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Ibrahima Diba, Arona Diedhiou, Adjoua M. Famien, Moctar Camara, Thierry C. Fotso-Nguemo. Changes in compound extremes of rainfall and temperature over West Africa using CMIP5 simulations. Environmental Research Communications, 2022, 4, 10.1088/2515-7620/ac9aa7 . insu-03859254

**HAL Id: insu-03859254**

**<https://insu.hal.science/insu-03859254>**

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To cite this article: Ibrahima Diba *et al* 2022 *Environ. Res. Commun.* 4 105003

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## Environmental Research Communications



## PAPER

## Changes in compound extremes of rainfall and temperature over West Africa using CMIP5 simulations

## OPEN ACCESS

## RECEIVED

10 June 2022

## REVISED

30 September 2022

## ACCEPTED FOR PUBLICATION

14 October 2022

## PUBLISHED

27 October 2022

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**Keywords:** CHIRPS, ERA5, CMIP5, compound extremes, West Africa

Supplementary material for this article is available [online](#)

## Abstract

This study aims to characterize changes in compound extremes of rainfall and temperature over West Africa. For this purpose, data from CHIRPS observations, the ERA5 reanalysis, and twenty-four (24) climate models involved in the CMIP5 Project were analyzed. First, climate models were evaluated in terms of their capacity to simulate summer mean climatology and compound extremes during the historical period (1981–2005), and secondly, changes in compound extremes were examined under RCP8.5 emission scenario between the near future (2031–2055) and the far future (2071–2095) relative to the historical period. Despite the presence of some biases, the ensemble mean of the models well reproduces the compound extremes patterns over West Africa at the seasonal and intraseasonal timescales. The analysis over the historical period with CHIRPS/ERA5 dataset shows a strong occurrence of the dry/warm mode over the northern Sahel during the June-July-August-September period (JJAS; main rainy season) and over the Guinean region during the February-March-April-May season (FMAM; first and main rainy season). These strong occurrences are due to a weak and highly frequent precipitation recorded in these zones. The compound wet/warm mode is frequent in JJAS over the Sahel and the Sudanian zone (transition area between Sahel and Guinean regions), while in FMAM, its occurrence is maximum over the Guinean region. The study also shows that the dry/warm mode will increase in the whole Sahel (western and central) and in the Guinean zone in the near and far futures while the compound wet/warm mode will decrease in the whole region. This study suggests that the West Africa region will be prone to drought intensified by warmer temperatures and calls for climate action and adaptation strategies to mitigate the risks on rain-fed agriculture, energy, and on animals and human health.

## 1. Introduction

Climate change is perceived through extreme events that alter the climatic signal and several studies (Hegerl *et al* 2007, Trenberth *et al* 2007a, Stott *et al* 2011, Diedhiou *et al* 2018) have shown that since the 1950s, climate variability is becoming a concern due to the increasing concentration of greenhouse gases in the atmosphere. According to World Meteorological Organization (WMO 2022), the last seven years have been the seven

warmest years on record. The year 2021 had a temporary cooling effect due to La Nina but this event did not reverse the overall warming trend. The global warming in 2021 was about  $1.11 (\pm 0.13) ^\circ\text{C}$  above the pre-industrial level. Sarr (2011) had shown an increase in floods in the Sahel during the decade 2000–2009, and later, Taylor *et al* (2018) confirmed tripling of storms events in the central Sahel associated with the warming of the Sahara. Indeed, Ali (2011) showed that after 1993, the Sahel experienced another type of climatic variability characterized by an alternation between very humid and dry years. Bichet and Diedhiou (2018a, 2018b) confirmed that the period 1981–2014 was characterized by lower occurrences and more intense precipitation along the Gulf of Guinea coast in West and Central Africa, and that West African Sahel has become wetter, but dry spells are shorter and more frequent.

Studies about extreme events are lacking in West Africa due particularly to a lack of daily meteorological data (Lamprey 2009, Didi *et al* 2020). The high occurrence of extreme events already has many negative impacts on human security in this region where the population is largely dependent on rain-fed agriculture (Dinku *et al* 2007, Nguemoa *et al* 2022). Economic and human losses as well as a decrease in agricultural production are among the direct and indirect impacts of extreme weather events (Meehl *et al* 2000). Sylla *et al* (2016) showed that global warming affects low-income populations in developing countries, making West Africa one of the world's most vulnerable regions to climate change. Estimating and understanding the variability of extreme events for the present and future climate is important for the formulation of adaptation and mitigation strategies and resource and urban planning.

Compound extremes, also known as simultaneous or coincident extremes, can cause greater negative consequences on society than individual climatic extremes (Hao *et al* 2018, McPhillips *et al* 2018). Numerous studies have focused on compound climatic extremes on the European, American, and Asian continents due to their major impacts on humans and ecosystems (Zscheischler and Seneviratne 2017, Hao *et al* 2018, Zhou and Liu 2018). Several works (e.g., Lyon 2009, Albright *et al* 2010, Hao *et al* 2013, Horton *et al* 2016, Orth *et al* 2016, Sedlmeier *et al* 2018, Zhou and Liu 2018, Wu *et al* 2019) have studied the compound climatic extremes events like the occurrence of drought and heat wave or the low rainfall and high temperatures in these regions. For example, Livneh and Hoerling (2016) showed that the significant rainfall deficit over the central United States in 2012 was accompanied by high temperatures, which had a significant impact on crop yields. Furthermore, Hao *et al* (2018) also highlighted an increase in the dry/warm compound extreme from 1901 to 2016 in Melbourne (Australia). All these pioneering studies cited above helped a good understanding of the compound extreme characteristics across the European, American, and Asian continents.

In Africa, studies about compound extremes over West Africa are nascent. Diba *et al* (2021) showed that the number of dry/warm modes has increased in Senegal in the 20th century and will continue to increase by 2090 and the number of wet/warm modes will decrease over Senegal during the near and far futures. Over West Africa, Camara *et al* (2022) found that reforestation decreases the occurrence of compound dry/warm events and increases the compound wet/warm over the reforested zone.

The objective of this study is to characterize changes in compound extremes of rainfall and temperature over West Africa using data from CHIRPS observations, the ERA5 reanalysis, and twenty-four (24) climate models involved in the Coupled Model Intercomparison Project Phase five (CMIP5).

The model description, the data and methods, and the definition and types of compound extremes are introduced in section 2. Section 3 presents and discusses the results followed by the conclusions in section 4.

