Climate Change May Result in More Water Availability in Parts of the African Sahel

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Abstract. The African Sahel is known for its climate variability that often translates into recurrent droughts. Rainfall has drastically decreased substantially across the Sahel from the 1950s until at least the late 1980s. It is unclear from the literature and from the fifth IPCC assessment report whether the trend in annual rainfall in the next decades would be decreasing as observed throughout the 20^{th} century or increasing as suggested by a significant number of climate models. There is however a low to medium confidence that extreme rainfalls would increase. The objective of this paper is to demonstrate that both possibilities (an increase or a decrease in rainfall in the future) may results in more opportunities to mobilize water for populations in the Sahel. To demonstrate that, the ability of 20 regional climate models is evaluated based on their ability to reproduce key parameters of the rainy season in Niger, West Africa. The outputs of the 10 best models are then downscaled at 52 climate stations in the country to generate precipitation projections up to year 2100. Results show that a wetter climate is more likely than a drier climate at horizons 2021–2050, 2051–2075 and 2071–2100 compared to the 1979–2014 period; The paper also examines the so-called 'Sahelian Paradox', an observed counter-intuitive phenomena where decrease in rainfall resulted in a higher surface runoff, pointing to opportunities for water harvesting in the eventuality of a drier climate.

Keywords: Climate change · Rainfall · General circulation models
Regional climate models · Runoff · Sahelian Paradox

1 Introduction

The African Sahel is well known for its rainfall variability which results in recurrent droughts and food insecurity and, from time to time, humanitarian crises. The entire region has the scares of persistent and severe drought episodes that occurred in the 70s and the 80s, following a very wet period in the 50s and the

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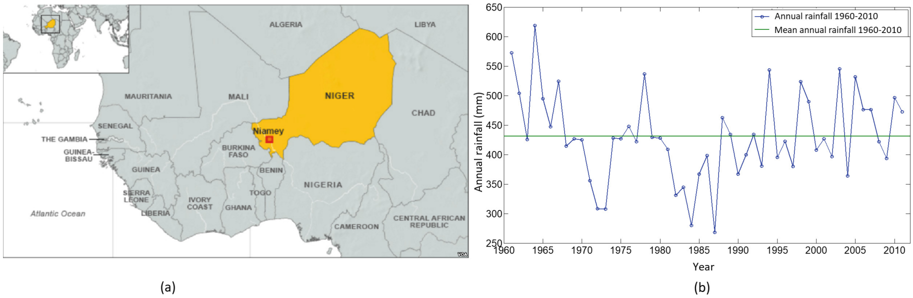


Fig. 1. Localisation of the Niger republic (a) and annual precipitation in Niger from 1960 to 2010 (b)

60s. The Niger republic (Fig. 1, panel a) is a landlocked country of 1,267,000 km^2 which has been struggling to achieve food self-sufficiency.

The vast majority of the population rely on rainfed agriculture for their subsistence, without any water storage infrastructure, hence their vulnerability to rainfall anomalies. The discharge of the only major river flowing through the country (the Niger river) has decreased drastically as result of lower rainfall in the watershed, but also because of the construction of large dams and irrigation schemes upstream (Fig. 1, panel b). The flow of the Niger river is reported to be 34% lower at Niamey in the 1970–1989 period compared to the 1950–1969 period [9]. Surprisingly, according to several authors [e.g. 3], surface runoff coefficients and stream flows have increased in most Sahelian areas because of land use change and the rise of the water table resulting from an increased infiltration. The increase in runoff despite the decrease in rainfall is called the *'Sahelian Paradox'* is an example of a counter-intuitive impact of a change in climate normal: the drought had at least one positive impact: it actually improved the opportunities to capture runoff in surface water reservoirs. On the other hands, a majority of global circulation models from the CMIP5 experiment suggest a wetter climate for the Sahel, with a few ones pointing to a dryer climate.

The objective of this paper is to examine past and future trends in precipitation and runoff in the Niger republic and assess how these trends may affect water availability within the country in the future. First, trends in rainfall and runoff are examined in a small watershed in central Niger to highlight the Sahelian Paradox. A rainfall runoff model is afterward developed and calibrated on the watershed. The outputs of an ensemble of 10 regional climate models of the CORDEX experiment were bias-corrected and fed into the rainfall runoff model to obtain a streamflow ensemble.

