al., 2011) with 27 levels for this experiment. The scheme convection is based on the work of Tiedtke (1989) and it advection is semi-lagrangien. Surface pressure, temperature, horizontal wind
components, water vapour content, and cloud water content are the prognostic variables of REMO. Its Lateral boundary formulation after Davies (1976), adjusts the prognostic variables in a boundary zone of 8 grid boxes. The land surface scheme (LSS) is based on the physical parameterizations of the global climate model ECHAM4 (DKRZ 1993, Roeckner et al. 1996). It was extended to a more sophisticated LSS, for example, by an improved surface runoff scheme (Hagemann & Gates 2003), inland glaciers (Kotlarski 2007) and vegetation phenology (Rechid 2009). The land surface parameters are taken from LSP2 dataset (Hagemann, 2002). REMO data is available in the context of the international regional downscaling framework called Coordinated Regional Climate Downscaling Experiment (CORDEX, Giorgi et al., 2009) over Africa on a 0.44° spatial grid for the period 1950 to 2100 and it has already been used over Africa (Gbobaniyi et al. 2014; Jacob et al. 2012; Haensler et al. 2011; Nikulin et al. 2012; Klutse et al., 2015; etc). The choice of this model is based on the data availability and also its skill over West Africa. Additionally, it has been used successfully in lot of impact studies in central Africa and in Europe. Jacob et al. (2012) has shown that REMO was able to simulate quite well the characteristics of other regions climate with the same set of parameterizations. The details of the model characteristics are summarized in Table 2.1.

Table 2.1: REMO characteristics

<table>
<thead>
<tr>
<th>Institute</th>
<th>Climate Service Centre, Hamburg, Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main driving Model</td>
<td>MPI-ESM-LR</td>
</tr>
<tr>
<td>Projection</td>
<td>Rotated spherical grid</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.44 degree</td>
</tr>
<tr>
<td>Vertical coordinates</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>27</td>
</tr>
<tr>
<td>Advection</td>
<td>Semi-lagrangian</td>
</tr>
<tr>
<td>Time step</td>
<td>240</td>
</tr>
<tr>
<td>Convection Scheme</td>
<td>Tiedke (1989)</td>
</tr>
<tr>
<td>Radiation Scheme</td>
<td>Morcrette et al., (1986); Giorgetta and Wild (1995)</td>
</tr>
<tr>
<td>Turbulence vertical diffusion</td>
<td>Louis (1979)</td>
</tr>
<tr>
<td>Cloud Microphysics Scheme</td>
<td>Lohmann and Roeckner (1986)</td>
</tr>
<tr>
<td>Land Surface scheme</td>
<td>Hagemann (2002); Rechid and al., (2009)</td>
</tr>
</tbody>
</table>

Further details about the REMO model can be found in: [http://www.remo-rcm.de/The-Regional-Model-REMO.1267.0.html](http://www.remo-rcm.de/The-Regional-Model-REMO.1267.0.html)
2.4 Methodology

Any scientific research work uses methods, techniques and appropriate tools to achieve the desired results. The methodology is nothing but the approach to be followed to achieve work goals as mentioned in the introductory Chapter. Due to the well known bias of climate model output, a bias correction technique is applied to correct REMO simulations for the present day and the future climate. In order to study the impact of climate on water resources, the raw and corrected output from REMO are used as input of the Max Institute for Meteorology Hydrology Model (MPI-MH). The overall methodology is summarized in the following hydro-climatic scheme (Figure 2.8). WFDEI data are validated by stations data based on seasonal and annual cycle scales. After this validation, REMO simulations are evaluated by WFDEI datasets in the second step. Finally, the regional climate model data are bias corrected following Piani et al. (2010b) before being used as input in MPI-MH. Corrected and uncorrected data are compared during the present day climate in order to see how well the bias corrected data improve the representation of the basin’s climate and hydrology and also to investigate the potential changes of the climate change signals due to bias correction.

![Scheme of the hydro-climatic ensemble](image)

**Figure 2.8:** Scheme of the hydro-climatic ensemble

The statistical bias correction and the hydrological modeling are described in detail in the following sub-sections.
2.4.1 Bias correction

The bias correction is based on fitted histogram equalization where the corrected variable is a function of the modelled counterpart \( V_{\text{cor}} = F(V_{\text{mod}}) \) and the derived transfer function is such that the intensity histogram of the corrected variable matches the intensity histogram of the observed one (Piani et al., 2010b). This means that the corrected variable is a function of the modelled one. To derive the transfer functions (TFs), modelled and observed data should have the same grid spatial resolution and the same length of time series. The transfer functions map the cumulative distribution function (CDF) of the modelled data onto the observed one directly (Chen et al., 2011). The TFs are obtained by computing the CDFs of the simulated data and then associating to each value of the modelled data \( V_{\text{mod}} \) the corresponding value of the observed data \( V_{\text{obs}} \) such that \( \text{CDF}_{\text{mod}}(V_{\text{mod}}) = \text{CDF}_{\text{obs}}(V_{\text{obs}}) \) for each grid point, month and variable. Piani et al. (2010b) and Hagemann et al. (2011), suggested that the perfect TF obtained by plotting the observed versus the modelled so that the bias corrected data match exactly the observed one, is unreliable because it has a lot of degree of freedom to be stable in time. Therefore, an ideal emerging TF with less number of parameters is fitted. After bias correction, the corrected and observed data should have the same PDF. REMO data are remapped onto a grid of 0.5\(^\circ\) (same grid as WFDEI) through conservative interpolation. The full common period (1979-2005) between both datasets is used to derive the transfer function coefficients which are then applied to 2006-2100 scenarios simulations. For the climate change scenarios, the same transfer functions are used because we assume that the bias behaviour of the model does not change with time, as it was suggested by Hagemann et al. (2011); this means that the TFs are time-independent and thus, applicable in the future. This is the main inconvenience of the bias correction. The datasets are first grouped according to calendar month and secondly sorted at each grid point by value (from the smallest to the highest) of the variable (precipitation and temperature). As these two variables have different distributions, they are corrected separately.

2.4.1.1 Precipitation bias correction

In the case of precipitation, the following transfer functions (TFs) were used:

\[
P_{\text{cor}} = a + bP \quad \text{(Eq2.1)}
\]

\[
\ln(P_{\text{cor}}) = a + bln(P - P_0) \quad \text{(Eq2.2)}
\]

\[
P_{\text{cor}} = (a + bP)(1 - e^{-(P - P_0)/\tau}) \quad \text{(Eq2.3)}
\]

Where \( P_{\text{cor}} \) represents the bias corrected precipitation, \( P \) is a given value to be corrected and, \( a, b, P_0 \) and \( \tau \) are fit parameters and \( \ln \) represents the natural logarithm. In the linear equation...
(Eq2.1), 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. This is done to equate the number of modeled and observed dry days (Piani et al., 2010b). These authors justify the employment of (Eq2.2) that it is expressed as a linear relation between the logarithms by the fact that daily precipitation intensity spectra follow exponential type distributions and many emerging TFs are linear in a log-log coordinates representation. (Eq2.3) which was novel in that methodology is composed by an exponential that tends to a linear asymptote \((a+bP)\); \( \tau \) is the rate at which the asymptote is approached and \( P_0 \) is the dry day correction term. For high intensities the TF of Eq2.3 tends to the linear term as Eq2.1, and it presents a systematic change of slope at the lowest intensities (Dosio and Paruolo, 2011). Eq2.2 was not used here because it was giving the poorest results.

Then, a TF is chosen depending on some conditions such as a preferably small number of parameters (robustness), goodness-of-fit and thresholds. A threshold of 1 mm is defined as a wet day, a cutoff value of \( N_{\text{min}} = 20 \) is prescribed for the minimum number of observed wet days for which fitting is acceptable. This threshold is taken in order to avoid the issues of the measurement of very small amounts of rainfall that can influence its accuracy. A simple additive correction factor (differences in the means) is applied if the observed wet days are less than the cutoff or the mean of observed precipitation is less than 0.01 mm/day; in this case, the mean is corrected only. If the number of wet days are greater than \( N_{\text{min}} \) and the mean of precipitation record \( \geq 0.01 \) mm/day, the linear TF (Eq 2.1) is applied; then, the mean and the standard deviation are corrected. In addition, the linear fit is accepted if \( a < 0 \) and \( 1/5 < b < 5 \). The authors of this method stated that the bias correction results are not affected significantly if these arbitrary values are changed. Finally the exponential TF is applied if all these above conditions are not met. In this later case, all the moments of the distribution can be corrected.

The monthly TFs were then interpolated to daily ones according to Piani et al. (2010b) by a smoothing technique. The daily transfer function (DTF) is given as follows:

\[
DTF^t = \alpha_t DTF^{(m)} + (1 - \alpha_t) DFF^{(m+1)}, \tag{Eq2.4}
\]

Where \( \alpha_t = \frac{t-t_m}{t_{m+1}-t_m} ; t_m \leq t \leq t_{m+1} \), and \( t \) is the value of the calendar day in a given month \( m \), \( t_m \) is the value of \( t \) at the center of same month.

### 2.4.1.2 Temperatures bias correction

For temperature, the bias correction is done in mean daily temperature (\( T_{\text{mean}} \)), minimum (\( T_{\text{min}} \)) and maximum (\( T_{\text{max}} \)) daily temperatures. The bias correction is less complex than the precipitation. As the histograms of mean daily temperature for a given month are comparably
well represented by a Gaussian distribution, the TF between two histograms is represented by a linear function (Piani et al., 2010b) since a Gaussian distribution is settled by its mean and standard deviation. To minimize the relative errors by correcting directly $T_{\text{min}}$, $T_{\text{max}}$ and $T_{\text{mean}}$, the diurnal range defined as $\Delta T = T_{\text{max}} - T_{\text{min}}$ and the skweness $\sigma = (T_{\text{mean}} - T_{\text{min}})/\Delta T$ are corrected. This will keep the consistency between all variables. The linear function (Eq2.1) is used. Further details on the method are given in Piani et al. (2010b).

The bias corrected and uncorrected temperature, are then used in the Penman-Monteith (1965) equation (not shown here) with other climate variables (such as radiations, wind, surface pressure, humidity) to estimate the potential evapotranspiration (PET). This gives possibility to estimate potential evaporation which takes into account both the effect of available energy and atmospheric humidity on evapotranspiration through vapor pressure deficit and wind speed (Li et al., 2005). These later authors suggested the suitability of this equation in humid, arid and semi-arid climates. Hence, this equation is used in our study area that covers humid and semi-arid areas. Evapotranspiration is generally the most significant component of the water budget, acting to recycle much of rainfall, in particular, over the Sahel region (Ruti et al., 2011). Here, we did not bias correct evapotranspiration because there are no reliable observations available at this resolution (half degree) and scale and also the variables required for its computation. The influence of the PET bias is relatively small when compared to precipitation that is the most troublesome in hydrological simulations. Moreover, to avoid also increasing uncertainties in PET estimation, the others estimated variables (e.g. radiations, humidity, pressure, and wind) are not bias corrected. The potential evapotranspiration (PET) and precipitation (P) were used to estimate the potential water balance (P-PET). This means that when we say bias corrected PET, we have in mind that only temperature is corrected. The influence of the PET bias is relatively small when compared to precipitation that is the most troublesome variable in hydrological simulations.

2.4.2 The Max Planck Institute for Meteorology -Hydrological Model (MPI-HM)

The MPI-HM is a global hydrological model which is a combination of a simplified Land Surface (SL) scheme (Hagemann and Dümenil Gates, 2003) and a Hydrological Discharge (HD) model (Hagemann and Dümenil, 1998, 1999; Hagemann and Dümenil Gates, 2001). The choice of MPI-HM is motivated by the fact that it is a distributed physically-based model which is recommended for studying interactions between atmospheric and hydrological processes (Li et al., 2005); it has been widely used for impact studies over different rivers around the world, including West African rivers (Chen et al., 2011; Hagemann et al., 2011, 2013) and also the challenge on how to adapt some parameters of this global model into local
conditions at the basin scale. Additionally, its consistency in transforming precipitation to runoff with the SL scheme and also due to its temporal and spatial scales similar to that in the climate forcing data is among the reasons of choice. It uses a half degree resolution (0.5°) and daily time steps. The SL scheme is designed to compute mainly the surface runoff and the drainage while the HD model computes the river flow on the land surface (Figure 2.9). The SL scheme uses a soil bucket scheme and its output such as surface runoff and drainage are used directly by the HD model which is a state of the art river routing model. Initially, the two sub-models were run separately. Most recently, Stacke and Hagemann (2012) implemented a dynamical wetland extent scheme in MPI-HM. We precise that the model does not take into account human activities (dams, water withdraw, etc) and land cover changes. The MPI-HM model requires as climate input: surface temperature, precipitation, and potential evapotranspiration. Moreover, it uses land sea mask, glacier mask, total field capacity and plant-available soil water capacity from LSP2 dataset (Hagemann, 2002) that has recently been updated (Hagemann and Stacke, 2014). The others boundary data are sub-grid slope, elevation, glacier fraction, permafrost fraction, river routing direction, and storage retention times.

The simulated variables of interest are river discharge, surface runoff, drainage, evapotranspiration, and soil moisture.
Figure 2.9: Structure of MPI-HM. Orange boxes indicate climate input variables, green boxes are water storages, and black arrows indicate water fluxes.

