

Impact of Climate Change on Rainfall Characteristics over West Africa

By

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(MET/19/3750)

A Thesis of the Doctoral Research Programme of the West Africa Climate Systems, under the West Africa Science Service Centre on Climate Change and Adapted Land Use, in the Department of Meteorology and Climate Science submitted to the School of Postgraduate studies in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Meteorology and Climate Science of the Federal University of Technology, Akure, Nigeria.

July, 2023

DECLARATION

I hereby declare that this thesis was written by me and is a correct record of my own research work.

It has not been presented in any previous application for any degree of this or any University.

All citations and sources of information are clearly acknowledged by means of references.

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CERTIFICATION

We certify that this Dissertation entitled “Impact of Climate Change on Rainfall Characteristics over West Africa” is the outcome of the research carried out by Boubacar DOUMBIA under the WASCAL DRP-WACS in the Department of Meteorology and Climate Science of the Federal University of Technology, Akure.

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ACKNOWLEDGEMENTS

This Ph.D programme is fully supported by the German Ministry of Education and Research (BMBF) through the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL). I am therefore grateful to WASCAL for granting me the financial support for the study and research visit University of Marburg.

I sincerely thank the executive Director and staff of WASCAL Head office, Accra, Ghana and the Director, Prof Z. D. Adeyewa and staff of WASCAL GRP-WACS FUTA, Nigeria for their strong support and encouragement throughout the period of the study. I am also grateful to Dr. A Akinbobola, the Head, and the staff of Meteorology Department, FUTA, Nigeria, for their cooperation.

I am greatly thankful to my supervisors Dr. E. A. Adefisan from FUTA and Prof B. J. Omotosho who trusted me and gave me the opportunity to accomplish this work. Thanks for your advice and guidance during these years.

I am also grateful to Dr. B. Thies, and Prof. J. Bendix the Head of the Laboratory of Climate Change and Remote Sensing (LCRS).

I am deeply thankful to all the staff of the Phillips University of Marburg.

Many thanks to my external examiners, Prof. Leonard AMEKUDJI and Prof. NANA. A. B. Kluste from Ghana.

Thanks to all my colleagues.

DEDICATION

This work is dedicated to everyone who contributed to my education from my family to all the teachers who trained me during these long years.

ABSTRACT

The impact of climate change and variability on West African precipitation has significant consequences for the socio-economic activities of the region. In this study Global Precipitation Climatology Center (GPCC), Climate Hazard Group Infrared Precipitation with Station data (CHIRPS) and Coupled Model Intercomparison Project (CMIP5 and CMIP6) are used to study rainfall patterns over West Africa during Monsoon months (JJAS). The study aimed to determine which of the models best reproduced the observation data over West Africa by comparing biases of each model and their ensembles over each subregion and the entire West Africa. This study utilized various datasets, including GPCC, CHIRPS, CMIP5, and CMIP6, to analyze the spatial distribution, variability, and trends of rainfall in West Africa during the summer months of June to September (JJAS). The analysis focused on the Sahelian, Savannah, and Guinean zones, using daily rainfall indices such as consecutive dry days (CDD) and wet days (CWD). The daily data has been processed over West Africa during the period (1983 to 2012) for historical, (2021 to 2050) for near forecasting and (2071 to 2100) for far future trends. The indices are, maximum 5 days (RX5DAY), heavy and very heavy rainfall (R10MM and R20MM), the percentile (R75p, R90p, and R95p) and simple daily intensity (SDII). The findings revealed a stronger correlation between CMIP6 model and the observation dataset, indicating that CMIP6 better reproduced the rainfall patterns over the region compared to CMIP5. The study indicated a change in the western and northeastern areas of West Africa. Central West Africa showed a dynamic influence on precipitation indices under various climate change scenarios. The SSP5-8.5 scenario from CMIP6 model predicted significant increases in R10MM, R20MM, and RX5DAY compared to the current climate. The study's findings have implications for flood modeling and watershed management.