## 2. Data and methods

### 2.1. CMIP5 simulations

We use in this study daily data of twenty-four (24) models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) listed in table 1. The CMIP5 ensemble includes both Coupled Atmospheric-Ocean General Circulation Models (AOGCM) and Earth System Models (ESMs) (Nikulin *et al* 2018). The CMIP5 project provides a set of coordinated experiences of global climate models. The main goal of these datasets is to improve understanding of climate, to respond to the outstanding scientific questions raised in the IPCC AR4 report, and to provide estimates of future climate change that will be useful to those considering its possible consequences (Taylor *et al* 2012). The CMIP5 models' outputs are available for historical simulations from 1850 to 2005 and all RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) from 2006 to 2100 at different resolution grids (see table 1 for details). Our analyses are focused on three periods: present-day of 1981–2005, near future of 2031–2055, and far future of 2071–2095 under the RCP8.5 (representative concentration pathway 8.5) scenario.

**Table 1.** Description of the CMIP5 climate models used in this study.

	Model	Grid (Lat ° Lon)	Modeling Center
1	ACCESS1-0	1.25° × 1.875°	Commonwealth Scientific and Industrial Research Organisation (CSIRO)–Bureau of Meteorology (BOM); Australia
2	ACCESS1-3	1.25° × 1.875°	Commonwealth Scientific and Industrial Research Organisation (CSIRO)–Bureau of Meteorology (BOM); Australia
3	BCC-CSM1.1	2.8125° × 2.8125°	Beijing Climate Center (BCC); China
4	BNU-ESM	2.8125° × 2.8125°	Global Change and Earth System Science (GCESS); China
5	CanESM2	2.8125° × 2.8125°	Canadian Centre for Climate Modelling and Analysis (CCCMA); Canada
6	CMCC-CESM	3.75° × 3.75°	Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC); Italy
7	CMCC-CMS	1.875° × 1.875°	Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC); Italy
8	CMCC-CM	0.75° × 0.75°	Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC); Italy
9	CNRM-CM5	1.4° × 1.4°	Centre National de Recherches Météorologiques–Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CNRM-CERFACS); France
10	CSIRO-Mk3-6-0	1.875° × 1.875°	CSIRO–Queensland Climate Change Centre of Excellence (QCCE); Australia
11	FGOALS-g2	2.8125° × 2.8125°	Center for Earth System Science (CESS); China
12	GFDL-CM3	2° × 2.5°	NOAA Geophysical Fluid Dynamics Laboratory, USA
13	HadGEM2-CC	1.25° × 1.875°	Met Office Hadley Centre (MOHC); United Kingdom
14	HadGEM2-ES	1.25° × 1.875°	Met Office Hadley Centre (MOHC); United Kingdom
15	INMCM4	1.5° × 2°	Institute of Numerical Mathematics (INM); Russia
16	IPSL-CM5A-MR	1.25° × 2.5°	Institut Pierre-Simon Laplace (IPSL); France
17	MIROC5	1.4° × 1.4°	Model for Interdisciplinary Research on Climate (MIROC); Japan
18	MIROC-ESM-CHEM	2.8125° × 2.8125°	Model for Interdisciplinary Research on Climate (MIROC); Japan
19	MIROC-ESM	2.8125° × 2.8125°	Model for Interdisciplinary Research on Climate (MIROC); Japan
20	MPI-ESM-LR	1.875° × 1.875°	Max Planck Institute for Meteorology (MPI-M); Germany
21	MPI-ESM-MR	1.875° × 1.875°	Max Planck Institute for Meteorology (MPI-M); Germany
22	MRI-CGCM3	1.125° × 1.125°	Meteorological Research Institute (MRI); Japan
23	MRI-ESM1	1.125° × 1.125°	Meteorological Research Institute (MRI); Japan
24	NorESM1-M	1.875° × 2.5°	Norwegian Climate Centre (NCC); Norway

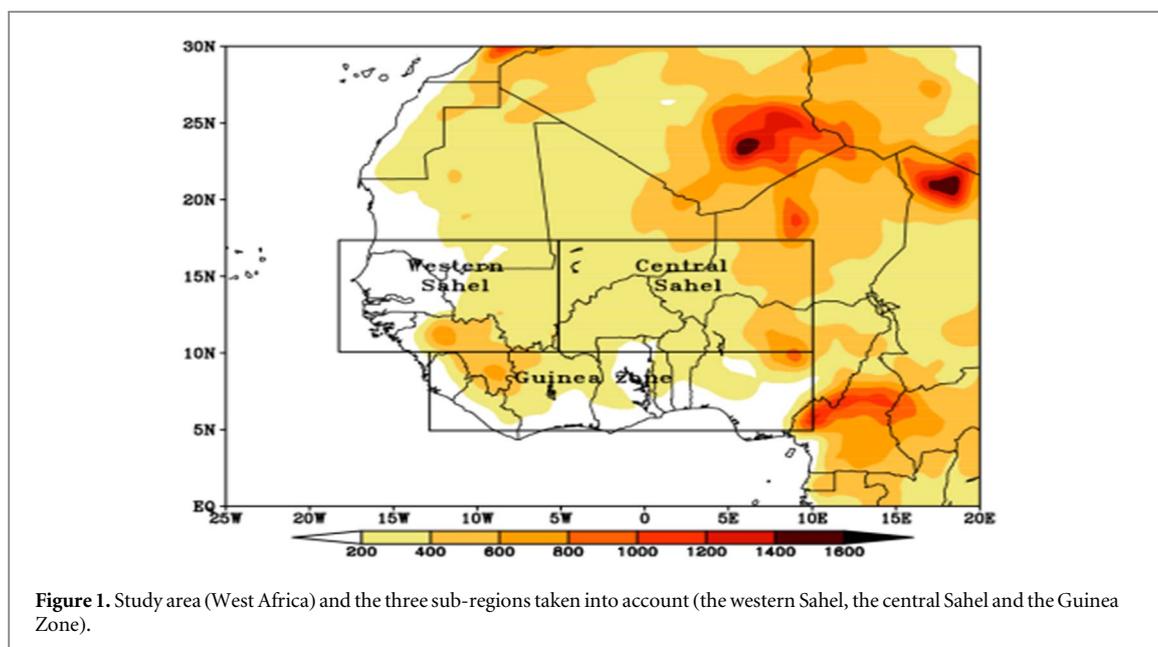
## 2.2. Observations datasets

Besides CMIP5 climate models, two datasets are combined to characterize compound extremes over West Africa: the CHIRPS (Climate Hazards Group Infrared Precipitation with Stations) observations from the California University (Funk *et al* 2015) and the new ERA5 data (Hersbach *et al* 2019). The CHIRPS are a fusion of *in situ* data and satellite measurements to create gridded precipitation at a 0.05° × 0.05° horizontal resolution. It's an almost global precipitation data and starts from 1981 to nowadays. ERA5 is the last climatic reanalysis provided by the European Center for Medium-Range Weather Forecasting (ECMWF) producing several atmospheric parameters. ERA5 reanalysis combine observation datasets with model outputs to create several climatic parameters. Reanalysis data have been used extensively to characterize the state of the art of the climate over Africa, especially in West Africa an area for which there are not many *in situ* measurements. The creation of ERA5 data began in early 2016 (Hersbach *et al* 2019). In this work, the ERA5 reanalysis have one hour (1h) temporal resolution and are calculated at 0.25° × 0.25° grids spatial resolution. These datasets were used to estimate the performance of the CMIP5 models experiments in simulating the summer rainfall and surface temperature in West Africa.