2 Materials and Methods

2.1 Study Area

The Study area is the Maggia river watershed located in the center south of the Niger republic. The watershed (Fig. 2) has an area of 2238 km^2 and has an

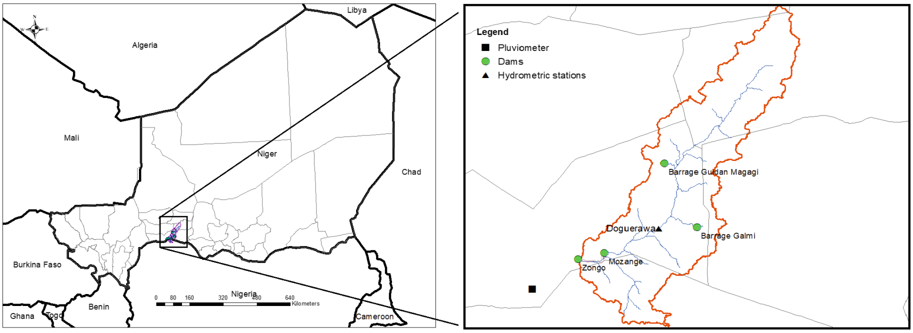


Fig. 2. Localisation of the Maggia river watershed

annual average precipitation which varies from 400 mm in dry years to 850 mm in wet years. The precipitation is concentrated in a 4 month rainy season (June to September) while the rest of the year is dry. The closest rainfall measurement station is that of Birinin'Konni while the only operational hydrometric station is that of Doguerawa, which was in operation between 1954 and 1979, and between 2010 and 2016. Four small dams on the watershed with capacity going from 1.5 millions m^3 to 30 millions m^3 were built in the 80s on the river network to insure irrigation in both the rainy season and part of the dry season. The filling of the dam and the success of irrigation in the dry season depends of the annual precipitation on the watersheds, and it is common for the area to experience crop production losses due to insufficient rainfall and river flows. One interesting feature in the watershed is the relationship between precipitation and streamflow. The time series of annual precipitation at Birnin'Konni between 1954 and 2014 is superimposed on Fig. 3 with the time series of annual streamflow at the Doguerawa station for the same period. While precipitation has been decreasing between 1950 and 1980, recorded streamflow kept increasing in a counterintuitive manner. The increase in runoff despite the decrease in precipitation has been documented in several other locations in the Sahel [3, 10]. This phenomenon, mainly attributed to land use changes, is called the 'Sahelian Paradox.' The prolonged drought in the Sahel had at least one positive impact: it actually improved the opportunities to capture runoff in surface water reservoirs.

2.2 Climate Change Projections in the Study Area

According to the International Panel on Climate Change [6], projected rainfall change over sub-Saharan Africa in the mid- and late 21st century is uncertain as the ensemble of climate models used for the assessment disagree in the direction of change over many areas in the region [8]. CMIP5 is an Intercomparison experiment that studies the strength and weaknesses of all major coupled atmosphere-ocean general circulation models. The outputs of CMIP5 were extensively used in the preparation of the fifth IPCC assessment report [6]. The CMIP5 multi-model average suggests either a slight increase in precipitation, or a strong agreement