All simulations were carried out from 1965 to 2100; the first six years of simulations were taken as spin-up in order to avoid the influence of initial conditions in the water storages. This allows an assimilation of the model reservoirs to reality as an initialization of the linear model reservoirs is a problem because measurements of the reservoir contents do not exist (Hagemann and Dümenil, 1998). All fluxes are computed at each land surface grid cell for every time step. The precipitation is divided into rainfall and snowfall depending on the temperature; after they reach the snow layer from where a throughfall enters in the surface
water layer. The separation of precipitation into rainfall and snow refers to Wigmosta et al. (1994) scheme. The snowmelt uses a degree day formula according to the HBV model (Bergstrom, 1992). Important evaporation takes place in this canopy storage. Then, overflow from the surface water storage reaches the soil layer as interception and is divided into infiltration and surface runoff as computed by the improved Arno scheme (Hagemann and Dümenil Gates, 2003). These authors state that in the former scheme known as “bucket” scheme, surface runoff is calculated as infiltration excess from a bucket which takes the subgrid variability of the soil saturation within a GCM gridbox (or catchment) area into account assuming a statistical distribution of soil water capacities in the gridbox. In this scheme, it is supposed the existence of a minimum soil water capacity \( W_{\text{min}} \) within a gridbox that is not necessarily zero as it was in the former Arno Scheme. Then, the distribution of the soil water capacities within a gridbox is:

\[
\frac{s}{S} = 1 - \left( \frac{W_{\text{max}} - W_{\text{act}}}{W_{\text{max}} - W_{\text{min}}} \right)^b,
\]  

(Eq2.5)

Where \( W_{\text{max}} \) is the maximum local soil capacity, \( W_{\text{act}} \) is the subgrid water content that corresponds to the fractional saturation of \( s/S \) of the gridbox, \( b \) is a parameter that represents the shape of soil water distribution curve, and it depends on the topography variability, \( s/S \) is the percentage of the gridbox area \( S \) where the field capacity is less or equal to an assigned value \( W_S \):

\[
W_S = W_{\text{min}} + \int_{W_{\text{min}}}^{W_{\text{act}}} \left( 1 - \frac{s}{S} \right) dw,
\]  

(Eq2.6)

When \( W_{\text{min}} \) is greater than zero, runoff occurs when the total water content within the gridbox is greater than this minimum; but if \( W_{\text{min}} \) is equal to zero, runoff may occur after each rainfall event (Hagemann and Dümenil Gates, 2003). \( W_{\text{min}} \) leads to more runoff in wet areas due to the increased shape parameter \( b \) and to less runoff in dry areas. Hence, the introduction of \( W_{\text{min}} \) greater than zero, and the derivation of individual parameters \( b \) for each grid point from the subgrid soil water capacity distribution, are mainly novel this new scheme. The infiltration is added to a bucket type soil layer. Drainage and ET occur depending on the soil water content. Drainage is calculated using a scheme after Dümenil Gates and Todini (1992). Actual evapotranspiration is derived from PET. This scheme scales drainage linearly when soil moisture is below a certain threshold, but it increases drainages exponentially when the threshold is exceeded (Stacke and Hagemann, 2012). The bare soil evaporation is estimated using Bauer et al. (1983) scheme where ET is supposed to be linearly dependant on PET. Furthermore, the actual evapotranspiration is based on the formulations used in the ECHAM model (Roeckner et al. 1992) and on Warrilow et al. (1986) and Bauer et al. (1983). At the wilting point, transpiration tends to zero and its
maximum is obtained when there is enough water available into the soil. The wilting point is the difference between the soil water capacity (or field capacity that represents the amount of water held in the soil) and the plant available water capacity (which is the maximum amount from the soil before they start to wilt).

In the HD model, the water flow is separated into the three flow process of overland flow, baseflow and river flow. Overland flow uses surface runoff as input, baseflow is fed by drainage from the soil and the inflow from other upstream grid boxes contributes to river flow. The sum of the three flow processes equals to the total outflow from a grid box (Hagemann and Dümenil Gates, 2003).

The flows storages act as reservoirs and have specific water retention times which control the water release. These retention times or retention coefficient (average residence time of water within the gridbox) depend on the average slope φ within a gridbox (\(k_0\) for overland flow), on the topography gradient \(Δh\) between two adjacent gridboxes and the gridbox length \(Δx\) defined as the distance between the centres of two adjacent gridboxes in the direction of the flow (\(k_r\) for riverflow), and on the gridbox length (\(k_g\) for baseflow). The inflows from all these three storages are combined as river flow and routed to the next downstream gridbox.

The river flow within a gridbox has eight possible outflow directions corresponding to eight values: North (N: 8), East (E: 6), South (S: 2) and West (W: 4) that are the four main directions and the four diagonal directions (NE: 9), (SE: 3), (SW: 1) and (NW: 7) are defined. However, for a specific gridbox only one outflow direction is allowed. The outflow from this gridbox reaches the neighbouring gridbox which has the lowest topography value of the surrounding gridboxes (Hagemann and Dümenil, 1998).

The parameters of the overland flow and riverflow are given in the following equations:

\[
k_{n0} = 17.87 \times 10^{-2} \frac{Δx}{φ^{0.1}}\quad \text{With} \quad n_0 = 1 \quad \text{(Eq2.7)}
\]

\[
k_{nr} = 9.92 \times 10^{-4} \frac{Δx}{(Δh/Δx)^{0.4}}\quad \text{With} \quad n_r = 5 \quad \text{(Eq2.8)}
\]

Where, the unit of the gridbox length \(Δx\) is in km and the retention coefficients \(k_{n0}\) and \(k_{nr}\) are given in days. In cases, where the average slope \(φ\) within a gridbox is Zero, \(φ\) (in equation Eq2.6) is replaced by the topography gradient \(Δh/Δx\) to the next gridbox in flow direction.

Their flow velocities are given by:

\[
v_{0,i} = \frac{Δx}{n_0 k_i}\quad \text{(Eq2.9)}
\]

Where, \(i \in \{n_0, n_r\}\)
In addition, the fractional amount of wetlands and lakes within a gridbox influence also the parameters of overland and riverflow for certain gridboxes (Hagemann and Dümenil, 1998). As we focus in a semi-arid to arid region, this fractional is not playing a major feature of the land surface. In addition, regarding the funding of Hagemann and Dümenil (1998) on the modified global distribution of fractional lake area and wetland fraction, the Sahel region has relatively very weak coverage of wetlands and lakes. So, that we do not discuss their parameterization in the current study.

As for the retention coefficient \( k_g \) of the baseflow, it is defined as follows:

\[
k_g = t_g \cdot \frac{\Delta x}{d_0}
\]

(Eq2.10)

Here, \( t_g \) is the retention time of baseflow (set to 300 days), \( d_0 \) is the typical diameter of a 0.5°-gridbox (50 km). We have found during the model tuning that the simulations did not change significantly by setting small variations of \( t_g \) values. Then, Hagemann and Dümenil (1998) stated that a trebling of \( t_g \) yielded no significant changes in the total discharge; on the contrary a reduction of \( t_g \) to a third or a tenth has an impact to the total discharge but this generally causes a worsening of the simulated discharge.

More details about the functioning of the model can be found in Stacke and Hagemann (2012); Hagemann and Dümenil Gates (2001, 2003).

### 2.4.2.1 Model performance criteria

In order to evaluate the performance of the optimized MPI-HM model over the USB, the following statistics are used:

- **Nash Sutcliffe Efficiency** (1970) which is commonly used to assess hydrological models goodness fit:

\[
NSE = 1 - \frac{\sum_j (Q'_o - Q'_s)^2}{\sum_j (Q'_o - \bar{Q}_o)^2}
\]

(Eq2.11)

- **Percent Bias (PBIAS)**: it is used to estimate the model error

\[
PBIAS = \frac{\sum_j (Q'_i - Q'_o)}{\sum_j Q'_o} \times 100
\]

(Eq2.12)

\( Q'_o \) denotes the observed discharge at the month \( j \), \( Q'_s \) is the simulated one, and \( \bar{Q}_o \) is the averaged observed streamflow. NSE ranges from \(-\infty\) to 1.0, with high values indicating better agreement. NSE =1 indicates a perfect match of simulated and observed data; NSE = 0 corresponds to the model predictions matching the mean of the measured data, and NSE < 0
shows that the measured mean is a better predictor than the model (Legates and McCabe, 1999).

The PBIAS measures the tendency of the simulated variable to be larger or smaller than the corresponding observed value, its optimal value is 0.0, and positive values indicate a tendency to over-estimation whereas negative values indicate a tendency for under-estimation (Gupta et al., 1999).

**2.4.2.2 Simulation analyses**

The analyses have been mainly focused in the seasonal cycles of river discharge, runoff, actual evapotranspiration, soil moisture and precipitation. In addition, we further investigated the seasonal spatial variability from July to October (JASO) which represents the high flows period in the Senegal River Basin. The changes represent the differences between the scenario period (2071-2100) and the reference period (1971-2000). Then, the change of available water resources which depends mainly on mean annual runoff is estimated as follows:

\[
\Delta AW = \frac{(R_{scen} - R_{ref})}{(R_{ref} - EWR)} \times 100 = \frac{(R_{scen} - R_{ref})}{(R_{ref} - 0.23R_{ref})} \times 100 = \frac{(R_{scen} - R_{ref})}{(0.77R_{ref})} \times 100
\]  

(Eq2.13)

\(R_{scen}\) is the annual mean runoff in the scenario period, \(R_{ref}\) denotes the annual mean runoff in the reference period, and \(EWR\) is the Environmental Water Requirements that represents fair conditions of freshwater ecosystems and it is around 23% of the mean annual runoff in our semi arid basin according to the work of Smakhtin et al. (2004) who found that EWR range globally from 20 to 50 percent of the mean annual river flow of a basin.

**2.4.2.3 Optimization of the Max Planck Institute for Meteorology-Hydrological Model**

This global standard version of the model has been optimized to local conditions in USB. After several sensitivity simulations in order to identify the main parameters that influence the performance of the model over USB, the following parameters were identified. The overland flow retention constant, the riverflow retention constant, minimum soil moisture threshold for drainage and critical soil moisture for drainage, and the evaporation factor coefficients have been optimized by manual adjustments in comparing the simulations with observed river flows. For example, to overcome the issue of discharge overestimation, we pointed out an underestimation of evapotranspiration in the SL scheme as it was suggested by Hagemann and Dümenil Gates (2001). Then, the evaporation has been increased from 1 to 1.15. Details about the parameters optimization are given in Table 2.1. Several different runs
have been performed in order to see which of them allow a better representation of the observed river discharge.

**Table 2.1: Optimization of some model parameters**

<table>
<thead>
<tr>
<th>Original parameters</th>
<th>Modified parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>overland flow retention constant (ALF_K)</td>
<td>ALF_K*0.15</td>
</tr>
<tr>
<td>riverflow retention constant (ARF_K)</td>
<td>ARF_K*0.15</td>
</tr>
<tr>
<td>minimum soil moisture threshold for drainage</td>
<td>PWDMIN=0.3</td>
</tr>
<tr>
<td>(PWDMIN=0.05)</td>
<td></td>
</tr>
<tr>
<td>critical soil moisture for drainage (PWDCRI=0.9)</td>
<td>PWDCRI=0.95</td>
</tr>
<tr>
<td>evaporation factor (UFAKEV=1)</td>
<td>UFAKEV=1.15</td>
</tr>
</tbody>
</table>

The two first parameters (retention constant which the average of residence time of water within the reservoir) were tuned in order to overcome the delay or shift of the simulated peak discharge that occurs one month after with regard to observed discharge. As for the parameters for drainage, they deal with the overestimation of dry season flows. Additionally, the evaporation factor was slightly increased to reduce the general overestimation. But here, we show only four runs. This model doesn’t have specific parameters for calibration by using observed discharge as it is usually done with some hydrological models (GR2M, GR4J, ModHyPMA, etc). This make it a little complicates to match well the observed discharge. We have corrected the flows direction (Figure 2.10) for each grid cell by using our local knowledge of the river basin. River flow directions are based on the land surface topography. It is assumed that every grid cell drains into the neighbouring grid cell with the lowest elevation (Stacke and Hagemann, 2012). Six stations were considered during the optimization, and the LSP2 datasets and its updated version by either using dynamical wetlands or no wetland. This was done in order to figure out the best combination of parameters in reproducing the observed river discharge at stations. In Figure 2.11, the model largely overestimates the river discharge at stations (Sokotoro, Dakasaidou, Bafing Makana) located more upstream (before the Manantali dam) with LSP3 dataset and dynamic wetland. As for stations after the dam (Kayes, Bakel, and Matam), the simulations are quite well
acceptable with LSP3 and no wetland. But the peak discharge is delayed for one month. Then, regarding these above results, we choose the LPS3 with no wetland.

Figure 2.10: Senegal river and river flow directions

Figure 2.11: Simulated and observed river discharge at stations over USB

In figure 2.12, we show the simulations with optimized parameters that were mainly the evaporation factor for the overestimation and the river retention constants. Other runs were done (not shown) before getting this current run that we suppose acceptable at stations after the dam (Kayes, Bakel, and Matam). The different characteristics of the basin in upstream
and downstream complicate the optimization in the whole basin. For this reason, we focus at Bakel station which is the outlet of the USB that is also the reference station of the river.

![Graphs showing river discharge](image)

**Figure 2.12:** Simulated and observed river discharge at stations over USB with parameters optimized

Hence, the following river discharge simulations are been focused at Bakel. After the optimization with WDFEI as climate input, the MPI-HM was forced by uncorrected and bias corrected data from REMO climate model.

### 2.5 Summary and Conclusions

The climate of the Senegal River Basin (Western Africa) is characterized by humid (Guinean Highlands) to semi-arid (northern basin) conditions with strong rainfall spatial and temporal variability. The northern basin records more than 70 days where precipitation is less than 1mm during the main rainy season (July, August and September) by contrast to the southern basin that has around 20 dry days. It has been found also an important decadal variability of precipitation at stations over the basin with higher amounts in upstream stations. Additionally most downstream stations of the whole upstream area, record maxima of river discharge (e.g. Bakel, Matam). During the three last decades of the 20th century, the precipitation and the river discharge have decreased substantially at the reference gauging station of the basin (Bakel). Therefore, the observed basin’s hydro-climate has shown a drying with considerable variability. Then, the future evolution of these observed tendencies is crucial in this basin.
where the majority its population’s activities depend on rainfall (e.g. agriculture). Hence, future high resolution of climate simulations is required in order to investigate the evolution of the hydro-climate of the basin. Furthermore, the bias correction methodology used to correct REMO output is described as well as the hydrological modeling procedures. The results from this ensemble methodology are given in the following chapters.
Chapter 3

3. Evaluation of REMO and Validation of WFDEI over Senegal River Basin

3.1 Introduction

In the present chapter, a high-resolution regional climate (REMO) simulation is evaluated over the Senegal River Basin. To assess the impact of climate change on water resources at the basin scale, detailed climate information is needed. It is well documented that climate impact assessment studies need suitable input data for hydrological models. Then, an evaluation of the climate model simulations in reproducing the present day climate over the SRB is necessary before studying the future evolution of the basin’s climate. Laprise et al. (2013) suggested that models projections cannot be credible if models are unable to reproduce skillfully the current climate. This evaluation aims to investigate the capability of REMO to reproduce the most predominant characteristics of the climate and also the probable existence of biases that is general to all climate models. But the importance is here to know the extent of the biases, and how climate simulations biases can be propagated into hydrological model results as it will be shown in Chapter 5. Although, the transferability of REMO skills from its native region (Europe) to other regions such as Africa was successful (by Jacob et al., 2012), its evaluation at the basin scale particularly in the Sahel is essential. Being so, the WFDEI dataset (Weedon et al., 2014) that are our reference observational datasets, are used during the evaluation of REMO output during the present day climate. From that, few stations data are used to validate the WFDEI data even though they have been validated globally.