The study area mixes several climatic and ecological zones. We analyze the performance of the CMIP5 models over two sub-regions of the Sahel (western and central) and over the Guinea region shown in figure 1. The Guinea region is characterized by its dense forests and the Sahel by its arid and semi-arid zones with short and tall grass savanna and trees. The Sahel is identified by its unique rainy season and the Guinea region by its two wet seasons regarding the annual rainfall regime (Sultan *et al* 2003).

## 2.3. Definition of compound extremes

Following Benestad and Haugen (2007), Seneviratne *et al* (2012), Bevacqua *et al* (2017) and Hao *et al* (2018), a compound climatic extreme event could be characterized as both or several extremes climatic events which occur successively or simultaneously or, the co-occurrence of climate events which are not extremes, but which, when combined, conduct to an extreme climate. The rainfall (and temperature) extremes can be considered as dry/wet (and cold/warm) when they are below/above specific thresholds (e.g., 25th/75th and 10th/90th percentiles). Following previous studies by Beniston (2009), Hao *et al* (2013), Morán-Tejeda *et al* (2013), Wu *et al* (2019), the compound extremes dry/warm, dry/cold, wet/warm and wet/cold can be defined when there are two extremes happening simultaneously. In this study, we used daily rainfall and daily maximum temperature data for West Africa provided by twenty-four models of the CMIP5 project to illustrate this approach. Based on



**Figure 1.** Study area (West Africa) and the three sub-regions taken into account (the western Sahel, the central Sahel and the Guinea Zone).

**Table 2.** Definitions of the two compound extremes used in this study.

Compound extremes	Definitions
Dry/Warm	Number of days with daily rainfall different to zero and below the 10th percentile of daily mean rainfall and daily temperature above the 90th percentile of daily maximum temperature
Wet/Warm	Number of days with daily rainfall above the 90th percentile of daily mean rainfall and daily temperature above the 90th percentile of daily maximum temperature

the definition above and the thresholds 10th/90th percentiles, we calculated the frequency of compound precipitation and temperature extremes of dry/warm and wet/warm modes (table 2) over West Africa. The individual rainfall and temperature extremes are defined using the extreme dry, wet and warm days. The extreme dry (wet) days are the number of days with daily mean rainfall different to zero and below (above) the 10th (90th) percentile of daily mean rainfall; while the extreme warm days are the number of days with daily temperature above the 90th percentile of daily maximum temperature. For consistency, all CMIP5 models outputs are interpolated to the HadGEM2-ES model grid (i.e.  $1.25^\circ$  latitude  $\times$   $1.875^\circ$  longitude). A better knowledge of the variability of the compound dry/warm and wet/warm modes will help West African countries to better identify areas that need supplementary irrigation as an adaptive strategy to protect agriculture in the near and far futures.

### 3. Results and discussions

#### 3.1. Models validation

We first validated the simulations of the CMIP5 models before characterizing compound extremes over West Africa. For this step, the standard deviation of CHIRPS rainfall data and the ERA5 surface temperature are compared to the CMIP5 models, and the correlation coefficient between these observations, reanalysis data, and the models. Figure S1 shows the Taylor diagrams over the three considered sub-domains (the western Sahel, central Sahel, and the Guinea region). Over the western Sahel (figure S1(a)), CSIRO-Mk3-6-0, MIROC5, and MPI-ESM-MR models show a poor performance (strong standard deviation); while the other CMIP5 models present a strong correlation and a standard deviation slightly stronger than the CHIRPS observations data. Over the central Sahel (figure S1(b)), the CMIP5 models generally present a good performance except for MIROC5 and MPI-ESM-MR models. These two models show a larger standard deviation than the CHIRPS observations. The weakest standard deviations are obtained with the INMCM4 model over the western and central Sahel (figures S1(a), (b)). All CMIP5 models present a strong correlation (up to 0.70) with CHIRPS data over these two sub-domains. Over the Guinea region (figure S1(c)), the INMCM4 and MIROC-ESM-CHEM present the weakest correlation coefficient ( $<0.4$ ) compared to CHIRPS data. The greatest standard deviation values are obtained with the BCC-CSM1.1, CSIRO-Mk3-6-0, and MIROC-ESM-CHEM models (figure S1(c)).

Over the western and central Sahel, the CMCC-CESM model presents a strong standard deviation than the ERA5 surface temperature data (figures S1(d), (e)). The weakest standard deviations of temperature are obtained with the INMCM4, MRI-CGCM3, and NorESM1-M models over these two sub-domains (figures S1(d), (e)). All CMIP5 models present a strong correlation (up to 0.70) with the ERA5 surface temperature data over the two Sahel zones (figures S1(d), (e)). Over the Guinea region (figure S1(f)), the CMCC-CESM and HadGEM2-ES present strong standard deviations values compared to the ERA5 surface temperature data. In this area, the correlation coefficient for all CMIP5 models with respect to the ERA5 temperature is good (up to 0.6) except for the INMCM4 ( $r = 0.38$ ) and NorESM1-M ( $r = 0.42$ ) models. The greater correlation coefficient ( $r = 0.77$ ) is obtained with the CSIRO-Mk3-6-0 model (figure S1(f)).

Generally, the analysis shows that there is not a strong dispersion between the models over the three considered sub-domains. Indeed, Rowell *et al* (2016) show a good performance of the CMIP5 models over the Sahel and Africa's Greater Horn. They also found that the uncertainty in projecting changes in seasonal mean temperature or precipitation is generally not reduced by evaluating standard regional performance metrics.

Generally, the summer rainfall spatial distribution (Figure not shown) and mean surface temperature (Figure not shown) over West Africa is well represented by CMIP5 models in spite of the presence of some biases in line with the findings of Nikiema *et al* (2016) and Akinsanola *et al* (2017). Some studies (Sarr *et al* 2015, Nikiema *et al* 2016) have also shown that the internal variability of models can also contribute to the biases of climate models.

The next section is devoted to the capacity of CMIP5 models to reproduce compound extremes of precipitation and temperature in West Africa.