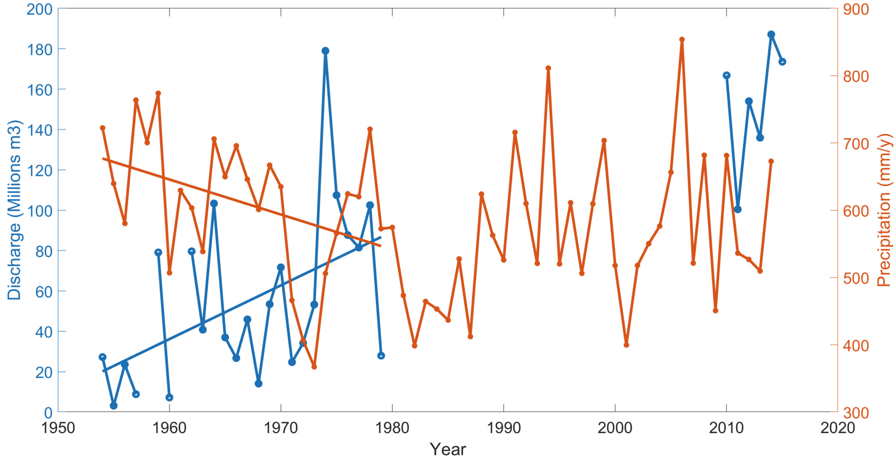


Fig. 3. Time series of annual precipitation at Birnin'Konni and annual runoff at Doguerawa, 1954–2014. The straight lines represent the trend in precipitation and runoff between 1954 and 1979 and illustrate the so-called 'sahelian paradox'

about a wetter future in most of the country in both periods, with a few spots where model prediction diverge. There is therefore a significant possibility that the country experiences a wetter climate in the coming decades, although the opposite is possible. One criticism often heard about general circulation models is that their spatial resolution is too low to describe the features of regional climates.

Dynamical or statistical downscaling is often used to post-process the outputs of general circulation models to reduce the bias due to the coarse spatial scale and inevitable simplifications in the physical processes description in the model algorithms. The CORDEX [COoRdinated Downscaling Experiment: 5] aims to simultaneously evaluate global climate models and produce climate projections for use in impact and adaptation studies, mainly through dynamical downscaling. To corroborate the projections of general circulation models, a set of 40 regional climate models outputs (20 different climate models listed in Table 1, two RCP scenarios: RCP4.5 and RCP8.5) were obtained from the CORDEX team.

The RCMs were evaluated on their ability to reproduce the following key rainy season characteristics in Niger: (a) start of the rainy season; (b) end of the rainy season; (c) length of the rainy season; (d) average annual rainfall; (e) time distribution of daily rainfall. At the end of the intercomparison, the following 10 models (in order of decreasing performance) were retained:

1. REMO2009-v1 IPSL-IPSL-CM5A-LR
2. RCA4-v1 IPSL-IPSL-CM5A-MR
3. REMO2009-v1 ICHEC-EC-EARTH
4. RCA4-v1 CNRM-CERFACS-CNRM-CM5
5. WRF331-v1 NCC-NorESM1-M

Table 1. List of RCMs used in the study

MODEL	CANRCM4-CanESM2	CCLM-4-8-17-IHEC-EC-EARTH	CCLM-4-8-17-OHC-HadGEM2-ESM	CCLM-4-8-17-MPI-M-MPI-ESM-LR4-v1	HIRHAM5-v1-NCC-NorESM1-M	RACMO22T-IHEC-EC-EARTH	RCA4-v1-CCMA-CanESM2	RCA4-v1-CNRM-CERFACS-CNRN-CM5	RCA4-v1-CSIRO-QCCCE-CSIRO-MK3-6-0	RCA4-v1-IHEC-EC-EARTH
RCM	CANRCM4	CCLM-4-8-17	CCLM-4-8-17	CCLM-4-8-17	HIRHAM5-v1	RACMO22T	RCA4-v1	RCA4-v1	RCA4-v1	RCA4-v1
INSTITUTION	CCCma (Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada)	Climate Limited-area Modelling Community (CLM-Community)	Climate Limited-area Modelling Community (CLM-Community)	Climate Limited-area Modelling Community (CLM-Community)	Danish Meteorological Institute	Royal Netherlands Meteorological Institute	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre
GCM	CanESM2	ICHEC-EC-EARTH	MOHC-HadGEM2-ES	MPI-M-MPI-ESM-LR	NCC-NorESM1-M	ICHEC-EC-EARTH	CCCma-CanESM2	CNRM-CERFACS-CNRM-CM5	CSIRO-QCCCE-CSIRO-Mk3-6-0	ICHEC-EC-EARTH