The chapter is organized as follows: Section 3.2 describes briefly the simulations analyses. In Section 3.3 the evaluation of the REMO simulations. The validation of WFDEI dataset by stations data is presented in Section 3.4. Section 3.5 discusses the results of these evaluation and validation. Finally, a short summary and conclusions section is presented.

3.2 Simulation analyses

The simulations analyses were mainly done by comparing the climate model output to the observational dataset WFDEI which in turn are then compared to stations data. A focus is given to the JAS season (July, August and September) which represents the main period of high rain and the annual cycle of precipitation and temperature. Additionally the 90th, 95th, and the 99th percentiles of mean JAS of these above variables are also computed for REMO
and WFDEI. The nearest grid point is considered while extracting stations data from WFDEI and REMO datasets. The REMO simulations (0.44°) are remapped onto the same spatial grid of the WFDEI (0.5°) through conservative remapping. The bias represents the difference between REMO simulations and WFDEI data. Moreover, the coefficient of variation of precipitation, the standard deviation of temperature, and the number of JAS dry days were also computed. The calculations are mainly done by the using the climate data operators (CDO).

3.3 Evaluation of REMO model

In Figure 3.1, the mean July, August, and September (JAS) from 1979-2005 of rainfall for REMO and WFDEI, and REMO biases are displayed. In this figure, it is well seen that REMO captures well the spatial pattern of rainfall (south-north gradient). The maxima of rainfall are found around the Guinean highlands for both, but REMO overestimates the precipitation (more than 16mm/day) particularly below 12°N where the maximum of WFDEI is 12mm/day. This overestimation is confirmed in the biases maps which depict only wet biases; they go up to 60% in the southern and in the northeast basin.

![Figure 3.1: Mean JAS precipitation of REMO, WFDEI, and REMO biases (%)](image)

As for the mean JAS temperature (Figure 3.2), spatial pattern is captured as with precipitation. The temperature ranges from 22°C in the South to 34°C in the North with REMO data that seem to be higher than the WFDEI data. Cold biases (from -0.2 to -1.4°C)
are found around the mountainous areas and warm biases (more than 1.4°C) above of 12°N in the majority of the basin.

**Figure 3.2:** Mean JAS Temperature (°C) of REMO, WFDEI, and biases (°C)

The seasonal cycles of precipitation and temperature are shown in Figure 3.3. REMO reproduces reasonably the signal of precipitation (figure 3.3a) with an overestimation of the JAS peak rainfall that is well defined in August for both datasets. The maximum of REMO is up to 250 mm/month by contrast to the maximum of WFDEI that is 170 mm/month. During the post and pre-monsoon (dry season), there is no significant difference between REMO and WFDEI data. As for temperature (figure 3.3b), the signal is quite captured by REMO although it underestimates the temperature from October (29.5°C for WFDEI against 28°C for REMO) to May (33°C for WFDEI and 28°C). The relative minima of temperature occur during August and September for both data. The overestimation/underestimation of precipitation and temperature is very noticeable in figure 3.4. The monthly wet biases of precipitation (figure 3.4a) occur during the summer period (up to 80%) and dry biases in the post and pre-monsoon where biases are beyond -40%. In case of temperature bias (Figure 3.4b), the model depicts warm biases from June to August (up to 1.4°C in July), by contrast in the dry season where REMO exhibits cold biases particularly in the most cold period (from November to February). The maximum of cold bias is obtained in December (-3°C).

Temperature biases exhibit colder “winter” (December, January and February), colder pre- and post monsoon and warmer biases (from June to August)
Figure 3.3: Seasonal cycle of Precipitation (a) and Temperature (b)

Figure 3.4: Monthly precipitation (a) and temperature (b) biases

Figure 3.5 displays the monthly mean of precipitation and temperature averaged over all longitudes of the Senegal River Basin (from 18°W to 6°W). This figure characterizes
somehow the West African Monsoon (WAM). The maxima of precipitation are localized in
the southern basin below 11°N in the Fouta Djalon mountainous for both datasets even
though higher values are obtained with REMO. The peak rainfall is well defined in August.
The high rainfall period corresponds also to the minima of temperature as it is well seen in
the temperature map. However, WFDEI exhibits the highest values of temperature
particularly in the northern basin.

Moreover, REMO generally overestimates the 90th, 95th, and 99th percentiles of precipitation
particularly in the southern basin as displayed in Figure 3.6. This later result is is consistent
with above results. The overestimation is more pronounced with the 99th percentile that
represents the extreme wet days; maxima values are around 70mm/day in REMO while they
are around 30mm/day in WFDEI. In the Guinean Highlands, the simulated precipitation is
almost twice than the observed data.

In case of the same percentiles for temperature (Figure 3.7), although both datasets show a
similar spatial pattern, the WFDEI data slightly overestimates the temperature. This is very
noticeable from central to northern basin which is the hottest part of the Senegal River Basin.

Figure 3.5: Hovmoller diagram of monthly precipitation and temperature averaged between 6°W and 18°W
over the Senegal River Basin.
where mean temperature goes up to 36°C by contrast to the southern basin which has the minima temperatures (around 27°C).

Figure 3.6: 90th, 95th and 99th Percentiles of Precipitations of REMO (Right) and WFDEI (Left)
Figure 3.7: 90th, 95th and 99th Percentiles of Temperature of REMO (Right) and WFDEI (Left)

Figure 3.8 displays the coefficient of variation of mean JAS precipitation over the Senegal River Basin of REMO and WFDEI. Both data depict similar spatial patterns with a south-north gradient where maxima are found in the northern basin and minima in the southern basin.

Figure 3.8: CV of mean JAS precipitation (1979-2005)
REMO overestimates the variability of precipitation particularly in the northern basin (up to 70%). This high variability in the northern basin is due to the heterogeneity of rainfall and the small mean of precipitation that is characterized by a short rainy season and a long dry season.

As for temperature (Figure 3.9), the climate model output depicts the highest variability that is almost twice the observational datasets. As like precipitation, the greater variability (0.85°C for REMO and 0.5°C for WFDEI) is found in the northern basin. In this part of the basin, maxima values of temperature are recorded.

**Figure 3.9:** Standard deviation of mean JAS temperature (1979-2005)

In case of the number of dry days (Figure 3.10), the spatial pattern of REMO is identical to the spatial pattern of WFDEI. The dry days exhibit a south-north gradient with greater dry days in the north (up to 70 days).

**Figure 3.10:** Number of JAS dry days (1979-2005)
REMO seems to have the highest number of dry days when compared to WFDEI. This shows that the model depicts more days of rain with very low intensities.

In Figure 3.11 the seasonal cycle of precipitation of REMO and WFDEI for 3 decades are shown. It is very noticeable that for all decades in WFDEI (figure 3.11a), the rainfall peak is well defined in August where the first decade (1979-1988) exhibits the lower magnitude (with less than 6mm/day) compared to the last decade that has the highest (7mm/day). The first decade is among the period which West Africa has faced the most severe drying due to decreased precipitation. As for REMO (figure 3.11b), it overestimates the peak rainfall in all decades; however, the first decade seems to have the greater amount of rainfall. Therefore, it should be noticed that from the first decade to the last decade, the magnitude of WFDEI precipitation increase while those in REMO decrease. This can be due to the shortcomings of the climate model that does not properly capture the decadal variability of precipitation over the Senegal River Basin.

Figure 3.11: Seasonal cycles of precipitation over decades of REMO of WFDEI (a) and REMO (b)
From that, stations data are used to validate the WFDEI over SRB as these gridded data are going to be used in the whole study as observational reference data.

3.4 Validation of WFDEI data by stations data

In this section, nearest grid point to stations coordinates (longitude and latitude) are extracted from WFDEI and compared to observed stations data. The seasonal cycle of rainfall in upstream basin (Mamou, Kenieba and Sagabari), central basin (Bakel, Matam and Nioro_Sahel) and northern basin (Saint Louis, Podor, and Kiffa) is shown in Figure 3.12. In all parts of the basin, the peak rainfall is well defined in August with the highest values in upstream stations (e.g. Mamou with more than 12mm/day) and lowest amounts are found downstream stations (e.g. Podor with less than 3mm/day). In the central basin, the peak rainfall ranges from 4 to 6mm/days. The signal of the precipitation is almost perfectly reproduced by the WFDEI in all stations; however, very slight underestimation is found particularly at Matam and Kiffa.
Figure 3.12: Seasonal cycle of precipitation at stations over SRB

The annual cycle of temperature (figure 3.13) shows that the WFDEI matches the stations even though there are noticeable deviations at Kenieba, Mamou and Saint Louis. As for the other stations, the seasonal cycle of temperature is rightly represented by the re-analyses data with the two peaks of temperature occurring in May and October.

Furthermore, the mean JAS of precipitation and temperature are presented in figures 3.14 and 3.14 for the WFDEI (the spatial map) and the stations (the small circles inside the map) respectively. It is an overlay of the stations onto the WFDEI data. This means that if the circles have the same color of the background map, then the WDDEI matches well the stations data. Precipitation ranges from 360mm/month (south) to 90mm/month in the north.
As for temperature, higher values go up to 32°C in the north and lower temperatures are found in the south (22°C). Maxima of precipitation are found in the southern basin while minima of temperatures are noticed in this same area which can be attributed to the evaporative cooling.

From these two figures, precipitation and temperature spatial coverage of stations are well reproduced by the WFDEI datasets

Figure 3.14: Mean JAS rainfall of WFDEI and stations over SRB

Figure 3.15: Mean JAS temperature of WFDEI and stations over SRB
3.5 Discussion
The evaluation of REMO JAS precipitation over the Senegal River Basin as showed in Figure 3.1, exhibits an overestimation rainfall. This was found also during in the temporal variation of precipitation averaged over SRB. The wet biases during the main rainy season were underlined by Gbobaniyi et al. (2014) around the Guinean Highlands. Additionally, during the dry season, REMO depicts dry biases. For temperature, the minima are found in the Guinean zone, and maxima are in the sahelian part of the basin that is south of the Saharan Heat Low (SHL) which is a key driver in the circulation of West African climate during summer. The warm biases could increase the thermal gradient between land and South Atlantic Ocean and thereafter enhance northward moisture transport within the monsoon flow which generates considerable rainfall over the region. Cold biases occur in orographic zones and warm biases above12°N. Its annual cycle (temperature) depicts warm biases during the monsoon period and cold biases during the post and pre-monsoon. The warm biases can be explained by an overestimation of the surface downwelling radiation which results to a misrepresentation of stratocumulus clouds (Jacob et al., 2012; Haensler et al. 2011). The drier and hotter northern basin depicts the highest variability in term of temperature and precipitation as described in figure 3.8 and figure 3.9.

Therefore, REMO simulations are associated with dry and wet biases in precipitation, warm and cold biases in temperature. The wet biases found during the high rain period are mainly associated with cold biases that result to a high evaporative cooling. Then, these biases of temperature and precipitation are likely to affect the hydrological simulations when they are used directly without correction. In Addition, the warm bias in the northern basin during the peak monsoon could lead to a high temperature gradient which could interact with the monsoon features, leading to a wider and more intense rainfall band (Gbobaniyi et al., 2014).

So far, a bias removal which is a statistical post-processing of model output is required. As for the validation of the WFDEI data by stations (as shown on the Figures in Section 3.4), the spatial and temporal variations were well captured. Thus, the WFDEI datasets are self-consistent to use for bias correcting REMO output.

3.6 Summary and conclusions
In this chapter, the performance of the regional climate model REMO was evaluated over the Senegal River Basin. The model reproduces generally the spatial pattern of precipitation and temperature and also their annual cycle. However, precipitation is generally overestimated by the model particularly around the Guinean Highlands. This overestimation is well noticed in the seasonal cycle of precipitation where wet biases are found during the main rain season. As for temperature, the model slightly underestimates the temperature around the
mountainous areas and overestimates it in the northern basin. Therefore, we state for this evaluation part that a bias correction of REMO simulations is needed in order to have reliable climate input for hydrological impact studies. Furthermore, the WFDEI matches well the stations data during its validation. Hence, these gridded observational data are going to be used to bias correct the climate model simulations. The comparison of bias corrected and uncorrected climate simulations are presented in Chapter 4.
Chapter 4

4. Impact of statistical bias correction on the projected climate change signals

4.1 Introduction

The use of RCMs has increasingly gained interest in recent years and the ability of RCMs to reproduce the present day climate has substantially improved (Xu et al. 2005). However, for impact studies, it is well documented that RCMs output is associated with biases that can affect the quality of hydrological simulations. During the evaluation part of REMO output (see in Chapter 3), wet and dry biases were found in precipitation, warm and cold biases were noticed in temperature. The biases in the regional climate model simulations can rise from shortcomings of the RCMs themselves, but also from erroneous forcing data as it was suggested by Schoetter et al. (2012). For hydrological impact study, a good quality of the input data is very crucial for the final conclusions that can be taken from the modeling results which are needed for water resources planners and managers. Beven and Feyen (2002) stated that the models will not be able to simulate accurate predictions if the areal precipitation is not adequately represented. Hence, to overcome this issue, we applied the bias correction methodology developed by Piani et al. (2010b) to bias correct precipitation and temperature data over the Senegal River Basin. These two variables are among the most prevailing climate drivers in modeling the hydrological processes, and also the most common climate change indicators. The statistical bias correction is designed to adjust all moments of the probability distribution function (PDF) of intensity for a specific variable (Hagemann et al., 2011). WFDEI data were used to correct the model output. Prior to this, the WFDEI datasets were validated by stations data over the Senegal River Basin. As our stations data are very sparse to cover the spatial and temporal resolution, good data coverage is needed (e.g. WFDEI) to correct the climate model biases. Therefore, stations data are only used to evaluate/validate the corrected simulations for some grid points (Lon/Lat).

The chapter is structured as follows. In Section 4.2, the analyses of REMO simulations are described. Section 4.3 presents the evaluation of bias corrected REMO simulation during the present day climate over the Senegal River Basin. The findings of the long-term high resolution climate projection and the potential impact of the bias correction on the projected climate change signal are shown in Section 4.4. Section 4.5 delivers a comparison of the
climate change signals between different time slices. The main results are discussed in Section 4.6. Finally, a summary and conclusions section ends this chapter.

4.2 Analyses of REMO simulations

In this chapter, daily uncorrected and bias corrected climate model simulations (such daily precipitation, mean, minimum and maximum temperatures) from the Regional Climate Model REMO from 1971 to 2100 were used. The climate model output have been bias corrected following Piani et al.(2010b). Details on the bias correction technique are given in Chapter 2.