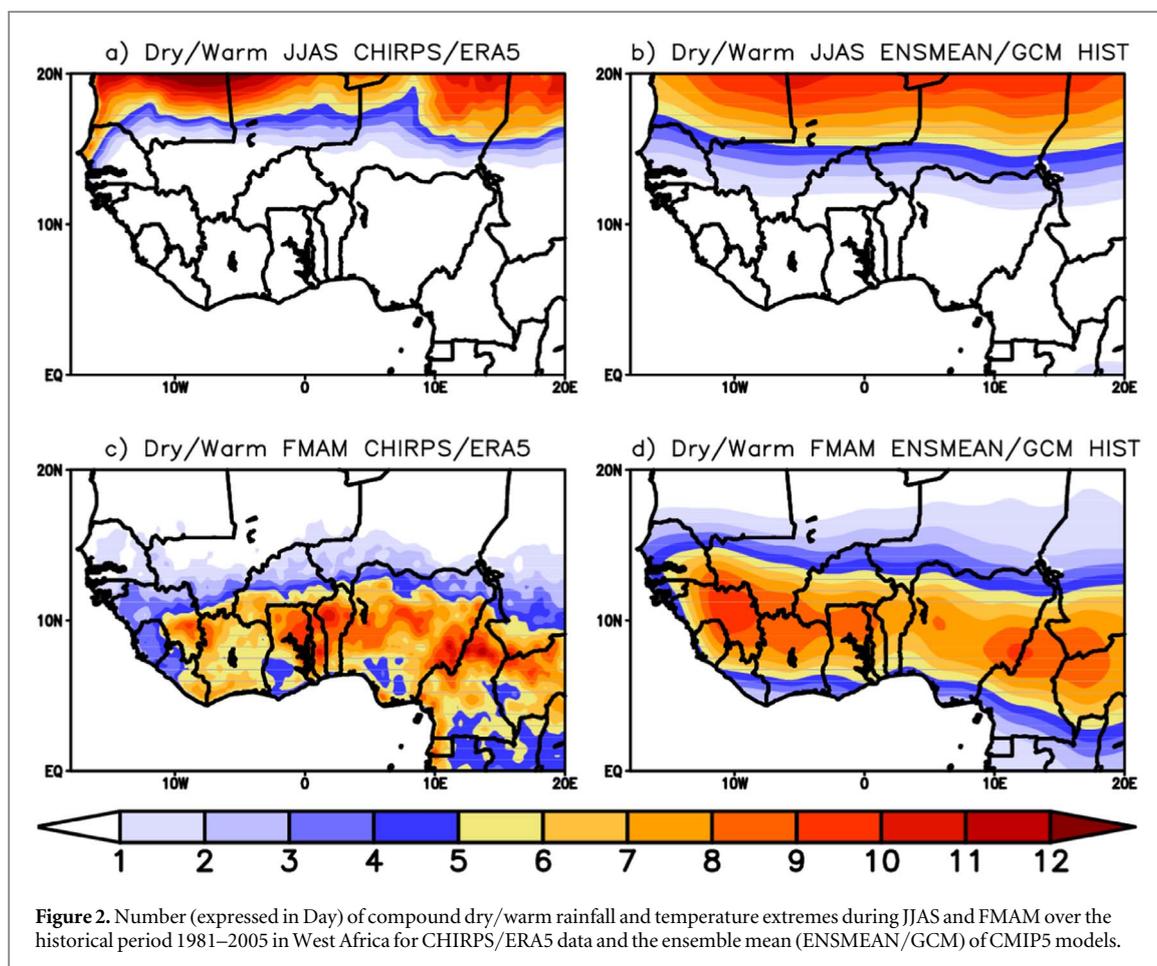
### 3.2. Compound extremes rainfall and temperature over West Africa

#### 3.2.1. Spatial pattern of compound extremes over historical period

Previous works about climatic extremes events over West Africa was essentially based on the extremes computed with an individual parameter, like strong/weak rainfall or maximum/minimum temperature (Diba *et al* 2016, Moron *et al* 2016, Oueslati *et al* 2017). Numerous works have largely studied the compound extremes rainfall and temperature on the European, Chinese and American continents (Hao *et al* 2018, Zhou and Liu 2018, Wu *et al* 2019). Here, we defined the compound extremes as the number of days with concurrent extremes during the considered season.

Figure 2 shows the number of compound extreme dry/warm mode in June-July-August-September (JJAS) and February-March-April-May (FMAM) seasons over the historical period 1981–2005 for the CHIRPS/ERA5 data and the ensemble mean (ENSMEAN) of all CMIP5 models used. Generally, the CHIRPS/ERA5 datasets show the high frequency of the compound dry/warm mode in the northern Sahel (over Mali, Niger, Mauritania, and Chad) during June-September (JJAS) (figure 2(a)) possibly linked to the low but highly frequent rainfall noted over that domain in the summer period (JJAS). When considering the February-May (FMAM) season, the observation datasets show the high frequency of dry/warm mode over the Guinean regions (figure 2(c)). The February to May period corresponds to the warm one in the Sahel. The December-January-February (DJF) season corresponds to the cold period over the Sahel zones. The ensemble mean of the models well represent the seasonal distribution of the dry/warm mode over West Africa and the position of the maxima and minima but overestimate the values than what was obtained in the observations datasets (figures 2(b), (d)). Moreover, populations and harvest yields may be negatively impacted by compound dry/warm mode because high-temperature values causes most threat to the human health and plants.

Figure 3 shows the number (expressed in days) of compound wet/warm rainfall and temperature extremes during June-September (JJAS) and February-May (FMAM) seasons for the historical period 1981–2005 over West Africa for the CHIRPS/ERA5 data and the ensemble mean (ENSMEAN) of all CMIP5 models used. The CHIRPS/ERA5 datasets show the high frequency of wet/warm compound mode over some parts of the Guinean regions and the Sahel during the June-September (JJAS) period (figure 3(a)) and over most parts of the Guinean regions during the February-May (FMAM) season (figure 3(c)). This may be linked to the high convection and strong rainfall amount over these zones during the rainy seasons. Indeed, the risks of experiencing compound wet/warm events (heavy precipitation and high maximum temperature at the same day) is strongly linked to the dependence (correlation) between rainfall and temperature. Warmer air is able to hold more moisture. This can lead to deep convection when this air is saturated with moisture and then to strong rainfall. The ensemble mean reproduces this strong occurrence of the compound wet/warm over the Sahel and the Guinean zones (figures 3(b), (d)) but overestimates the occurrences over the Sahel and the Guinean regions during the June-September (JJAS) and the February-May (FMAM) seasons. Crop yields may be negatively impacted by this compound wet/warm mode because the plants' organisms can be destroyed by heavy rainfall and high temperatures during their development and growth. These findings indicate that a high frequency of compound wet/warm extremes exists over the Sahel and the Guinean zone during the rainy seasons.