MODEL	IPSL-IPSL-CM5A-MR-CanESM2	MIROC-MIROC5-ICHEC-EC-EARTH	MOHC-HadGEM2-ES-MOHC-HadGEM2-ES	MPI-M-MPI-ESM-LR-MPI-M-MPI-ESM-LR	NCC-NorESM1-M-NCC-NorESM1-M	NOAA-GFDL-GFDL-ESM2M-ICHEC-EC-EARTH	ICHEC-EC-EARTH-CCCma-CanESM2	IPSL-IPSL-CM5A-LR-CNRM-CERFACS-CNRM-CM5	MOHC-HadGEM2-ES-CSIRO-QCCCE-CSIRO-Mk3-6-0	NCC-NorESM1-M-ICHEC-EC-EARTH
RCM	RCA4-v1	RCA4-v1	RCA4-v1	RCA4-v1	RCA4-v1	RCA4-v1	REMO2009-v1	REMO2009-v1	REMO2009-v1	WRF331-v1
INSTITUTION	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre	Swedish Meteorological and Hydrological Institute, Rossby Centre	Helmholtz-Zentrum Geesthacht, Climate Service Center, Max Planck Institute for Meteorology	Helmholtz-Zentrum Geesthacht, Climate Service Center Germany	Helmholtz-Zentrum Geesthacht, Climate Service Center Germany	Uni Research and the Bjerknes Centre for Climate Research
GCM	IPSL-IPSL-CM5A-MR	MIROC-MIROC5	MOHC-HadGEM2-ES	MPI-M-MPI-ESM-LR	NCC-NorESM1-M	NOAA-GFDL-GFDL-ESM2M	ICHEC-EC-EARTH	IPSL-IPSL-CM5A-LR	MOHC-HadGEM2-ES	NCC-NorESM1-M

6. RCA4-v1 MPI-M-MPI-ESM-LR
7. RCA4-v1 MIROC-MIROC5
8. CCLM-4-8-17 MPI-M-MPI-ESM-LR
9. RCA4-v1 CCCma-CanESM2
10. RCA4-v1 NOAA-GFDL-GFDL-ESM2M.

The outputs of the best models were further statistically downscaled at 53 cities across the country, using a quantile matching algorithm. The minimum, median and maximum percent change in precipitation were calculated at each of the cities over the 2021–2050, 2052–2075,2076–2100 periods, then linearly interpolated to create maps of expected changes in precipitation over the country. These changes are presented in Figs. 4 (RCP4.5) and 5 (RCP8.5).

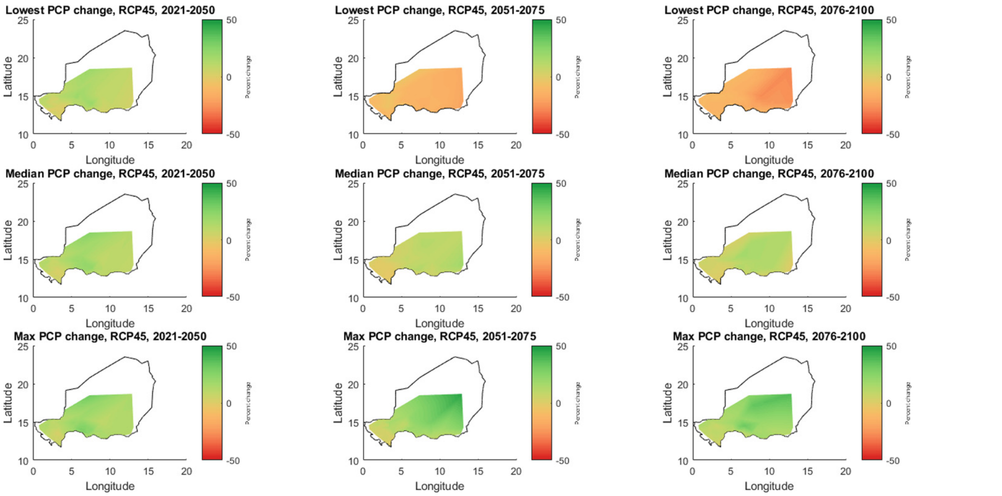


Fig. 4. Projected minimum, median and maximum change in precipitation over Niger under RCP4.5, for the 2021–2050, 2051–2075, 2076–2100 periods

2.3 Hydrological Modelling

In order to further understand the impacts of climate change on the hydrology of the Maggia river, a SWAT [Soil and Water Assessment Tool: 1] model of the watershed was developed. SWAT is a popular semi-distributed rainfall model commonly used for regional scale hydro-ecological modeling. The model was set-up with the following data:

1. Digital elevation model: Shuttle Radar Topography Mission [7].
2. Land use maps: Global Land Cover Facility [2].
3. Soil maps: Food and Agricultural Organization of the United Nations Organization for Education, Science and Culture [4].