The analyses are done in seasonal, annual and interannual time scales. The climate indices used here are: the maximum consecutive of wet days (CWD), the maximum consecutive of dry days (CDD); a day is considered wet/dry if the rainfall amount is greater/less than 1mm respectively. Heavy and extreme wet rainfall events are considered for rainfall values that are above the 95th and 99th of the reference period (1971-2000), respectively. The maximum five days total precipitation; this indice is very important in hydrology because extreme hydrological events (e.g. flood) are proceeded usually with several days of heavy rainfall events. Ten years running standard deviation is also used for temporal variability. These above indices were used for precipitation. As for temperature, warm days and warm nights are computed by using the maximum and minimum temperature that are exceed the 90th and 10th during the reference period, respectively. The changes are computed as the difference between the projected scenario (2071-2100) and the control period (1971-2000). In addition, the potential water balance represents the difference between the precipitation and the potential evapotranspiration (P-PET).

4.3 Evaluation of REMO historical runs after bias correction

4.3.1 Precipitation

Figure 4.1 depicts the mean July, August and September (JAS) rainfall. The overestimation of rainfall before correction around the Guinean highland is reduced from more than 16 to 12 mm/day after correction. In this region bias correction improves the results considerably. The biases in the corrected REMO data range from -5 to 5% while the original REMO simulation showed biases that go up to 55%.
Figure 4.1: Upper part of the figure: Mean JAS Rainfall for the period 1979 to 2005 as simulated with REMO (left); as observed (WFDEI; center) and after bias correction (right). The lower two panels depict the bias between uncorrected REMO and WFDEI (left) and bias corrected REMO and WFDEI (right).

The simulated data (from REMO) and observed data (WFDEI and station data) seasonal cycles of precipitation averaged over the SRB are presented in figure 4.2. For the Senegal basin, the data are averaged over the whole basin; as for the stations, the nearest gridbox is extracted. It is well seen that the overestimation of rainfall (wet biases) during the summer in REMO (blue curve), which was also seen in the hindcast simulations of REMO (Gbobaniyi et al. 2014) has been successfully corrected in all parts of the basin.
Figure 4.2: Seasonal Cycle of Rainfall over SRB and stations [UC: uncorrected, BC: bias corrected]

The number of dry days (NDD) and the 95th percentile of JAS precipitation are plotted in figure 4.3 and their biases in figure 4.4. The zonal patterns are well captured for all metrics (NDD, 95th P) form south to north. As for the 95th percentile of rainfall, the uncorrected data largely overestimates the high rainfall (60mm) in the southern basin around the Guinean
highlands where the amount is 30 mm in the WFDEI. The biases maps (figure 4.4) shows that the biases have been successfully removed for the 95th percentile. Therefore, the bias correction almost perfectly removed the biases in the simulations.

In case of the number of dry days, the northern basin has the maxima of dry days (more than 60 days). This northern area is also known to be the driest and hottest part of the basin.

![Biases Maps](image1)

**Figure 4.3**: Number of dry days (NDD) and the 95th percentile of JAS precipitation

In the case of the number of dry days, the bias correction also improved the results of the REMO simulation; however the biases are still substantial in the corrected data. Generally, the biases of the 95th percentile of daily precipitation amounts, the number of dry days shown in figure 4.4 are well reduced. However, remaining biases in the dry days are noticable.
4.3.2 Potential Evapotranspiration (PET) and Potential water balance (P-PET)

The annual mean of potential evapotranspiration is plotted in figure 4.5. It shows a high gradient of PET between the south (1200 mm/year) and the north (3000 mm/year). There are slight differences between the corrected and the uncorrected data; this is well noticed on the biases maps. More positive biases are found in a large part of the basin although there are some parts in the north where there is no deviation.

It should be noticed that biases of uncorrected and corrected data present very similar spatial patterns.
Moreover, the potential water balance (P minus PET) and its relative departure is presented in figure 4.6. A surplus of water (P-PET >0) is found above 14°N by contrast to the northern basin which exhibits a water balance deficit. The bias correction has reduced the positive biases in the potential water balance in the southern part of the SRB, even though only temperature is different (corrected and uncorrected) in the estimation of PET. The relative departure in the corrected REMO simulation is small in the whole basin, except in the central basin where some biases persist.

![P-PET mean JAS over Senegal Basin](image)

**Figure 4.6**: Mean JAS Water Balance (top) and its relative departure (bottom) over SRB

### 4.3.3 Mean, minimum, and maximum Temperatures

The zonal pattern of the mean JAS temperature (figure 4.7) depicted in the observations is quit captured by the simulations. However, the model has a warm bias in the northern basin and cold bias in the south which have been removed after bias correction. In the case of the seasonal cycle of mean temperature (figure 4.8), the most prominent features are the warm biases in the summer and the cold biases in the dry season present at all stations. Both biases were corrected for the whole basin and stations.
Figure 4.7: Upper part of the figure: Mean JAS temperature for the period 1979 to 2005 as simulated with REMO (left); as observed (WFDEI; center) and after bias correction (right). The lower two panels depict the bias between uncorrected REMO and WFDEI (left) and bias corrected REMO and WFDEI (right).

Figure 4.8: Seasonal Cycle of temperature over SRB and stations [UC: uncorrected, BC: bias corrected]

As for extreme temperatures (maximum and minimum) presented in figures 4.9 and 4.10 respectively, the zonal pattern of these temperatures is reproduced in all simulations with
maxima in the northern basin and minima in the southern basin. The bias correction has successfully improved the correction of the original simulations of REMO. This is well noticed in the biases maps where they are around zero.

Figure 4.9: JAS maximum temperature over Senegal River Basin

As for the mean temperature, the seasonal cycles of minimum and maximum temperatures (figure 4.11) show that warm biases (from June to October) and cold biases (from November to May) are well removed from the original simulations.

Figure 4.10: JAS minimum temperature over Senegal River Basin
Figure 4.11: Seasonal cycle of minimum and maximum temperatures averaged over Senegal River Basin

Hence, the bias correction has significantly improved the timing and the magnitude in both spatial and temporal variation of rainfall and temperature over the SRB. We conclude for this evaluation part that the bias correction has successfully improved the historical simulations also when comparing to station data.

4.4 Climate change signal with and without bias correction

4.4.1 Precipitation

In this part, we analyze the potential impact of the bias correction on the projected climate change signals over the Senegal Basin. Most of the analyses focus on the end of 21st century because substantial changes are expected during the late century as it was suggested by
Roudier et al. (2014) and Aich et al. (2014). Figure 4.12 displays the historical and projected changes of mean JAS rainfall for both, bias-corrected and non-bias-corrected REMO simulations for the historical period as well as for the end of the 21st century for two different emission scenarios. Furthermore the differences between the corrected and non-corrected simulations (in the following, “delta” is the difference of the climate change signals between corrected and uncorrected simulations; the difference between corrected and uncorrected model output, is defined as deviation) are depicted, respectively. The projected decrease is more pronounced in the RCP8.5 simulation (more than 2 mm decreased) than in RCP4.5.

In general an increase of rainfall is projected for the end of this century around the Guinean highlands for both datasets and scenarios and considerable decrease of rainfall is projected to occur above 12°N. In these mountainous areas, the moisture supply from the sea and the surface heating leads to an ascent of moist air which cools and favors condensation of water vapor that is responsible of precipitation generation. Additionally, this region is known to receive the highest bulk of precipitation in WA.

**Figure 4.12:** Mean JAS rainfall and its absolute changes for uncorrected data (left), for bias corrected (Middle), and their differences (right) for RCPs 4.5 and 8.5.
Only a small difference (deviation) is present between uncorrected and bias corrected simulation in the historical simulations although a deviation up to 5 mm/day is noticed around mountainous areas. The bias correction has affected the climate change signal in both scenarios (delta) and it is more pronounced in RCP8.5. The bias correction seems to reduce the drying over the SRB.

Furthermore, the precipitation seasonal changes in AMJ (April-May-June), JFM (January-February-March), and OND (October-November-December) are presented in figure 4.13, figure 4.14 and figure 4.15 respectively for all simulations and scenarios. In AMJ season, precipitation decreases generally in RCP8.5 (-60%) for both datasets. This decrease is more pronounced in the northern-eastern parts and western-northern parts of the basin. As for the scenario RCP4.5, slight decrease is found in the majority of the basin, except the north-western part of the basin where an increase is found in the corrected and original data. Within the same scenario, both data depict similar spatial pattern.

**Figure 4.13:** Precipitation AMJ seasonal change

In the cold and dry season (JFM), an exceptional increase is found in the northern part of the basin (up to 30%) with the extreme scenario in the uncorrected data by contrast to the southern basin where precipitation is likely to decrease. This increase in the driest part of the basin can be explained by the standardization technique we used; the huge percentages (more than 70%) are due to the division by very small amounts. As for the change in the moderate scenario, the highest decrease is noticed in the central basin (-75%) in the uncorrected data.
No change is found in the northern basin with bias corrected in RCP4.5. Thus, in this season, the bias correction has altered the climate change signal by the end of 21st century.

In addition, in the post-monsoon season (OND), within the same scenario, both data exhibit a similar spatial pattern of the projected signal. The changes are higher with RCP8.5 than with RCP4.5 particularly in the northern basin. Moreover, localized increase and decrease are found in some parts of the basin. The changes are more substantial in the uncorrected data than in the bias corrected data.

In order to characterize the spatial variations of the West African Monsoon (WAM), a Hovmoller diagram (time-latitude cross sections) of monthly precipitation, averaged over 18° W and 6° W, is presented in Figure 4.16. The rainfall band is supposed to become narrower by the end this 21st century for both scenarios and particularly for RCP8.5. Its magnitude and its latitudinal position are likely also to be reduced. This rainfall band is reduced in the bias corrected data particularly in August (from 16 mm/day in the uncorrected to 12 mm/day in the bias corrected).

Figure 4.14: Precipitation JFM seasonal change

Moreover, localized increase and decrease are found in some parts of the basin. The changes are more substantial in the uncorrected data than in the bias corrected data.
Figure 4.15: Precipitation OND seasonal change

Its magnitude and its latitudinal position are likely also to be reduced northward. This rainfall band has been reduced in the bias corrected data particularly in August (from 16 mm/day in the uncorrected to 12 mm/day in the bias corrected). This rainfall band is reduced in the bias corrected data particularly in August (from more than 16 mm/day in the uncorrected to 12 mm/day in the bias corrected), with largest deviation (-6 mm/day) south 12°N.
Figure 4.16: Monthly precipitation (mm/day) over Senegal River Basin averaged between 18°W and 6°W for the historical period (1971-2000) and of 21st century (2071-2100) for RCPs 4.5&8.5.

The projected changes of the 95th percentile of daily rainfall amounts (only wet days >1mm/day rainfall are considered) are shown in Figure 8. An increase (up to 15 mm/day) is found particularly from central to southern basin in the uncorrected data for the RCP4.5 scenario. After the bias correction, the projected changes range from -5 to 5 mm/day. For RCP8.5, the uncorrected model projections shows a substantial decrease in the 95th percentile of daily rainfall amounts over most parts of SRB (up to 15 mm/day less). Only for the region south of 12°N, an increase of up to 15 mm/day is projected.

Similar to what has been described previously for the mean JAS rainfall the delta between corrected and uncorrected projections of the 95th rainfall percentile shows mainly negative departures in the southern basin and more pronounced for the RCP4.5 simulation. Especially
in the southern part of the basin projected changes in high rainfall intensity is reduced by the bias correction by more than 5 mm/day. Additionally, positive delta differences are found above of 12°N for RCP8.5.

**Figure 4.17:** Mean JAS 95th percentile of Rainfall and its absolute changes for uncorrected data (left), for bias corrected (Middle), and their differences (right) for RCPs 4.5 and 8.5.

In Figure 4.18 we present the projected changes of the number of dry days by the end of 21st century for both scenarios. Generally and for both scenarios, the NDD is projected to increase by the end of the current century over the whole basin. Larger increases in NDD are seen in the north and in RCP8.5 (from 2 to 16 days) while in RCP4.5 projected changes ranges from 2 to 8 days. The difference between the corrected and the uncorrected data during the reference period depicts a south-north gradient of the number of dry days where the bias correction leads to drier days in the northern basin (up to 6 days) by contrast to the southern basin which shows less dry days with bias corrected simulations. As for the projected signal, the main deviations are likely to occur in the northern basin (up to 3 days).
Figure 4.18: Mean JAS NDD and its absolute changes for uncorrected data (left), for bias corrected (Middle), and their differences (right) for RCPs 4.5 and 8.5.

Figure 4.19 displays the changes at the end of 21st century (2071-2100) of the maximum consecutive wet days (CWD), the maximum consecutive dry days (CDD), and the frequency of heavy rainfall that are above the 95th percentile of rainfall during the present day (1971-2000). From this figure, it is very noticeable a clear decrease of wet days length (up to 20 days) and an increase of dry days to more than 35 days. The increase of the length of consecutive dry days is more pronounced in the northern basin which is the driest and hottest part of the Senegal basin.
We present in figure 4.20 the variation coefficient of rainfall. It shows that more changes are expected in RCP8.5 (up to 60%) in the sahelian part of the basin for the uncorrected RCP8.5 scenarios. For both scenarios, the south-east of the basin exhibits small deviations in the bias corrected data. Although they have a similar spatial pattern, the magnitude of the climate change signal is affected by the statistical bias correction.

The coefficient of variation of annual mean of precipitation is presented in figure 4.21. High variability is found in the northern basin (up to 80%), and it decrease southward in all datasets (10%). However, the variability is more important in the uncorrected data than in the bias corrected data. We have seen in the previous results that the bias correction seems to reduce the precipitation, and the high variability can be due to the very short rainy season and the small amount of rainfall in the northern basin. Thus, localized precipitation events could have great impact on the variability. Additionally, it should also be taken into account the influence of the global tropical oceans and the North Atlantic SSTs that highly influence the Sahel rainfall (Giannini et al. 2003). Uncorrected and bias corrected data show similar spatial patterns.
Figure 4.20: Mean JAS CV and its changes for uncorrected data (left), for bias corrected (Middle), and their differences (right) for RCPs 4.5 and 8.5

Figure 4.21: Mean annual CV of precipitation over SRB

In order to investigate the decadal variability of extreme precipitation, the 10 years running standard deviation of the maximum 5-day precipitation total and the extreme wet days (99th percentile) are shown in Figure 4.22a and 22b respectively.