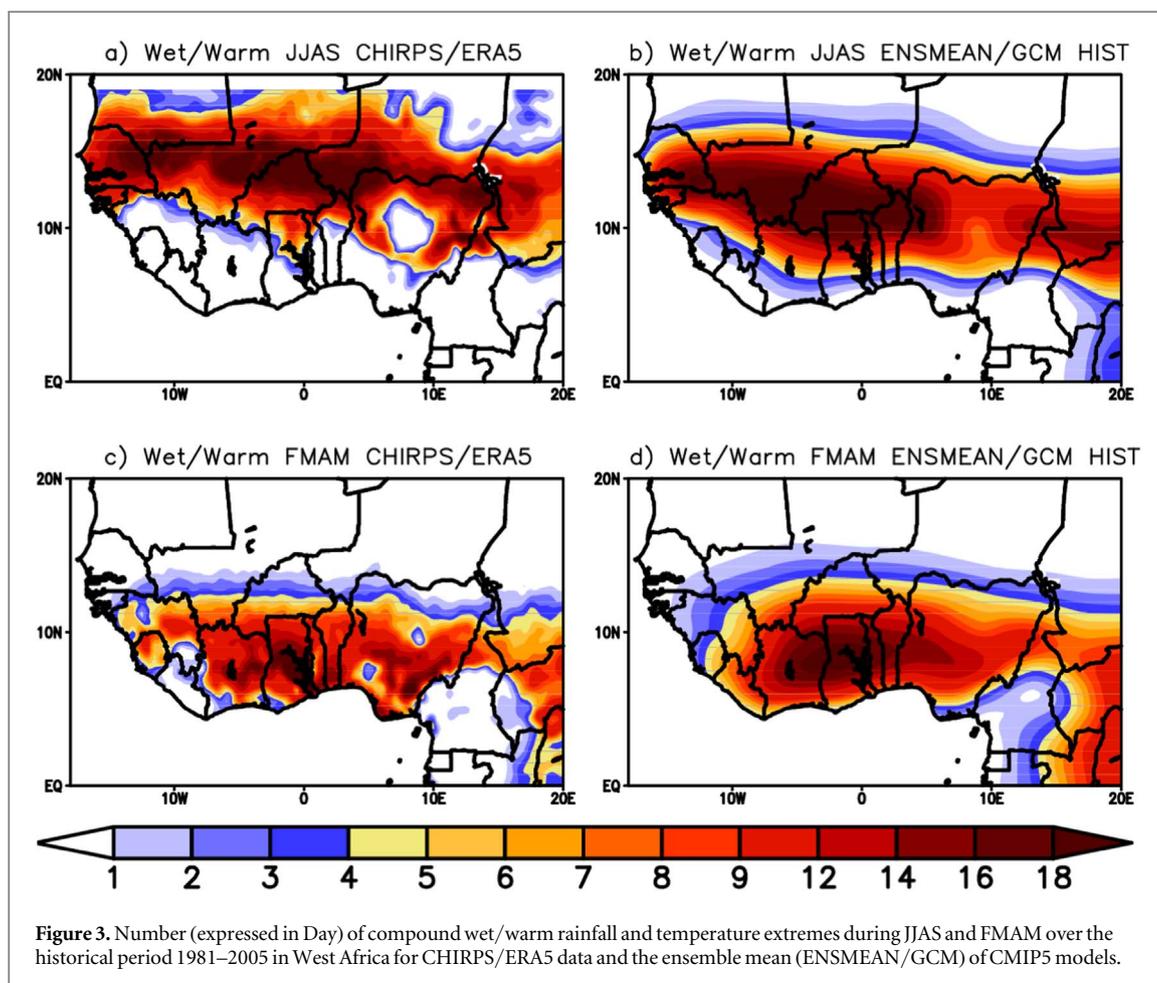
**Figure 2.** Number (expressed in Day) of compound dry/warm rainfall and temperature extremes during JJAS and FMAM over the historical period 1981–2005 in West Africa for CHIRPS/ERA5 data and the ensemble mean (ENSMEAN/GCM) of CMIP5 models.

Zhou and Liu, (2018) show that the pattern of the occurrence of compound extremes can be partly explained by the correlation between precipitation and temperature.