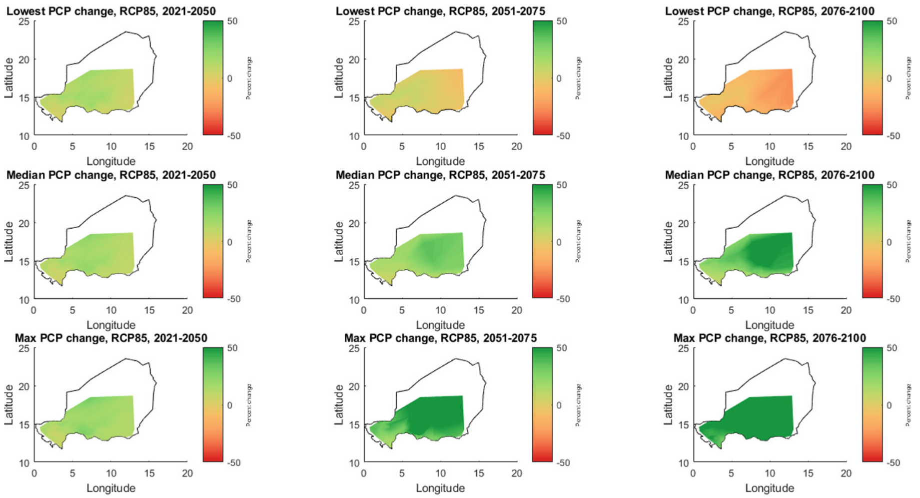


Fig. 5. Projected minimum, median and maximum change in precipitation over Niger under RCP8.5, for the 2021–2050, 2051–2075, 2076–2100 periods

4. Climate data: WATCH-Forcing-Data-ERA-Interim [11].
5. Streamflow data: recorded streamflow data at the Doguerawa hydrometric station.

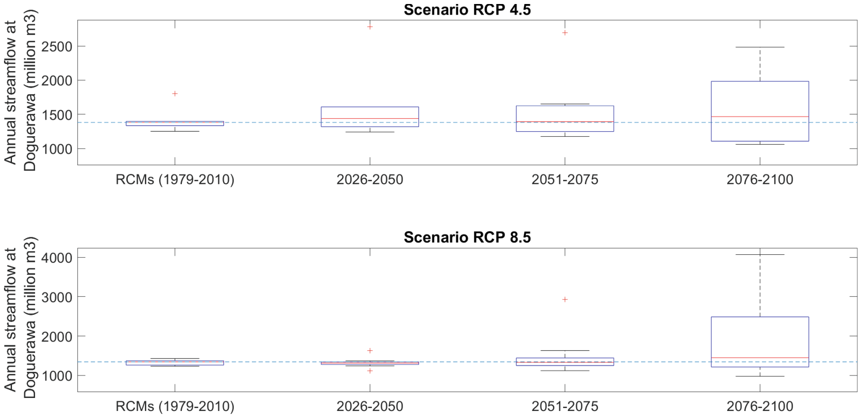
The SWAT model was calibrated using the most recent streamflow observations (2010–2016) to better represent the current state of the watershed. Given the short length of the observed streamflow time series, the model was not validated. The fit between the observed and simulated time series was evaluated using the Nash Suttcliffe model efficiency coefficient E:

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_t^m - Q_t^0)^2}{\sum_{t=1}^{T}(Q_t^0 - \bar{Q}_o)^2} \qquad (1)$$