The bias correction highly reduced the total 5-day precipitation from present day climate to end 21st of century when compared to uncorrected simulations. Both data depict a decadal
variability that is more amplified with raw data for RCP8.5 (up to 36 mm). The variability is higher during the decades 2011-2021, 2041-2051, 2061-2071 and 2071-2081 with RCP8.5. As for RCP4.5, the most substantial variations are found after mid century to 2081 (maximum reached at 39 mm) with original climate model output. The bias correction somewhat mismatches the magnitude of the decadal variability of accumulated precipitation. Furthermore, the extreme wet days (figure 4.22b) are likely to be more variable (up to 2.8%) during the decades 2021-2031, 2061-2071, 2081-2091 with RCP8.5 for both data. Additionally, in RCP4.5 the decadal variability is projected to be more important from 2061 to 2081 for all simulations. In this later result the bias correction does not alter the climate change signal. These results show also that the radiative forcing that is related with the greenhouse gases emission, has an important impact on the projected climate change signals.

Figure 4.22: 10 years running standard deviation of extreme wet days (99P) and maximum 5 days precipitation

By the end of 21st century, mean precipitation (figure 4.23) is likely to decrease for both corrected and uncorrected data. The precipitation’s peak in the uncorrected simulations is 2 mm higher than the corrected peak in August. Then, the bias might substantially reduce the rainfall signal over the SRB. From the reference period to the scenario period, the bias corrected data exhibit one well defined peak in August by contrast to the projected uncorrected signal where the peak is maintained until September. This situation can be explained by the fact that we have conserved the same statistical relationship between observed and simulated data in a changing climate. Moreover, the bias in August is higher
than the increase of precipitation in September; this can also justify the conservation of the peak rainfall in August by the bias correction.

**Figure 4.23**: Seasonal Cycle of Rainfall [Top line for historical (blue), RCP45 (green) and RCP8.5 (red), in the bottom line we have the absolute change [UC: UnCorrected, BC: Bias Corrected]]

4.4.2 Potential Evapotranspiration (PET) and potential water balance (P-PET) changes

The changes in PET plotted in figure 4.24, show that by the end of 21st century, an increase of potential evapotranspiration is likely to occur in the entire basin from 10 to 15% in RCP4.5 and from 10 to 25% in RCP8.5 either corrected or uncorrected data. The changes are more pronounced in the uncorrected simulations than that in the bias corrected. Small decrease (-5%) is found in RCP8.5 for corrected in the most southern part of the basin. Both datasets in all scenarios present the same signal of increase in general even though there are deviations in magnitude. This is shown in the delta maps that represent the different between the bias corrected and the uncorrected data. As shown in the changes maps, the climate change signal is reduced by the bias correction.
Figure 4.24: Mean JAS PET and its relative changes for uncorrected data (left), for bias corrected (Middle), and their differences (right) for RCPs 4.5 and 8.5.

The seasonal cycle of PET averaged over the SRB at the reference period (1971-2000) and at the end of century (2071-2100), and its relative changes are displayed in figure 4.25. In all months, PET is expected to increase from reference to scenario period for corrected and uncorrected data. As seen above in the spatial variation, the temporal variation shows also that the changes are higher in RCP8.5 than in RCP4.5. The maxima are found in the main rain period (JAS) and from December to February. We have noticed that only few differences exist between uncorrected and bias corrected data. This can be due to the fact that only temperature is different in the estimation of PET, and others parameters such as radiations, wind and humidity may have non negligible effect on the computation of PET. Then, it has to be taken into account the nonlinearity in the relationships between the drivers of evaporation (e.g. temperature) as suggested by Weedon et al. (2011).

The spatial patterns of the potential water balance are displayed in Figure 4.26. This water balance is expected to decrease in almost in the whole basin in both datasets and scenarios. The decrease is drastically higher under the extreme scenario (RCP8.5) for the central to
northern parts of the basin. The decrease ranges from -4 to -1 mm/day. The delta between the two signals shows no changes in the majority of the basin with RCP4.5. As for RCP8.5, deviations are very noticeable in the whole basin.

Figure 4.25: Monthly PET (historical and scenarios) at top and its relative changes at bottom
The seasonal cycles of the potential water balance (P-PET) for the historical period and for the two scenario simulations are displayed in figure 4.27. Additionally the respective differences (delta) between the uncorrected and corrected simulations are depicted. It is clearly seen that this water balance decreases from the present day climate by the end 21st century. The projected decrease of the potential water balance in the bias corrected data is larger than in the uncorrected simulations.
4.4.3 Mean, Minimum, and Maximum temperatures
In the case of mean JAS temperature changes (figure 4.28), slight differences are found between the corrected and uncorrected data in the historical period. This is well seen in the delta where deviations are noticed in the northern basin (~ 1 °C). Then, a general increase is projected by the end of 21st century for both scenarios and datasets over the whole SRB. It ranges from 1 to 4 °C in RCP4.5 and it goes up 6 °C in RCP8.5. The warming in the extreme scenario RCP8.5 is almost twice the warming of the moderate scenario RCP4.5. The increases are more severe in the uncorrected data than in the bias corrected data. The delta change shows that the expected warming is likely to be reduced by the bias correction because only negative differences are found. As well as JAS, general increase of temperature changes is found in the other seasons (OND, JFM, and AMJ) in all data where the increase is more pronounced for RCP8.5(Figure 4.29, 30, and 31).
**Figure 4.28:** Mean JAS Temperature and its changes, for uncorrected (left), corrected (Middle), and their differences (right) for RCPs 4.5 and 8.5

**Figure 4.29:** Mean temperature AMJ seasonal change
Then, the increase with RCP8.5 is almost the double that one with RCP4.5 and the highest values are found in the uncorrected data for all seasons. Small differences occur in the magnitude of the climate change signal between the simulations. Moreover, the eastern basin will face the most severe increase of temperature (up to 6°C) in the pre and post-monsoon seasons (AMJ and OND).

**Figure 4.30:** Mean temperature JFM seasonal change

**Figure 4.31:** Mean temperature OND seasonal change
This can be explained by the increase of infra red radiations that are trapped by water vapour in OND season and the direct solar radiation effect on land surface in AMJ season. The warming is more severe in the eastern and in the central basin particularly for RCP8.5. Figure 4.32 shows the standard deviation of annual mean temperature. The higher variability is found with uncorrected in RCP8.5 from the central to eastern basin (up to 1.1°C). The original and corrected data present the same spatial pattern although slight differences exist in magnitude.

Figure 4.32: Annual standard deviation of mean temperature over SRB

The changes in the extreme temperatures (minimum and maximum) are shown in figure 4.33 and in figure 4.34 respectively. For the minimum temperature, the changes are more drastic in RCP8.5 (up to 5.5°C) than in RCP4.5 (up to 3°C) in the uncorrected data for the whole basin. The same tendency is found in the maximum temperature where an increase of 6.5°C is likely to occur in RCP8.5. The northern and the central-east parts of the basin are expected to face the highest temperatures increases. The climate change signal is reduced by the bias correction. This is shown by their delta that exhibits only negative values for both scenarios over the entire basin. The reduction of the climate signal is more pronounced in RCP8.5 than in RCP4.5.

This general warming will lead probably to increased risks of droughts in this semi-arid region by higher evaporation fluxes.
Figure 4.33: Minimum JAS Temperature and its changes, for uncorrected (left), corrected (Middle), and differences (right) for RCPs 4.5 and 8.5.

Figure 4.34: Maximum JAS Temperature and its changes, for uncorrected (left), corrected (Middle), and differences (right) for RCPs 4.5 and 8.5.

The Warm days (Figure4.35a) and warm nights (Figure4.35b) percents exhibit considerable increase towards the end of century up to 95% with RCP8.5. The increase in this later scenario (70-95%) is almost twice than the increase with RCP4.5 (40-65%) for both
warmings and they are more pronounced from central to southern basin. The uncorrected data show the highest increase of warm days and nights. With regards to the range between warm days and nights (Figure 4.35c), it varies from -10 to 0%. These negative values indicate that the percent of warm nights is greater than the percent of warm days. These spatial findings are also confirmed in their temporal variations (from 2006 to 2100) as shown in Figure 4.36. The projected warm days and warm nights as presented in Figure 4.36a and Figure 4.36b respectively, depict an increase towards the end of century with substantial interannual variations (15-95 %). This warming was also observed by Ly et al. (2013) over West Africa from 1960 to 2010. The general warming is greater in RCP8.5 (with a maximum of 95%) than in RCP4.5 (with a higher of 60%). The warming with uncorrected data seems to be higher than the warming of bias corrected data in all scenarios

This suggests the cooling effect of the statistical post-processing on temperature. The warm range (Figure 4.36c) in RCP8.5 shows a decreasing range particularly in the 3 last decades of the century. As with regards to the RCP4.5, there is no clear tendency of decreasing or increasing warm range although in some periods it increases (e.g. 2056-2066) and seems to decrease from 2076 to 2090. Moreover, the projected climate signals in not changed by the statistical bias correction technique.
Furthermore, the seasonal cycle of mean temperature and its potential changes are displayed in figure 4.37. As seen in the previous results, a general increase is noticeable in all data and scenarios. The uncorrected data depicts the higher magnitude of the climate change signal. The increase of temperature could result to the increase of greenhouse gases emission.

Figure 4.37: Seasonal Cycle of temperature [Top line for historical (blue), RCP4.5 (green) and RCP8.5 (red), in the bottom line we have the absolute change]
Figure 4.38 summarizes the average changes of precipitation and temperature over the Senegal River Basin. It is noticeable that by the end of 21st century precipitation is likely to decrease (around -14 %) and temperature is expected to increase (around 2°C in RCP4.5) for both datasets although the increase of temperature is more pronounced in the original data and the decrease of precipitation is higher in the bias corrected data. Moreover, the decline of precipitation and the increase of temperature in RCP8.5 is almost twice higher than that in these variables with RCP4.5. Hence, the uncorrected and bias corrected simulations show similar climate change signals even though their magnitudes are slightly different.

![Figure 4.38: Average changes of precipitation and temperature over SRB](image)

### 4.5 Comparison of time slices precipitation and temperature changes over Senegal River Basin

In this section, we compare the climate change signal between three times slices such as 2011-2040, 2041-2070, and 2071-2100 for both data and scenarios. Figure 4.39 displays the monthly changes of precipitation averaged over SRB. The major differences are found in the dry season from October to June for RCP4.5 (Figure 4.39a) and RCP8.5 (Figure 4.39b). The long term future (2071-2100) exhibits slightly the highest changes particularly with RCP8.5. Particular increases are noticeable in June, October and November in the time slices 2011-2040 and 2041-2070. This situation can be due to extreme precipitations that usually do not occur in these months.
In case of the temperature (figure 4.40), it will increase in all data, all scenarios, and all time slices. For RCP8.5, the differences between the time slices are well defined; more the time slice is far, more the increase is higher. These results are similar to that obtained with the stabilization scenario, except for the period 2041-2070 where its temperature increase is higher than that of the long term future from June to November. Then, in this latter monthly period, the climate change signal is somehow affected by the bias correction because while it increases in the uncorrected data, it decreases in the bias corrected data.

Figure 4.39: Monthly changes of precipitation
Furthermore, the annual average changes of precipitation and temperature are shown in figure 4.41. For the temperature, the most important changes occur by the end of century with RCP8.5 (up to 5°C). In addition, the magnitude of the projected signal is higher in the original than that corrected. However, precipitation is likely to decrease from the near future to the long term future (-10 to -37%) over the whole basin. The changes in the near future are less important than that in the other periods. Around the mid century and the near future, the changes with RCP4.5 are slightly higher than that with RCP8.5, and the corrected data have the lower magnitude. The climate change signal in all data has the same tendency. Hence, the bias correction mainly affects the magnitude of the projected signal. These findings on precipitation show the higher temporal variability of precipitation over the Sahel.
4.6 Discussion

During the evaluation part of bias corrected data, we have shown that in the southern part of the basin where the pattern is more complex (mountainous areas) and rainfall amounts are higher; the substantial wet biases of the uncorrected REMO could be removed by the bias correction (Figure 4.1). The bias correction was also able to correctly reproduce the seasonal cycles of precipitation (Figure 4.2) when compared to stations data. The reason of the remaining biases of NDD (Figure 4.4) is that the bias correction method can only correct an underestimation of the dry day’s number, but not an overestimation. In addition, it can be due also to the chosen thresholds to truncate REMO precipitation because climate models are known to produce very huge days of lower rainfall intensity and too large extreme rainfall, when compared to observation (Ibrahim et al., 2012).

The persistence of P-PET biases (Figure 4.6) could be due to the lack of consistency in model output (e.g. lack of feedbacks from evaporative fluxes) that is not solvable by bias correction (Piani et al., 2010b). As for mean temperature, the results are also similar to that found in precipitation where the bias corrected data match well the observations (Figures 4.7&8), and likewise minimum and maximum temperatures (Figure 4.11).

Figure 4.11: Annual average changes of temperature (top) and precipitations (bottom)
These above findings show that bias corrected data can be self-consistent for hydrological impact studies because it reproduces correctly the key variables (precipitation and temperature) in hydrological modeling.

Regarding the projected precipitation change signal in Figure 4.12 the model generally depicts a decrease over most parts of SRB except of the southern tip. Here, the Guinean highlands are under the effect of the sea breeze and the monsoon flux which bring moisture flow favourable for the growing of Mesoscale Convective Systems (MCSs) which in turn generate considerable precipitation. The severe precipitation decline over the northern basin can be related to the weakening of the monsoonal flow which does not move far enough northward. This decrease is similar to that found by Laprise et al. (2013) with CanESM2 and MPI-ESM-LR, and CanESM2-driven CRCM5 over West Africa.

The local increase of precipitation over the mountainous areas may compensate the heating via evaporative cooling. As the seasonal migration of the tropical rainbelt characterizes mainly the precipitation over the continent, small shift in its position can lead to considerable changes in rainfall (Diaz et al., 2012). Furthermore, as SSTs are likely to increase due global warming, this will reduce the thermal gradient between ocean and land and thus decrease the northward extent of the monsoon (Messager et al., 2004). This later authors suggested that the increase of precipitation over coastal regions (e.g. Guinea) is associated by an increase of the meridional moisture transport in the lower troposphere due to warmer SST and considerable evaporation.