### 3.2.2. Intraseasonal, annual and interannual variabilities of compound extremes over historical and future periods

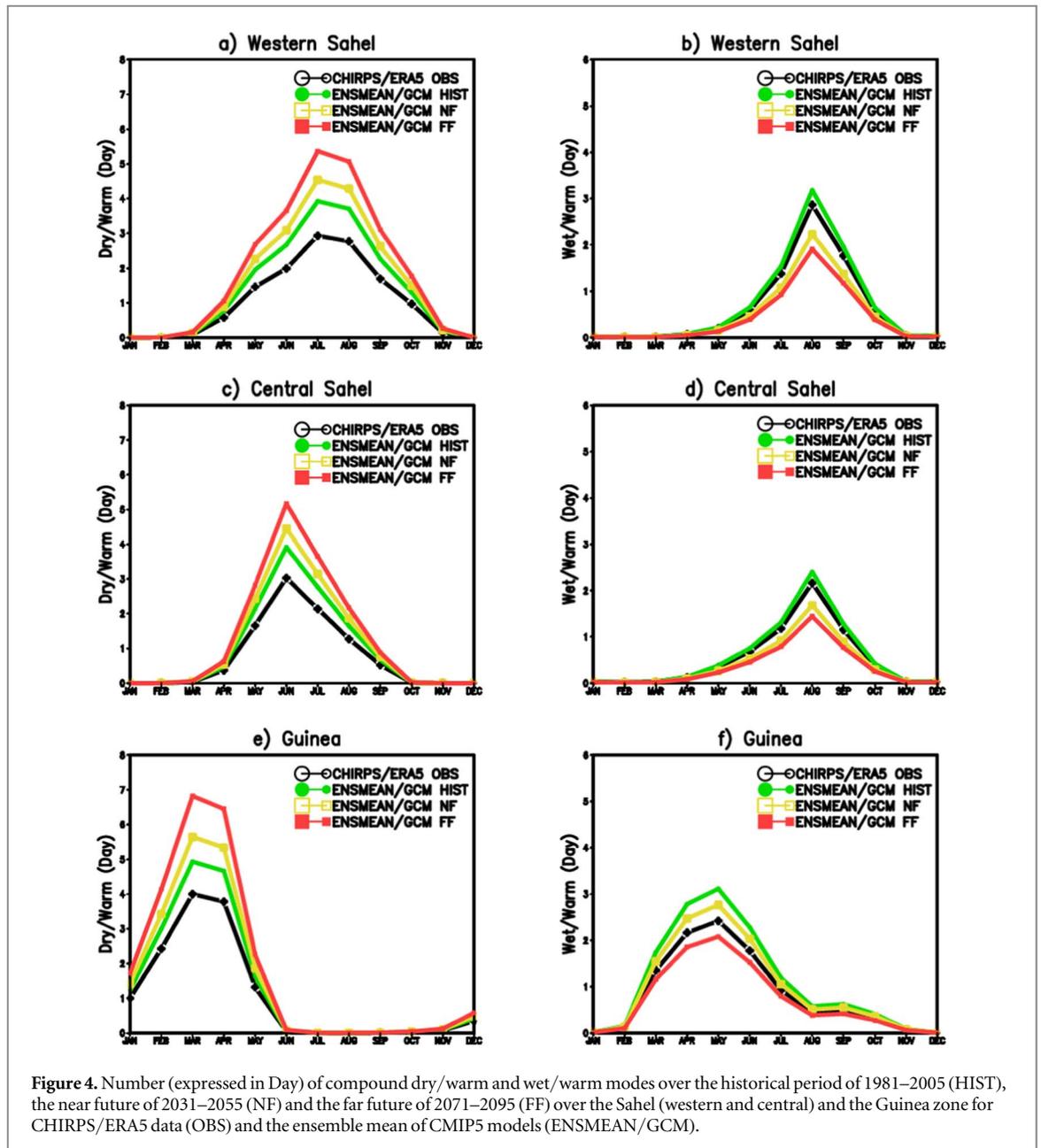
Figure 4 displayed the annual cycle of the compound dry/warm and wet/warm modes over the Sahel (western and central) and the Guinea zone from CHIRPS/ERA5 climatology and the ensemble mean of the models for the present and future climate. CHIRPS/ERA5 climatology shows a dry/warm peak in July and a wet/warm peak in August over the western Sahel, a dry/warm peak in June, and a wet/warm peak in August over the central Sahel (figures 4(a)–(d)). The ensemble mean of the models well simulates the dry/warm, the timing of these peaks over the two Sahel zones. Over the Guinea Coast, the CHIRPS/ERA5 datasets exhibit a dry/warm peak in March and a wet/warm peak in May (figures 4(e), (f)). The ensemble mean of all CMIP5 models well simulates these peaks (figures 4(e), (f)). Generally, the results show that the ensemble mean well reproduces the annual cycle of compound dry/warm and wet/warm modes over the Sahel zones and the Guinea zone with sometimes an overestimation or underestimation. The results show that the compound dry/warm will increase and the wet/warm mode will decrease over the three considered regions during the near and far futures (figure 4).

To diagnose further the compound extreme over West Africa, the Hovmoeller diagram of the compound dry/warm and wet/warm modes averaged across 20°W and 20°E for CHIRPS/ERA5 climatology and the ensemble mean of the models is displayed in figure 5. The intraseasonal variability of the dry/warm and wet/warm modes follows that of precipitation in West Africa. In West Africa, the intraseasonal variability of precipitation is strongly linked to the south–north shift of the Intertropical Convergence Zone (ITCZ). In this region, the rainy period has three phases: the pre-onset (installation phase), the onset (period of heavy rainfall amount in the Sahel), and the retreat to the south of the rain band. Both CHIRPS/ERA5 climatology and the ensemble mean of the models show the maxima of dry/warm mode in March over the Guinea region (figures 5(a), (b)). Over the Guinea region, the wet/warm mode occurs in the first rainy period between March and June (figures 5(e), (f)), in fact during this period the rainfall maximum remains centered from the coasts to about 5°N until the end of June, whereupon the precipitation rates decrease. Afterwards, the precipitation increases in the proximity and the north of 10°N (over the Sahel where appears again the wet/warm mode)



(figures 5(e), (f)). The monsoon jump appears in early June when the core of the monsoon rainfall shifts northward to approximately  $10^{\circ}\text{N}$ , this period corresponds to the rainy season over the Sahel (Sultan and Janicot 2003). When considering both CHIRPS/ERA5 climatology and the ensemble mean of the models, the second maxima of dry/warm mode are recorded from June to August between  $12^{\circ}\text{N}$  and  $20^{\circ}\text{N}$  (over the Sahel) (figures 5(a), (b)). This period corresponds to the highest temperatures and less precipitation over the northern Sahel. The results show that the compound dry/warm will increase strongly between the latitudes  $8^{\circ}\text{N}$  and  $10^{\circ}\text{N}$  from March to April and the wet/warm mode will decrease strongly from May to July over the Sahel during the far future of 2071–2095 (figure 5).