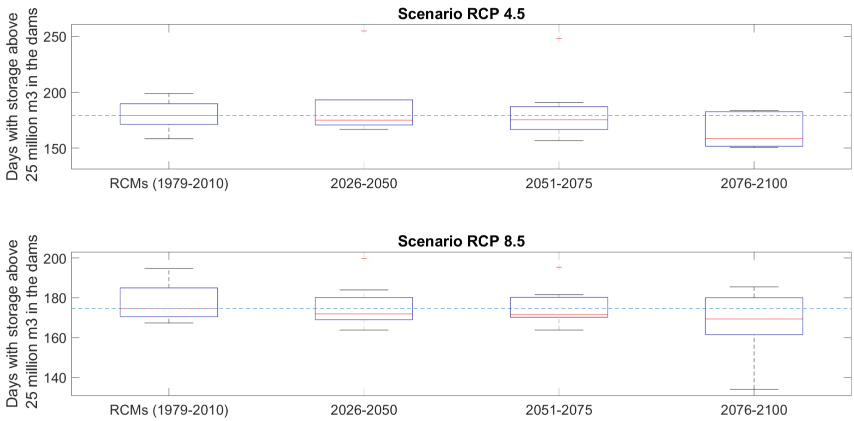
where Q_t^m is the modelled streamflow at time t, Q_t^o is the observed streamflow at time t and $\bar{Q}_o$ the average streamflow. E can vary from $-\infty$ to 1, and a good model typically have a Nash coeffeicient of 0.7 and above. The calibration in this project was found to be satisfying given the quality of the data, with a Nash Suttcliffe coefficient of 0.76. The SWAT model was therefore forced with the downscaled outputs of the 10 selected RCMs under RCP4.5 and RCP8.5, and the projected changes in the discharge at doguerawa and the number of days the dams contain more than the average volume (25 millions m^3) were calculated.

3 Projected Changes in Hydrological Variables

The boxplots in Fig. 6a show that streamflow at doguerawa is expected to be higher in the future under both scenarios, with more and more variability



(a)



(b)

Fig. 6. Projected changes in (a) the discharge at the Doguerawa station and (b) the number of days per year the storage in the dams is above average under RCP4.5 and RCP8.5

(uncertainty) in the future. These results are consistent with the projections in precipitation in the area, and point to the possibility of more agricultural production. Another impact of climate change is the increase in evaporation because of the warmer climate. Evaporation losses is an important component of the water budget in the study area, and even in the current climate around 32 millions m^3 of water are lost each year to evaporation. An increase in evaporation can hence offset the increase in rainfall. To check that hypothesis, the average numbers of days where the cumulative volume of water in all dams is above average was calculated under the current and future climates (Fig. 6b). As expected, the number of days where the storage is above average decrease in the figure, suggesting that storing water in large dams may not be the solution for the future. The reason water losses are hard to master in large reservoir is that their shape is imposed by nature and they generally have a large surface to volume ratio. Evaporation control is much easier in smaller reservoirs because (a) they can be engineered so that their surface to volume ratio become small and (b) there are a number of evaporation control technologies at different phases of development that may be applicable to small reservoirs. That's why Sahelian farmers should consider alternative techniques for harvesting and storing water which are less sensitive to evaporation than large open water reservoirs. These techniques ranges from infiltration promotion to covering the water body with a plastic firm or a layer of chemical products. While these techniques are expensive nowadays, they are likely to become cheaper and more efficient in the coming decades.

4 Conclusions

Past and future trends in precipitation and runoff over the Niger republic were examined in this paper. Much as the rest of Sahel, the country has seen a drastic decrease in precipitation during the 70s and the 80s, followed by an apparent recovery. Surprisingly, the drought resulted in an increased surface runof in some areas in the Sahel, suggesting that new opportunities for water harvesting may arise in a dry climate, if evaporation is adequately taken care of. The paper also examined the predictions of 10 different regional climate models over the Maggia watershed in the center south of the Niger republic, and found that runoff is likely to increase but that the increase will be offset by evaporation in large dams. In both cases, the use of decentralized storage systems and evaporation suppression techniques should be seriously considered as a way to maintain and increase water supply and agricultural production.

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