The drastic decrease of rainfall over the northern part as projected by REMO might be related to the strengthening of warm and dry air advection from the Sahara. Diallo et al. (2012) suggested that the drier conditions associated with the large warming over this region, results probably of lower evaporative cooling and cloudiness. In general the bias correction does not alter considerably the projected sign of the signal as has been shown for other regions of the globe (Hagemann et al., 2011) and also conserved the larger scale spatial structure of the projected changes. However, it clearly affects the magnitude of projected changes in mean precipitation change signal in both scenarios (delta) and it is more pronounced for the RCP8.5 scenario simulation and particularly in the southern part of the basin. Generally the bias correction has a dampening effect on the projected precipitation signal as it is also noticed in the other seasons (OND, AMJ and JFM). The strong impact of the bias correction on the southern parts of the basin can also be seen in the characterization of the WAM (Figure 4.16). Particularly below 12°N the bias correction substantially lowers the simulated precipitation amounts. The narrowing of the rainfall band can be due to warmer SSTs that result to a decline in the magnitude of the AEJ (Messager et al., 2004) which leads
to a narrower tropical rainbelt and thus drier summer in the Sahel (Nicholson, 2008). However one has to keep in mind that the region is characterized by a rather complex topography with only limited stations coverage in the gridded observations. It has to be mentioned, that the finding that bias correction has the potential to alter the projected patterns of precipitation is not limited to this study or region but has been shown for other catchments, e.g. Hurkmans et al. (2010) have underlined an alteration of the spatial pattern of precipitation and temperature over the Rhine Basin due to bias correction. In addition, the bias correction method cannot correct e.g. the timing of the monsoon onset. So, if this is not correctly simulated by the models, or if it changes in the future, the bias correction probably cannot help.

A potential reason for the difference in corrected and uncorrected precipitation projections can be the strong deviations of corrected and uncorrected data at the higher end of the precipitation distribution. If the 95th percentile of daily precipitation is assessed we find that the impact of the bias correction is much more pronounced (Figure 4.17). Already during the control period the bias correction strongly reduces the simulated high intensity precipitation amounts over the whole catchment area. It is therefore not surprising that the projected increase in the 95th percentile of daily rainfall is almost completely removed by the bias correction. This inability of the bias correction to represent increased high intensity rainfall events is widely discussed in the literature (Leander and Buishand, 2007) and has to be taken into account when using the data as input to impact assessment studies. The reduction in the projected decrease of the 95th percentile of daily precipitation in the bias corrected data, which is visible over the majority of the domain, seems more to be related to the change in number of dry days (Figure 4.18). An increase in the number of dry days (daily rainfall with less than 1mm) potentially reduces the 95th percentile of daily rainfall when included into the calculation (as done in this study). Therefore a lower increase in the number of dry days with as seen in the bias corrected data potentially leads to a lower decrease in the 95th percentile of daily precipitation. This presented result is consistent with the work of Tian et al. (2013) who found a change in the distribution of precipitation intensity due to bias correction. One could notice that the bias correction technique usually reduces the precipitation amounts. Moreover, the northern basin is likely to experience the highest frequency of heavy rainfall (12 %) even though there is prolonged dry spells as found by Vizy and Cook (2012). This later findings was also pointed out by Klutse et al. (2015) over West Africa. The spatial patterns of the projected climate change signals are similar between uncorrected and bias corrected data although slight deviations exist in term of magnitude (Figure 4.19). Thus, rainfall is likely to decrease towards the end of 21st century with a slight increase of extreme
events. This increase could be the result of moisture supply for convection from the North Atlantic Ocean due the global warming which increases the atmospheric water vapour that in turn can lead to localized extreme precipitation. The increase of extreme events over the region was suggested by Giannini et al. (2013) by using CMP3 and CMIP5 simulations. Furthermore, apart from the dampening effect of the bias correction on the largest 5-day precipitation total, accentuated decadal variability is projected in the coming decades (Figure 4.22a). This could increase the uncertainty in potential flood risks because extreme hydrological events are usually preceded by several heavy rainfall events.

Linked to the general warming is an increase of potential evaporation which potentially enhances the drying over this semi-arid region (Figure 4.24 & 25). This feature is more pronounced in the RCP8.5 scenario and over the semi-arid regions of the SRB, while in the southern tip of the basin an increase P-PET is projected (Figure 4.26). Consequently to the impact of bias correction on the precipitation signals also for P-PET, the bias correction has a balancing impact on the projected signals. Regarding the projected general warming (Figure 4.28) the magnitude projected by REMO in the corrected and uncorrected data is similar to the findings of Laprise et al. (2013) over the Sahel. This later results is confirmed by the general increase of extreme temperatures (minimum, maximum) towards the century. The night warming is higher than the day warming (Figures 4.35 and 4.36); this means that minimum temperature increases faster than maximum temperature as found by Sillmann et al. (2013b). It has been noticed that more the radiative forcing is higher more the changes are substantial. The faster increase of minimum temperature may be due to the the higher effect of greenhouse gases in absorbing infrared radiation during nights. The global increase of warm nights and days could lead to increased water losses through evaporation that reduce soil water content in this semi-arid region which depends highly on crop productivity. The higher evaporation rate will lead to more atmospheric water vapor which generate cloud by condensation; the increase of cloudiness will in turn increase also minimum temperature. This general warming confirms the work of Ly et al. (2012) and Sillmann et al. (2013b) over West Africa. Generally the bias correction has a slight cooling effect on the projected temperature signals, more pronounced under the RCP8.5 scenario and towards the moisture parts of the domain.

4.7 Summary and conclusions

In this present Chapter, the impact of bias correction on the climate change signal over the Senegal River Basin has been investigated. The bias correction methodology developed by Piani et al. (2010b) was applied in order to remove the biases of the REMO output. Transfer
functions have been derived between present day simulations of the Regional climate model (REMO) conducted in the context of the CORDEX project and the WFDEI (observed datasets). The coefficients of these functions have been applied to correct REMO projections for the end of 21st century period for RCPs 4.5 and 8.5. The investigation has been done on the key hydroclimatological variables such as precipitation, temperatures (mean, maximum, minimum), and the potential water balance which represents the difference between precipitation and potential evapotranspiration. Furthermore the maximum consecutive wet days (CWD), the maximum consecutive dry days (CDD), the heavy rainfall events (95th percentile), the maximum 5-day precipitation total; the extremely wet days (99th percentile) were analyzed.

In the historical period (1979-2005), where transfer functions were derived by fitting of probability density function, the evaluation of REMO data show its overestimation of rainfall particularly in the mountainous areas where rainfall exceeds 16mm/day before the bias correction. However, after bias correction, the corrected simulations exhibit a good agreement when comparing them to observations in all seasons. At this same period, an underestimation of temperature was found in the original data in the long dry season and a little overestimation in the main rainy season (JAS) as well as the other seasons (OND, JFM and AMJ). These biases were removed after correction. Moreover, the evaluation by using station data was successful because the timing and the magnitude were very well captured after the bias correction in all stations. The overestimation of the heavy rainfall events (95th percentile), and the underestimation of low rainfall events (number of dry days) in the uncorrected data have been corrected after the bias correction. The highest departure was found in the driest part (northern); this is supposed to substantially impact the water resources in this region. A surplus of P-PET (P-PET >0) was found around the Guinean Forest Savannah, and a high water balance deficit (P-PET <0) in downstream.

As regards to the projected simulations, the results show that precipitations are likely to decrease by the end of 21st century for both scenarios in the majority of the basin, except the Guinean highlands where an slight increase is found. This same pattern was found in the 95th percentile of heavy precipitation where the decrease is more severe in the RCP8.5. The basin’s drying results to an increase of consecutive dry days that is combined with a decrease of wet day’s length. Moreover, the basin is likely also to face more decadal variability of extremely wet days and accumulated 5-days precipitation that are more pronounced with uncorrected data with RCP8.5. The drying is enhanced by the global warming of warm days (related to maximum temperature) and nights (related to minimum temperature) towards the 21st century. For mean temperature, a general increase is noticed in the entire basin for all
scenarios. The increase of all temperatures in RCP8.5 is almost twice than that in RCP4.5 for bias corrected data, and more increase is found in the uncorrected simulations. As well, the potential water balance (P-PET) shows a deficit above 12°N; this deficit is due the exceedance of potential evapotranspiration. The long term future (2071-2100) appears to be the period where the highest changes are likely to occur with RCP8.5 for precipitation and temperature when compared to other time slices.

In summary, climate change is supposed to substantially impact the water resources in the Senegal River Basin by the end of 21st century. Generally, a potential change of decreasing precipitation and increasing temperature are found. In addition, the potential water balance decreases northward. The bias correction was able to remove the systematic biases toward the low and high intensities of precipitation and temperature in the historical simulations, as seen in Haensler et al. (2013) and Muerth et al. (2012). This is a considerable added value. Thus, we conclude that the bias correction was realistic in reproducing the spatial and temporal variability of the present day climate.

Furthermore it does not substantially impact the spatial pattern of the climate change signal over the SRB. However, differences are noticed in term of magnitude between corrected and uncorrected data, and a modification of the climate change signal is noticeable in some months and localities. These results can help to better understand the issues of rainfall and temperature on crop productivity, water supply, risk of flood and drought, and ecosystems resilience to climate change.

Based on these promising findings, the bias corrected data will be used as input in hydrological model to investigate if there is an added value of the bias correction to give a more accurate simulation of present day river regimes, and its potential impact on the projected hydrological variables (such as runoff, soil moisture, evapotranspiration); this is tackled in Chapter 5.
Chapter 5

5. Modeling the impact of climate change on water resources in the Senegal River Basin

5.1 Introduction
Climate change is likely to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions (e.g. Sahel) by the end of this century under the RCP8.5 scenario (IPCC PART-A, 2014). In addition to global warming that highly affects evapotranspiration; changes in runoff and streamflows pattern are likely to occur over semi-arid regions (e.g. Sahel). Furthermore, the high variability of Sahel rainfall and its increasing population water demands will lead to an increase of its vulnerability to climate change. Then, the potential change of the hydrological cycle can potentially have substantial impacts on rainfed agricultural and energy sectors. These impacts have also affected the Senegal River Basin; its water resources have been seriously affected by the well known droughts since the years 70s as shown in Chapter2 (Figure 2.4). However, how climate change will affect the seasonal variability of streamflow and runoff over the basin is still unclear and poorly documented, particularly in its upper basin which generates 80% of the river flow. Then, in hydrological impact studies, climate model outputs are always used as hydrological model forcing to study the potential impact of climate change on runoff. Physically-based hydrological models may offer the best potential (Ruelland et al., 2012). Distributed and physically based models such as Land surface models simulate hydrological processes as well as biophysical and geochemical processes of the soil-plant-atmosphere system. The usability of conceptual model parameters that are determined under present day climate is dubious whether it will be valid throughout the 21st century under a changing climate (Hurkmans et al., 2010; Li et al., 2005). Moreover, empirical black box models which are similar to unit hydrograph methods use simple relationship between input (rainfall) and output (streamflow) and do not detail the internal processes. For these raisons, we use the Max Planck Institute for Meteorology-Hydrological Model (MPI-HM) which is a distributed physically-based model in order to assess the potential impacts of climate change on water resources in the Senegal River Basin. The model description is given is Chapter 2 (Section 2.4.2). We focus mainly in the Upper Senegal basin (USB) with its outlet at Bakel (reference gauged station) as it is shown in Figure 2.1. The WFDEI data are used during the procedure of parameters optimization to local conditions, and uncorrected and corrected
simulations from REMO are used to study the potential impact of climate change on the basin’s hydrology.

The structure of the present Chapter is organized as follows: The evaluation of the historical hydrological simulations with and without bias corrected input is given in Section 5.2. Section 5.3 deals with the results of the future hydrological runs. The main findings are discussed in Section 5.4. The Chapter ends with a short summary and conclusions Section.

5.2 Evaluation of MPI-HM simulations during the reference period with REMO input

5.2.1 Precipitation biases and PET changes
This section assesses mainly the biases and changes of precipitation that is one the most important climate forcing data of the MPI-HM model. Then, bias corrected and uncorrected simulations are compared in order to see how their different variations may affect the hydrological simulations. Figure 5.1 shows the precipitation biases for uncorrected and bias corrected data during the reference period.

![Bias corrected precipitation](image)

![Uncorrected precipitation](image)

**Figure 5.1:** Precipitation biases of bias corrected (top) and uncorrected (bottom) precipitation

The wet biases during the main rain season (Figure 5.1b) and dry biases during the post and pre-monsoon in the uncorrected data have been removed in the corrected data (Figure 5.1a).
Thus, the bias correction has significantly improved the monthly variations of precipitation. This result is similar to that found also in the other forcing data, i.e. temperature and potential evapotranspiration (not shown). As for the projected precipitation changes (Figure 5.2), no substantial change in rainfall occurs from November to March for all datasets in all scenarios.

**Figure 5.2:** Precipitation (top) and PET (bottom) changes of bias corrected and uncorrected simulations

However, a general decrease of precipitation is found in the summer period (particularly in RCP8.5). This decrease is higher in the uncorrected data than in the bias corrected data. The climate change signal exhibits the same tendency of decrease and increase of precipitation, except in September where a noticeable increase is found in the uncorrected data with RCP4.5. The bias correction tends to reduce the magnitude of the climate change signal of precipitation over the USB. These differences in magnitude may also affect the hydrological simulations by using these data as climate forcing. In addition, the PET is projected to increase in all months for all data (Figure 5.2) by the end of 21st century. Then, the decrease of precipitation combined with the increase of PET may likely to considerably affect the water resources in the USB.
5.2.2 Seasonal cycle of precipitation, runoff, soil moisture and evapotranspiration

The monthly variations of rainfall, soil moisture, runoff and actual evapotranspiration from bias corrected data are presented in Figure 5.3. At the beginning of the hydrological year (May), soil moisture and runoff are at their annual minimum while precipitation and evapotranspiration are increasing. This period is within the dry and hot season in which all first rains evaporate or infiltrate. After about one month soil moisture increased enough to result in the generation of runoff. Rainfall reaches its peak in August while soil moisture, evapotranspiration and runoff reach their peaks in September. The same variations have been noticed also in the uncorrected data (Figure 5.4). These variations correspond to our expectations even though we don’t validate them due to a lack of observed data.

![Figure 5.3: Averaged Rainfall, Runoff, Soil moisture, and Evapotranspiration over USB with BC data.](image)
Figure 5.4: Averaged Rainfall, Runoff, Soil moisture, and Evapotranspiration over USB with UC data

5.2.3 Relative contribution of drainage and surface runoff to total runoff

The contributions of drainage and surface runoff to the total runoff are shown in figures 5.5 and 5.6 for both corrected and uncorrected data respectively. The total runoff is obtained by the sum of drainage plus surface runoff.