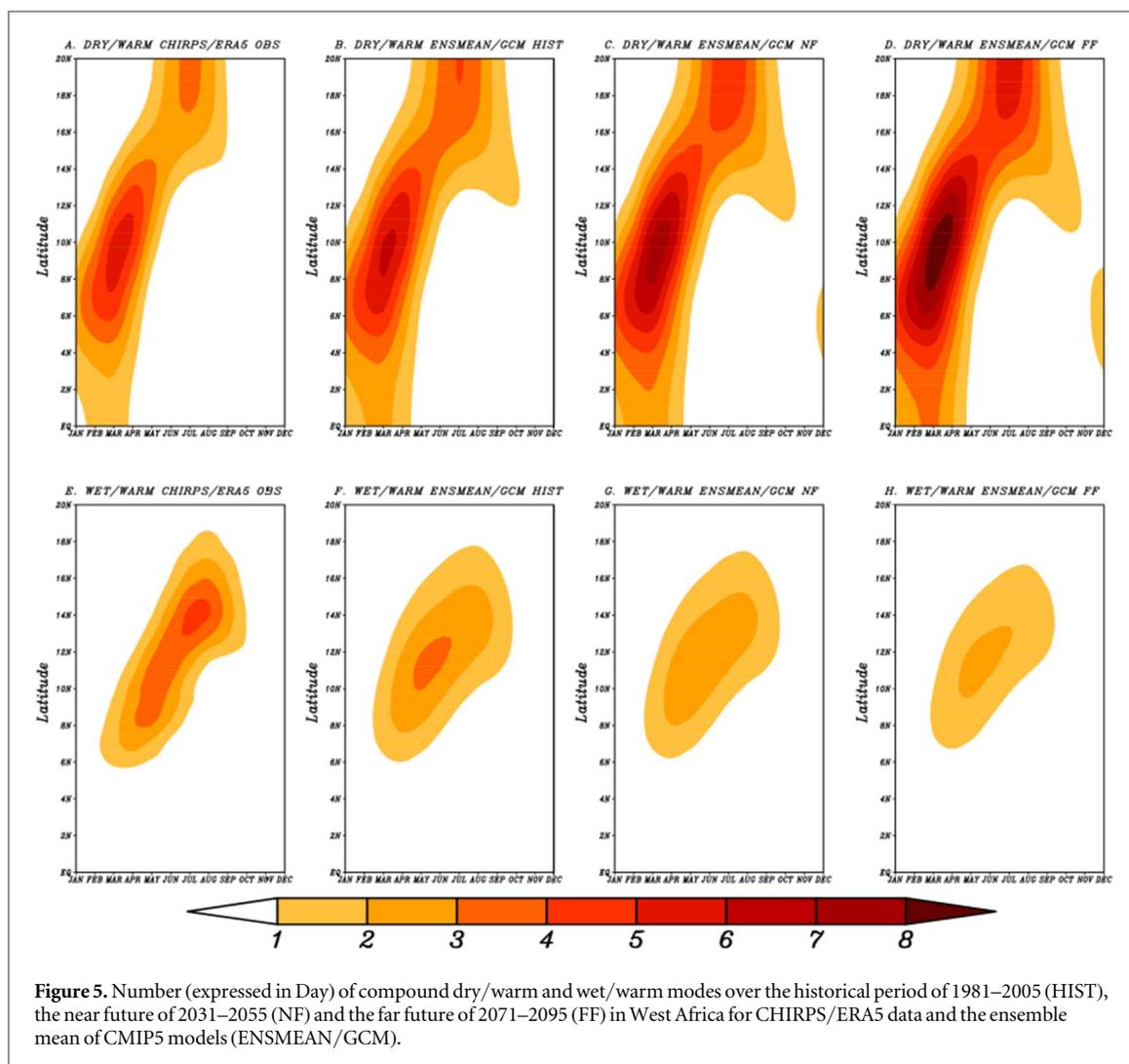
Furthermore, a high occurrence of the compound dry/warm mode over West Africa could lead to a rainfall deficit which also could lead to drought, famine, and the collapse of the economies of West African countries. The analyses show a good performance of the CMIP5 models in representing the seasonal and intraseasonal variabilities of the compound extremes of rainfall and temperature over West Africa despite some overestimation and underestimation. Figure S2 shows the changes on the interannual variability of the compound dry/warm and wet/warm modes during the near future of 2031–2055 and the far future of 2071–2095 relative to the mean of the whole historical period of 1981–2005 over the Sahel (western and central) and the Guinea zone for the ensemble mean of the models. When analyzing this figure, results show that there will be a strong interannual variability of these two compound extremes during the near and far future for the three considered areas. Over the western Sahel, the compound wet/warm will decrease strongly during the far future and the dry/warm mode will strongly increase at the beginning (from 2031 to 2035) and the end (from 2049 to 2055) of the near future and the end of the far future (from 2089 to 2095) (figures S2(a), (b)). Over the central Sahel, the compound wet/warm will decrease strongly during years 2079, 2084, 2085, 2092 and 2094 and the dry/warm mode will increase strongly at the end of the near future (from 2049 to 2055) and the end of the far future (from 2089 to 2095) (figures S2(c), (d)). Over the Guinea zone, the compound wet/warm will decrease strongly during the far future and the dry/warm mode will increase strongly at the end of the near future (from 2046 to 2055) and the end of the far future (from 2086 to 2095) (figures S2(e), (f)). The next step is to assess further the changes in compound extremes (rainfall and temperature).



**Figure 4.** Number (expressed in Day) of compound dry/warm and wet/warm modes over the historical period of 1981–2005 (HIST), the near future of 2031–2055 (NF) and the far future of 2071–2095 (FF) over the Sahel (western and central) and the Guinea zone for CHIRPS/ERA5 data (OBS) and the ensemble mean of CMIP5 models (ENSMEAN/GCM).

### 3.2.3. Changes of compound extremes over West Africa

Climate change affects many climatic variables, including precipitation and temperature. Changes in the compound extremes dry/warm and wet/warm during the near future (2031–2055) and the far future (2071–2095) for the ensemble mean (ENSMEAN) of all CMIP5 models are shown in figure 6. All projections are focused on data forced by the RCP8.5 emission scenario (representative concentration pathway 8.5). We computed the values of the two compound extremes for all twenty-four models used over the historical period (HIST), the near future (NF), and the far future (FF) to diagnose the dispersion between all CMIP5 models to simulate the changes of the two extremes in the future over the Sahel (western and central) and the Guinea coast. The compound dry/warm mode will increase over the three considered sub-domains during the near and far futures (figures 6(a)–(c)). This increase of the dry/warm mode will be more pronounced during FMAM over the Guinea coast in the far future compared to the western and central Sahel. Generally, the analysis shows that there will be no dispersion between the models in simulating the dry/warm mode over the Sahel (western and eastern) during JJAS and over the Guinea coast during FMAM in the future (figures 6(a)–(c)). Moreover, an increase in the compound dry/warm during a year could lead to a rainfall deficit which could lead to drought and famine over West Africa. The compound wet/warm will decrease over the three considered sub-regions during the near and far futures (figures 6(d)–(f)). This decrease will be more pronounced over the western Sahel and the Guinea coast in the far future (figures 6(d), (f)). Biasutti (2013) and Roehrig *et al* (2013) have shown that over the Sahel, the majority of climate models suggest a decline in rainfall over its western part in the next few decades.



**Figure 5.** Number (expressed in Day) of compound dry/warm and wet/warm modes over the historical period of 1981–2005 (HIST), the near future of 2031–2055 (NF) and the far future of 2071–2095 (FF) in West Africa for CHIRPS/ERA5 data and the ensemble mean of CMIP5 models (ENSMEAN/GCM).