Figure 5.5: Monthly variations of total runoff, drainage and surface runoff (SRO) with bias corrected input.
In both datasets, it is well noticed that during the period of low flows in the dry season (from December to May), the total runoff is essentially composed by drainage which account for 100%. In mid May (beginning of the rainy season in upstream) and in mid October (end of rainy season), the contributions of sub-surface and surface runoff are relatively equal. During the high flows period in the main rainy season, the surface runoff contributes to more than 80% in the total runoff. In this period, the baseflow is too slow due soil saturation that leads to fast surface runoff. Although both datasets show the same behaviour of these above hydrological variables, the uncorrected data largely overestimates the total runoff. The peak of the discharge in September for the uncorrected data is almost thrice that one of the bias corrected input.

The annual mean of ET, runoff and soil moisture is shown in figure 5.7. It is very noticeable a south-north gradient with the maxima of all variables localized toward the southern part of the basin. In this latter part of the basin, the bias corrected data exhibit the lowest values, compared to those uncorrected. Hence, higher amount of runoff is generated in the southern basin; lower contributions from the central basin and very small portion come from the northern basin. The major differences between both simulations and variables occur with runoff. This is due to the wet precipitation biases input which have great impact of the runoff simulations. Hence, runoff is more sensible to precipitation that ET and soil moisture although all of them follow the spatial pattern of rainfall over USB.
Figure 5.7: Annual mean of evapotranspiration, runoff and soil moisture during the reference period (1971-2000)

5.2.4 River discharge simulations during the present day climate

The MPI-HM river discharge simulations are evaluated by comparing simulated and observed hydrographs. The main goal of this section is to assess whether the bias corrected input enables a better reproduction of observed river regimes, and how the biases of climate forcing data affect simulated river discharge. In Figure 5.8a, the simulated mean river discharge is compared to observed mean discharge during the reference period (1971-2000) at the outlet of the USB (Bakel). This figure demonstrates a clear improvement of simulated discharge when using bias corrected input. The uncorrected data highly overestimate the monthly discharge. During the dry season (January to June), the corrected data tend to overestimate the low flow and then slightly underestimate the beginning of high flow (July-August).
Figure 5.8: Simulated and observed mean (a), 10th percentile (b) and 90th (c) percentile of river discharge at Bakel

The model largely overestimates also the extreme flows (Figure 5.8b and Figure 5.8c) particularly during the main rainy season with uncorrected climate forcing (blue curve). Moreover, using bias corrected input, the peak flow in September is well captured even though the model overestimates the low flows in the dry season (from December to June) as shown in Figure 5.8b.

It is clearly seen that the bias correction has considerably reduced the biases in the uncorrected data. The wet biases of precipitation (uncorrected data) also contribute to the overestimation of river discharge during the main rainy season. In agreement with the results of Graham et al. (2007), our results show that the magnitude of hydrological changes is highly affected by RCM biases, particularly the precipitation biases. For instance, these mean
Biases have led to very large overestimation of riverflow, emphasizing that the hydrological components are very sensitive to rainfall intensity.

Moreover, the observations are affected by flow regulation at the Manantali dam (upstream), which is not considered in the MPI-HM and might likely explain a part of the mismatch. The results show that the major differences of simulations occur during the high flow period with very huge values in the uncorrected data.

**5.2.5 Model performance assessment**

Table 5.1 summarizes the model performance evaluated by using the simulated mean monthly discharge. A Nash-Sutcliffe Efficiency coefficient of 0.92 is found between the simulated and the observed streamflow with bias corrected input. This high efficiency shows a good agreement between both datasets, indicating the chosen model combination (REMO + MPI-HM) is able to reasonably reproduce both the timing and magnitude of observed streamflows. Conversely to the corrected input, the efficiency is about -21.98 for the uncorrected input, showing how far the simulation deviates from the observation. Furthermore, the PBIAS of bias corrected input is 3.88%, which shows that the simulated discharge slightly deviate from those observed; by contrast to the uncorrected input where the PBIAS is up to 300% which depicts the huge overestimation of the model.

**Table 5.1: Model performance criteria**

<table>
<thead>
<tr>
<th>Performance criterion</th>
<th>Uncorrected input</th>
<th>Bias corrected input</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASH</td>
<td>-21.98</td>
<td>0.92</td>
</tr>
<tr>
<td>PBIAS (%)</td>
<td>300</td>
<td>3.88</td>
</tr>
</tbody>
</table>

Hence, in this evaluation part, the bias corrected input provides realistic river discharge simulations. Overall, bias correction is useful for a better representation of present day river discharge. Hence, bias correction method can help to reconstruct historical mean streamflows which are fundamental bases for future adaptations strategies planning, in African countries where observed data are sparse.

In the following section, the impacts of climate change on hydrological variables are presented.
5.3 Potential changes of hydrological variables with and without bias correction

This section focuses mainly on the potential changes of river discharge, runoff, and evapotranspiration, soil moisture by the end of 21st century (2071-2100) under both RCPs 4.5 and 8.5 GHGs emission scenario. In addition, the change of the projected signal from corrected and uncorrected input is considered in order to see if the bias correction alters the climate change signal.

5.3.1 Monthly changes of river discharge

The changes in river discharge at the upper basin outlet (Bakel) and its 10th and 90th percentiles changes are presented in figure 5.9. From all input data, a general decrease is found particularly in RCP8.5; only in August and September that an increase is found in RCP4.5. From the 10th to the 90th, a reduction of the magnitude of decrease is noticed, and by the same way an increase is found mainly in the peak flows period. The bias corrected input does not change substantially the signal of the mean discharge, and the low and high flows even though slight differences exist in term of magnitude.

![Mean monthly discharge change and percentiles (10th and 90th) river discharge changes](image)

**Figure 5.9:** Mean monthly discharge change and percentiles (10th and 90th) river discharge changes

5.3.2 Seasonal changes of runoff, evapotranspiration and soil moisture

Figure 5.10 displays the seasonal change of runoff from July to October. Considerable decrease of runoff is found in the majority of the basin where the decrease reaches -80 % in the eastern basin with RCP8.5. With this later scenario, the runoff decline is higher in the uncorrected data than in the bias corrected simulation. As with the stabilization scenario
(RCP4.5), it is noticeable also that runoff is likely to decrease in the USB, except localized parts such as the mountainous areas where slight increase is depicted. Additionally, the bias corrected and the uncorrected simulations present similar spatial pattern of the climate change signal in both scenarios. However, small differences exist in the magnitude of the projected signals of both simulations.

Figure 5.10: Seasonal changes of total runoff [UC: uncorrected, BC: bias corrected]

The seasonal change in actual evapotranspiration (ET) for both scenarios and from corrected as well as uncorrected bias data is displayed in Figure 5.15. Figure 5.15 shows a general decrease of ET, with largest decrease localised between 12°N to 17.5°N for both data and lowest decreases mainly south of 13°N. The maximum decrease reaches -40% in the northern basin for the RCP8.5, while the expected change in the RCP4.5 in this region does not exceed -10%. The decrease of ET can be explained by the decline of soil moisture content (see next section). Overall, the results show that the bias corrected and uncorrected data show a similar spatial pattern of the projected climate change signal, though the magnitude of changes are quite different.

The seasonal change of actual evapotranspiration presented in Figure 5.11 shows a decrease of ET from 12°N to 17.5°N for uncorrected and bias corrected data with RCP8.5 where the peak decrease reaches -40% in the northern basin in both data. As with RCP4.5, a small decrease (-10 to 0%) is found south of latitude 13°N for both datasets where the northern
basin may face a decrease of -10%. The decrease of ET can be explained by the decline of soil water content. Furthermore, no change is found in the southern basin for all data and scenarios. From these results, it is noticeable that the bias corrected data have the same spatial pattern of the projected climate change signal as the uncorrected data. However, slight differences occur in the magnitude of the signal that seems to be reduced by the bias correction.

Figure 5.11: Seasonal changes of Evapotranspiration [UC: uncorrected, BC: bias corrected]

Figure 5.12 displays the seasonal change of soil moisture. By the end of 21st century, the soil water content is projected to drastically decrease over the majority of the basin from the central to the northern part (-40 to -10%) in RCP8.5 for bias corrected and uncorrected data. The soil moisture decrease ranges from -20 to 10% in the moderate scenario (RCP4.5) for both simulations. This decrease is due to the decrease of precipitation and the increase of temperature. As seen previously with ET changes, similar spatial pattern is found in the climate change signal of soil moisture between the raw and corrected simulations. This shows that the projected signal is not altered by the bias correction.
5.3.3. Changes in the seasonal cycle of evapotranspiration, soil moisture, and runoff

The seasonal cycle changes of soil moisture, evapotranspiration and runoff are shown in Figure 5.13. Soil moisture and evapotranspiration are generally decreasing in all data and scenarios. The decrease is more pronounced with RCP8.5 than with RCP4.5. The maximum ET changes are reached in June and November (-0.8 mm/day) for all data. In case of soil moisture decrease, the peaks are reached in September with RCP4.5 (-50 mm) and RCP8.5 (-135mm) for uncorrected and bias corrected simulations. Hence, the climate change signal within the same scenario has a similar tendency in both data. As for runoff, the main changes (decreases) occur during the period of high flows (JASO) for all simulations and scenarios. In the uncorrected data, the changes are higher in RCP8.5 (-0.8 mm/day) than in the corrected data (-0.2mm/day). With RCP4.5 scenario, the potential change of runoff signal with bias corrected input is very small by comparison to the runoff signal with uncorrected climate input. It is noticeable with this later scenario that the uncorrected data depict two noticeable runoff peaks in August (increase) and September (decrease); these peaks are not found with corrected input. This later finding shows that the bias correction may change the projected runoff signal in some months.
Figure 5.13: Climatological changes of evapotranspiration, runoff, and soil moisture [UC: uncorrected, BC: bias corrected]

5.3.4. Annual changes of available water resources and CV of ET, runoff and soil moisture

Figure 5.14 clearly shows that by the end of 21st century, available water resources are likely to decrease drastically in the majority of the basin, particularly under RCP8.5 (where the peak reaches -100%). This decrease is enhanced northward and becomes more acute in the most northeast part. Consistent with results mentioned above, no change of available water resources is found around the Guinean highlands, except for the uncorrected input under RCP4.5. In some localized parts of the basin, slight increases are found particularly in the uncorrected data (RCP4.5). All datasets and both scenarios exhibit similar spatial pattern. The decrease of available water resources follows the change pattern of runoff which is affected by the decrease of precipitation and the increase of potential evapotranspiration.
The annual coefficient of variation of ET, runoff and soil moisture is displayed in Figure 5.15. All of these above variables depict an important south-north gradient of CV where minima are found in the southern basin while the maxima are found in the northern basin. The CV of soil moisture and ET are similar and it ranges from 5% (south) to 45% (north). However, the CV of runoff is higher than all the others variables, particularly in the northern basin (more than 100%). The high variability of runoff is mainly due to the fluctuations of precipitation. Note that in the previous chapter, we found that precipitation is more variable in the northern basin, emphasizing then runoff is very sensitive to precipitation variations.

**Figure 5.14**: Available water resources changes [UC: uncorrected, BC: bias corrected]
Figure 5.15: Annual CV of ET, runoff and soil moisture [UC: uncorrected, BC: bias corrected]

5.3.5. Runoff coefficients and its changes

The runoff coefficients were computed in order to estimate the rainfall quantity (portion) that becomes runoff. The coefficients of the uncorrected input are almost thrice the coefficients of bias corrected input as shown in Figure 5.16. Small runoff coefficients are found with corrected input (up to 0.1); this means only 10% of the rainfall is running off. This low runoff coefficients can likely be explained by a higher infiltration in the southern and well vegetated basin in one hand, and small rainfall amounts in the majority of the basin which is permeable and flatter.
Furthermore, slight changes of the runoff coefficients are likely to occur mainly during the high flows period (JASO). The uncorrected input exhibit higher changes when compared to bias corrected input with a clear reduction in RCP8.5. However, slight increase of runoff coefficients is found with RCP4.5 from July to September, though a deviation is noticed between the two signals in August.

**Figure 5.16**: Seasonal cycle of runoff coefficients (top) and its absolute changes (bottom)
5.3.6 Correlations analysis and yearly variations of rainfall and river discharge

Correlation between runoff changes and other hydrological variables changes (such as soil moisture, PET, precipitation and ET) is displayed in Figure 5.17. This was done in order to investigate the influence of such variables changes on runoff changes.

During the dry season, soil moisture and actual evapotranspiration changes are positively correlated (>0.8) to runoff changes; these correlations decrease in the main rainy season (from June to September) to values around zero. These situations can be explained by the fact that in the dry period, the runoff is mainly composed by drainage which is strongly determined by the available soil water content. As evapotranspiration depends also in the availability of water content as like runoff, these two variables are highly correlated.

Conversely to ET, the PET changes are mostly negatively correlated to runoff changes because PET is more influenced by temperature. High temperature and drier moisture conditions lead to negative correlation with soil moisture and runoff. While the southern part reaches its rainfall peaks, the northern part remains still dry (majority of the basin), then the average correlation is more affected by the dry part of the basin (bigger) in case of the precipitation.
The change in runoff is highly affected by the change of soil moisture. In addition, the bias correction does not change considerably the signal of correlations changes over the Senegal upper basin for both data sets and scenarios.

Figure 5.18 exhibits 10 years running mean rainfall averaged over USB and 10 years running mean of river discharge at the outlet Bakel. As it was shown earlier (e.g. see section 5.2.1), the uncorrected simulations of rainfall over USB are higher than that bias corrected, and the simulated river discharge using corrected climate input has the lower interannual variability. Moreover, it is also noticed a decadal variability of rainfall and river discharge. For the extreme scenario (RCP8.5), only the decade (2021-2031) depicts a clear increase in both variables while the others decades show a decrease of rainfall and river discharge until the end of 21st century. As for the RCP4.5, slight increase is found in the decades (2011-2021), (2041-2051) and the last decade of the century for precipitation and streamflow. Therefore, the basin is likely to face considerable variations of rainfall and streamflow.

Figure 5.18: 10 years running mean of rainfall over USB (Left) and discharge at the outlet Bakel (Right) [UC: uncorrected, BC: bias corrected]

5.4 Discussion

The delay peak of rainfall (in August) with regard to the peaks of soil moisture, evapotranspiration and runoff (in September) found in figures 5.3 can be explained by the slow process of soil saturation in this semi arid region (majority of the basin). The thick vegetation in upstream where almost the totality of flow is generated and the water travel time to downstream, could also contribute to the delay between peaks. The long dry season with very warm temperature affect highly the soil water content. The evapotranspiration is less variable than the others parameters and it is moisture limited during the dry season and energy during the wet season. Soil moisture, evapotranspiration and runoff (Figure 5.7)
follow similar spatial pattern as the well known south-north gradient of rainfall. As for the evaluation of the MPI-HM river discharge simulations that are compared to observed hydrographs (Figure 5.8), a better reproduction of observed river regimes is found by the bias corrected input. The huge biases from the uncorrected data input are related to the wet biases of uncorrected precipitation (as seen in section 5.2.1). In addition, an underestimation of ET could also contribute to the overestimation of river discharge during the main rainy season. The large biases from the uncorrected data can be related also to the strong non-linearity of terrestrial hydrology which may well be that small bias instationarities in the meteorological forcing may be amplified to large bias instationarities of terrestrial hydrological variables (Ehret et al., 2012). This means that small deviations in the input data may lead to large difference in the behaviour of output which suggests a propagation of input biases into the hydrological simulations. The overestimation during the dry season (Figure 5.8) may be due to the limitation of the hydrology model in properly handling extreme dry climate. During the evaluation part, the bias correction experiment generally reproduces faithfully the river regimes.

For the projected changes of river discharge (Figure 5.9), the general decrease found with RCP8.5 is consistent with its main driver (precipitation). However, the slight increase of streamflow found in August and September can be explained by an increase of precipitation resulting from more atmospheric cooling due to high evaporation and an increase of the atmospheric water holding capacity. The seasonal decrease of runoff (Figure 5.10) found over the basin in all scenarios and data is more related to the decline of precipitation and higher evaporation. The seasonal decrease of precipitation has affected negatively seasonal evapotranspiration (Figure 5.11) and seasonal soil moisture (Figure 5.12). Furthermore, this decrease is also found in the annual cycle of runoff, soil moisture and evapotranspiration (Figure 5.13). Hence, the decrease of rainfall diminishes soil water content, which in turn reduces water loss through evaporation. Then, the weakness of evaporative fluxes decreases the atmospheric moisture for cloud generation and precipitation. The available water resources (Figure 5.14) follow the decrease of runoff. However, the bias correction can alter the climate change signal of available water resources in some specific localities, even though the spatial pattern is generally preserved.

Lower runoff coefficients (Figure 5.16) are found, suggesting the high sensitiveness of the basin to precipitation variations. Finally, in all scenarios, the climate change signal has the same interannual variations (Figure 5.18), and the fluctuations of rainfall are similar to river discharge fluctuations. This later result is consistent with our early findings, where we highlighted that the basin is extremely sensitive to precipitation changes. Another interesting
point found is the bias correction affects mainly the magnitude of the projected signals, but do not alter (change) the sign of the change generally.

5.5 Summary and conclusions

An assessment of climate change impacts on water resources in the USB has been carried out. Despite considerable progress in recent years, output of both global and regional circulation models is still afflicted with biases to a degree that precludes its direct use, especially in climate change impact studies (Ehret et al. 2012). Then, to cope with this issue, bias correction is often used in hydrological impact studies although for specific locations and seasons it may affect the climate change signal (Hagemann et al. 2011). For these reasons, bias corrected and uncorrected climate data from the regional climate model REMO were used as input for the MPI-HM model to simulate river discharge, runoff, soil moisture and evapotranspiration. This is in agreement with the work of (Muerth et al. 2013) who recommended presenting both results with and without bias correction in situations where only a few climate simulations are used in case that the climate change signals of outliers can be modified by bias correction. The global MPI-HM model parameters were optimized for local conditions of the USB in order to better capture the river flow variations. The results during the historical period (1971-2000) show that the bias corrected input give better representation of the river flow regimes at the outlet of the upper basin (Bakel) in the seasonal cycle. The same applies to the simulation of low flows (10th percentile) and high flows (90th percentile), thereby showing a slight overestimation of stream flow during the dry season. This can be related to the influence of other global parameters for which a tuning to local conditions might be necessary, or by missing processes such as the representation of soil crusts or human impacts. It was found also that the rainfall peak occurs one month (August) before the peaks of soil moisture, runoff and evapotranspiration (in September). The results from uncorrected climate input are largely overestimated, indicating then the advantage of the bias correction of temperature and precipitation for a better representation of the river flows.

Then, by the end of 21st century (2071-2100) under the (RCPs) 4.5 and 8.5, a general decrease of river discharge, runoff, actual evapotranspiration, soil moisture is projected even though there are some localized increases in some parts of the basin (particularly in Guinean highlands) with the uncorrected simulations. This decrease is mainly related to the decline of precipitation. The most extremes changes of soil moisture, ET, and runoff are likely to occur in the northern basin which is the driest and hottest part of the USB. Additionally, the available water resources exhibit substantial decrease (from -100% to -25%) in the majority of the basin for all data, except the Guinean highlands where an increase (50%) is found under RCP4.5 in
the uncorrected data. Additionally, runoff is highly variable when compared to rainfall, soil moisture and evapotranspiration particularly in the drier northern basin. The small runoff coefficients of the basin have shown that a lower portion of the rainfall becomes runoff and also the sensitiveness to precipitation fluctuations. Furthermore, the runoff changes are considerably influenced by soil moisture changes as it is found in the correlation between them. Similar decadal variability was found between rainfall and river discharge with higher variability in the uncorrected data.

The comparison of results from uncorrected and bias corrected input (in all variables) demonstrates that the bias correction does not substantially change the signal of future changes of hydrological variables for both scenarios over the Upper Senegal Basin even though there are slight differences in term of magnitude of the projected signal in some part of the basin.

The projected changes over the USB are associated with various sources of uncertainties, especially those arising from the choice of the various models used in the climate model – hydrology model modeling chain. These comprise the driving GCM, MPI-ESM-LR, the RCM REMO used for downscaling and the hydrological model MPI-HM. In addition, the effect of the bias correction technique is another source of uncertainty. These uncertainties need to be taken into account when interpreting the results. To reduce these uncertainties, it would be desirable to conduct analogous hydrological simulations with different components of the modeling chain, i.e. using different RCM outputs, different bias correction techniques, and different hydrological models, which would enable uncertainty analyses in future investigations.
Chapter 6

6. Concluding remarks

6.1 Summary

In this thesis a statistical bias correction was applied to the regional climate model REMO simulations in order to assess the climate change impact on the climate and the hydrology of the Senegal River Basin. Within this work, one regional climate simulation was taken in the present day climate and two scenarios (RCP4.5 and RCP8.5) simulations were considered in the future. Uncorrected and bias corrected data were used to evaluate the ability of the bias correction to simulate the present day climate and to assess the projected climate change signals. Then, bias corrected and uncorrected data were used also as input of the Max-Planck Institute for Meteorology Hydrological Model to investigate the potential impact of climate change on water resources over the Upper Senegal Basin.

On the basis of the application of the bias correction, it was possible to analyze its impact on the predominant climatic features of the Senegal River Basin and on key hydrological variables (e.g. precipitation, temperature, runoff, soil moisture, evapotranspiration). The analyses were based on seasonal and interannual time scales between corrected and non-corrected simulations.

In the introductory Chapter of this present thesis, several key research questions and objectives have been outlined. Then, the major findings within this work can be concluded with respect to these focal points.

In Chapter 3, it was shown that REMO reproduces fairly the spatial patterns and temporal signals of temperature and precipitation over the Senegal River Basin. However, wet and dry biases were found in precipitation fields, warm and cold biases were exhibited also in temperature data that may probably affect hydrological simulations. The seasonal pattern (JAS) showed mainly wet biases of rainfall; these biases were more amplified in the southern basin that depicted also cold biases. Therefore, it was concluded that REMO output needed to be corrected for suitable climate impact studies over the basin. Furthermore, the WDFEI data matched well the stations during its validation. Thus, the WFDEI datasets were taken as observational reference data to bias correct the regional climate model output over SRB.

The impact of a statistical bias correction technique on REMO simulations over the Senegal River Basin was presented in Chapter 4. Based on the evaluation of model historical runs...
with and without bias correction, the previously existing biases underlined in Chapter 3 were substantially reduced. The magnitude and the timing of observed climate were successfully reproduced by the bias corrected data. This later finding shows the added value of bias correction for a better representation of the present day climate. As for the projected climate change signal, precipitation is likely to decrease in the majority of the basin; by contrast to temperature which generally increases. Additionally, it was noticeable that the changes in the uncorrected simulations were slightly higher than those in the bias corrected even though similar spatial patterns were found between both datasets. The severe changes were found with the extreme scenario RCP8.5. The northern basin is supposed to face the most drastic changes by the end of 21st century. Moreover, the results show in general a decrease of consecutive wet days (CWD) and an increase in the length of consecutive dry days (CDD) although slight increase of heavy rainfall is found particularly in the northern basin with similar spatial patterns of both data. Higher decadal variability is expected for extreme wet days and also for maximum 5-day precipitation towards the century. The global warming of mean temperature seemed to be more related to faster increase of minimum temperature compared to maximum temperature with strong interannual variability. The projected climate change signal is not substantially altered by the bias correction even though differences in term of magnitude exit between both datasets.

The potential impact of climate change on water resources in the Upper Senegal Basin was presented in Chapter 5. Raw and corrected climate data were used as input of the Max-Planck Institute for Meteorology-Hydrological Model. The model successfully reproduced the observed flow regimes by using bias corrected data as input. As for uncorrected forcing, huge overestimation of streamflow was depicted by the model for mean, low and high flows. This confirms again the usefulness of bias correction for a better representation of present day river discharge, so that it can help to reconstruct historical mean streamflows in areas where data are very sparse. In addition, runoff depicts the higher variability with regards to evapotranspiration and soil moisture particularly in the southern basin. Very low runoff coefficients were found in the basin that shows its sensitiveness to precipitation fluctuations. As for the projected potential changes of river discharge, soil moisture, runoff and evapotranspiration, the basin is likely to experience considerable decrease in both data and scenarios. The decrease in these key variables is confirmed by the probable decline of available water resources that was well noticed. In general the decrease of water resources is more acute in the northern basin. However, the climate change signal was slightly changed in some months and localized parts of the basin. As well as the interannual variability,
rainfall and river discharge exhibited similar temporal variations towards the century with an important decadal variability. The bias corrected signal was lower than the uncorrected one. In summary this thesis showed that the bias corrected REMO simulations ably represent the basin climate features and river flow regimes, and therefore proved to be used for local impact studies over the Senegal River Basin. A clear added value in the present day climate of the seasonal and annual cycle of hydro-climatic variables was found with bias corrected simulations. This result confirms two of our hypotheses about the usefulness of the bias correction during the historical period in reproducing well the variations of precipitation, temperature and river regimes with corrected data. In the future, climate change is likely to impact considerably the basin’s climate (with substantial changes of precipitation and temperature) and also the availability of water resources (with higher decrease of soil moisture, actual evapotranspiration and runoff). These latest findings prove our two other hypotheses where we assumed that climate change will highly affect both the climate and the hydrology of the basin. Thus, all our hypotheses have been proved.

The impact of the bias correction on the projected climate change signal, affects mainly the magnitude of the signal rather than its direction of change although some modification may occur in particular months and localities. Therefore, it has to be kept in mind that our results have been based in one climate model only; they should be taken with caution.

6.2 Outlook

As our results have been based in one climate model only even though this does not impact the findings of this study with regard to the influence of the bias correction, the magnitude of projected changes presented in this study should be taken with caution. Therefore, others RCM models in the CORDEX framework and bias correction techniques are needed for further investigations in order to take into account the climate models and statistical post-processing uncertainties. Another alternative is to improve the spatial resolution of RCM simulations to very high resolution (e.g. 12Km) or to use multi-model ensemble climate projections. Currently, a team of climate modelers in Germany and West Africa is developing a regional climate modeling system (“dynamical downscaling” of global modeling results) specifically for Northwest Africa, and we hope to use that data for impact studies. Furthermore, a deep investigation on the physical mechanisms that lead to changes in extreme climate over the region is also planned.

In case of the hydrological modelling, general improvements will be needed such as implementation of soil crusting and a deeper soil layer into the MPI-HM which might result in better representation of the hydrological regimes. The implementation of a deeper layer
will allow more water to infiltrate into the soil, and increase the bucket of drainage. This will reduce the surface runoff that dominates the flows during the high flows period where the overestimation mainly occurs. As for the soil crusting, it can take into account the quick run due to rainstorm in very dry conditions.

We recommend also including the impacts of human activities and land uses changes on river flow for further investigations. The implementations of human activities such as the Manantali dam where lot of water evaporate from its reservoir, will take into account the water losses from this dam, the denaturalized flow and reduce also the overestimation of river flow because this evaporation was not included in the model. In this semi-arid region, the degradation of the natural vegetation for farming, agricultural, and urban purposes, reduce infiltration and soil holding capacity. These situations are likely to be exacerbated in the future and can enhance runoff. Then, taking into account to this could to better represent the flow regimes.

Due to uncertainties in hydrological model, different hydrological models are required for further investigation. Classical uncertainty analysis such the generalized likelihood uncertainties estimation (GLUE) can be used for uncertainties analyses for those uncertainties related to model parameterization, model calibration, and model validation.

The severe droughts during the 1970s have significantly impacted the water resources in the Senegal River Basin. This decline has augmented human interference such as dam building with hydropower generation, increased irrigation and agriculture and built up of industries. Though this human interference is much less in magnitude and duration compared with many world rivers, these activities have affected water quality by an increase of soil erosion, increased waste discharge and eutrophication by fertilizers. Nowadays, the Senegal River is additionally threatened by chemical and biological pollution related to the release of wastewater and pesticides. Very few studies have addressed the potential impacts of climate change on surface water quality and also the relationships of hydro-climatic variables to surface water quality. Then, in the future, we expect to investigate on such impacts and relationships in the Senegal River. A high frequency of data collection will be needed to better understand the magnitude and timing of nutrients concentrations and the source of cycling organic matter.

Most of above mentioned perspectives depend mainly on the availability of data. We hope that within the coming years it should be possible to tackle all listed above view the great efforts that WASCAL is doing in technological development with regard to regional climate modeling and observational networks. As for the sampling, funding is required for an intensive data collection and laboratory analyses.
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C. Annexes

C.1 Annex1: Conferences


Mbaye et al. (2015c): Assessment of Climate change impact on water resources in the Senegal River Basin. Our Common Future under Climate Change, 7-10 July 2015, Paris(Poster presentation)

C.2 Annexe2: PUBLICATIONS


Mbaye et al. :Climate change signals over Senegal River Basin using five Regional Climate Models of the CORDEX Africa simulations (in preparation)