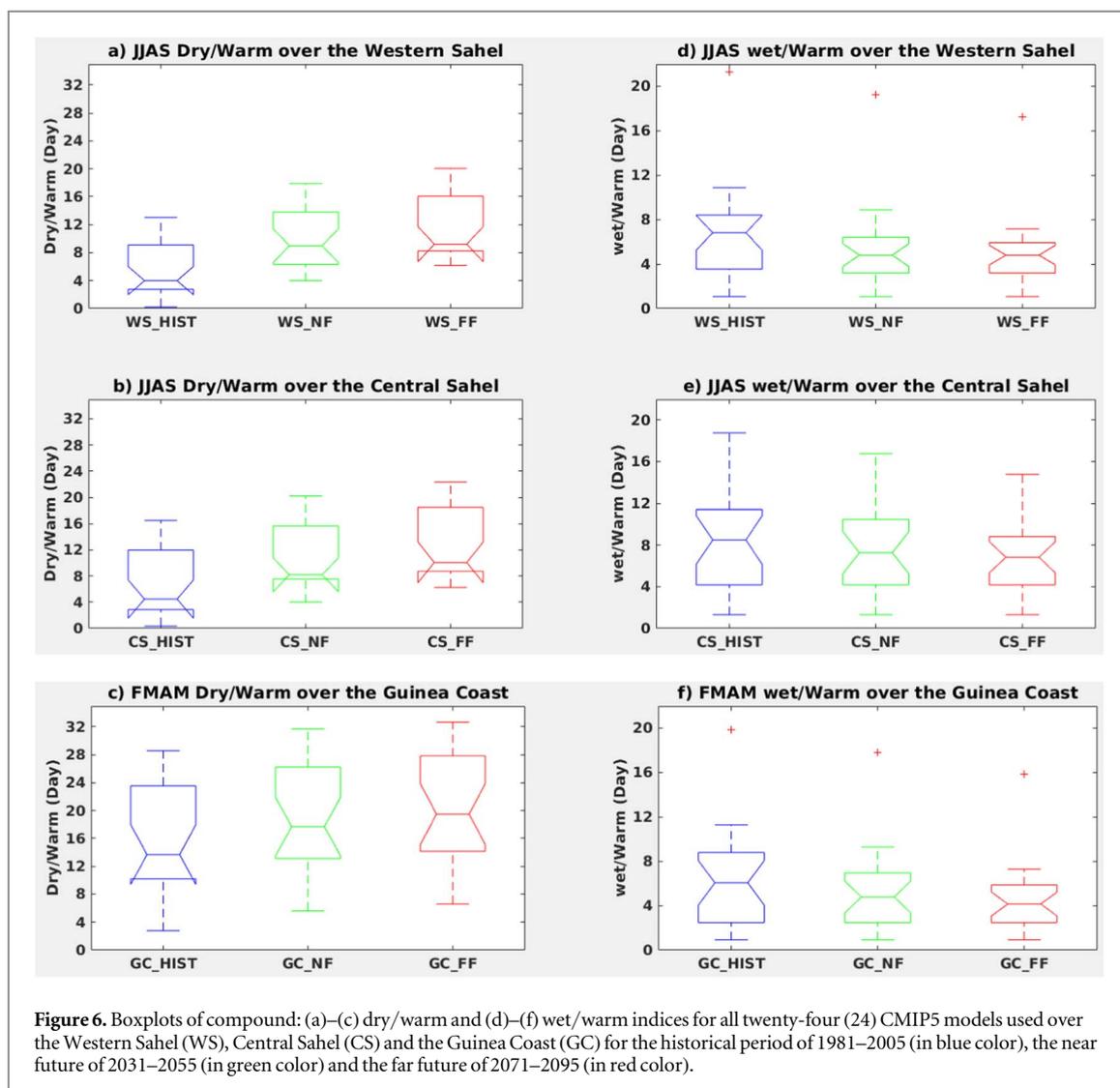
Generally, the analysis shows that there will be a little dispersion between the models in simulating the wet/warm mode over the western Sahel and the Guinea coast in the future (figures 6(d), (f)). However, there will be no dispersion between the models in representing the wet/warm mode over the central Sahel in the future (figure 6(e)).

Recently, Descroix *et al* (2013) showed an increase in the occurrence of high rainfall amount events over the Sahel despite the decrease in the annual rainfall over this region. Moreover, Ali (2011) also found that after 1993, the eastern Sahel experienced a gradual recovery (return to wet conditions). However, this evolution is sometimes accompanied by the frequency of extreme climatic events like floods and strong dry spells.

Several studies (e.g., Madden and Williams 1978, Dai *et al* 1999, Trenberth and Shea 2005) have probed the relationship between temperatures and precipitation. For example, Madden and Williams, (1978) extensively investigated the connection between precipitation and maximum temperature, showing strong anticorrelation between these two parameters on short timescales (up to interannual) during the warm season. They show that these are caused primarily by reductions of solar heating by clouds and increases in surface latent heat release by surface wetness increases due to precipitation. Zhou *et al* (2008) also show that trends in temperature are highly dependent on precipitation amount at a global scale.

#### 4. Conclusion

Compound extremes of rainfall and temperature were characterized over West Africa using data from CHIRPS observations, the ERA5 reanalysis, and twenty-four (24) climate models involved in the CMIP5 project. The validation step shows that the CMIP5 models well reproduce the spatial distribution of rainfall and mean surface temperature over West Africa, but simulate sometimes depending the region lower or higher values than what was observed from observations data.



The analysis of the compound extremes of rainfall and temperature shows a strong occurrence of the dry/warm mode over the northern Sahel during June–September (JJAS) period, as well as over the Guinean regions during February–May (FMAM). These strong values are probably due to the weak precipitation recorded in these zones during the considered seasons. Results show a strong occurrence of the compound wet/warm around  $14^{\circ}\text{N}$  (over the Sahel) and over some parts of the Guinean regions during JJAS and most parts of the Guinean zone during FMAM. This could be due partly to the strong convection and high precipitation amount over these zones during the corresponding season.

The analysis also shows a good performance of the CMIP5 models in representing the compound extremes of rainfall and temperature over West Africa at the seasonal and intraseasonal timescales in spite of the presence of some biases.

The study shows that the dry/warm mode will increase over the Sahel (western and central) and the Guinean zone during the near and far futures under the RCP8.5 emission scenario. The compound wet/warm will decrease over the Sahel (western and central) and the Guinea zone in the near and far futures.

Results provide strong evidence that temperature variations in West Africa are linked to the hydrologic cycle. This study shows that most parts of the western and central Sahel and the Guinean zone will need supplementary irrigation as an adaptation strategy for the protection of the agricultural sector in the near and far futures.

This study could be extended to the occurrence of drought and extreme heat over West Africa. Despite the results obtained, additional works are needed to better characterize the spatial distribution of the compound extremes of rainfall and temperature over West Africa for the present-day but also for the future using climate change scenarios because extremes in rainfall and temperature have disproportionate impacts on humans and environment.

## Acknowledgments

The authors would like to thank the Assane SECK University of Ziguinchor, the ‘Fond d’Impulsion de la Recherche Scientifique et Technologique’ program of MESRI (Senegal), the LMI-ECLAIRS2 and the LMI-NEXUS for their support.

## Data availability statement

Data used in this study are the outputs of the CMIP5 simulations. The Earth System Grid Federation (ESGF) website for downloading the CMIP5 models is: <https://esgf-node.llnl.gov/search/cmip5/>.

## Funding

This research was partly funded by the IRD (Institut de Recherche pour le Développement; France) grant number UMR IGE Imputation 252RA5.

## Any ethical statement

The authors declare any ethical statement and no conflict of interest regarding the publication of this paper.

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