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LIST OF ABBREVIATIONS

AEJ:	African Easterly Jet
AEWs:	African Easterly Waves
BMBF:	German Ministry of Education and Research
CDD:	Consecutive Dry Day
CHIRPS:	Climate Hazards group Infrared Precipitation with Satellite data
CMIP:	Coupled Model Intercomparison Project
CWD:	Consecutive Wet Day
ENSO:	El Nino North South Oscillation
ETCCDI:	Expert Team on Climate Change and Detection Indices
GPCC:	Global Precipitation Climatology Center
GPCP:	Global Precipitation Climatology Project
IPCC:	International Panel on Climate Change
ITCZ:	Inter-Tropical Convergence Zone
ITD:	Inter-Tropical Discontinuity
JJAS:	June-July-August-September
MBE:	Mean Bias Error
NCAR:	National Center for Atmospheric Research
R10mm:	Heavy Precipitation

R20mm:	Very Heavy Precipitation
R75p:	75 th percentile
R90p:	90 th percentile
R95p:	95 th percentile
RCMs:	Regional Climate Models
RegCM:	Community Regional Climate Model
RMSE:	Root Mean Square Error
Rx5day:	Highest five (5) day Precipitation
SDII:	Simple Daily Intensity Index
SSP:	Shared Socioeconomic Pathways
SST:	Sea Surface Temperature
STD:	Standard Deviation
STJ:	Subtropical Jet stream
TAMSAT:	TAMSAT stands for 'Tropical Applications of Meteorology using SATellite and ground-based observations'
TEJ:	Tropical Easterly Jet
TRMM:	Tropical Rainfall Measuring Mission
WAM:	West African Monsoon

WASCAL: West African Science Service Centre on Climate Change and Adapted Land
Use

WASM: West African Summer Monsoon

WAWJ: West African Westerly Jet

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Rainfall is essential in West Africa and socio-economic activities of its inhabitants are highly linked to rainfall variabilities.

West Africa is a highly populated area with around 419 million; 52.3% of population are rural and the total land area is 5,112,903 km² based on World Population Prospects (2022) https://en.wikipedia.org/wiki/West_Africa. The region is demographically and economically one of the fastest growing on the African continent. Most of the people derive their livelihood from agriculture that is highly dependent on climatic conditions. While the entire region is favorable for rainfed agriculture, the savanna and the Sahel are also characterized by livestock activities. Agriculture is a dominating economic factor in the region; and it is particularly depending on atmospheric moisture supply from the southern Atlantic, called the monsoon, which produces the precipitation. The annual cycle of the West African monsoon precipitation is a primary feature of West African Climate Sow *et al.* (2020). The rainfall mainly start from April to October, with major differences between the wetter Guinean region where precipitation displays two annual peaks (in June and in September), the semi-arid Savannah with a rainfall period from May to September and the more arid Sahelian region, where it displays a single peak in August Sow *et al.* (2020).

However, rainfall is more and more affected by climate change. Increasing dry and wet spells led to extremes, drought and flood years over the past decades, causing a change in the annual cycle of monsoon precipitation e.g. Sylla *et al.* (2015); Sarr *et al.* (2017); Faye *et al.* (2021).

Particularly the western Sahel seems to be the most sensitive region to anthropogenic climate change Sylla *et al.* (2016). Studies revealed substantial increases in both, dry days and extreme precipitation intensity. Between 1983 and 2012, also the Gulf of Guinea have experienced more intense precipitation events Todzo *et al.* (2020). In the entire region, an increasing trend of extreme heavy precipitation is observed over the last decades Barry *et al.* (2018). This implies that West African countries area already facing important adaptation challenges Sow *et al.* (2020). Recently, Quenum *et al.* (2021) found a positive trend in consecutive dry days (CDD), simple day indices (SDII) and extreme heavy precipitation (R30mm), and a negative trend in consecutive wet days (CWD).

Furthermore, projection on climate change point to further changes of the rainfall in a future climate. A few studies by Kumi and Abiodun (2018) for instance showed that an increase in global warming will enhance the onset of late rains over the entire West African region under the RCP4.5 scenario, but reported an opposite behavior under RCP8.5.

While the findings points to increasing problems in rainfall supply, several studies e.g. Sow *et al.*, (2020) found strong uncertainties in the simulation of several important parameters, such as the CWD and the CDD over the Sahel and the Guinean areas. Several studies based on CMIP6 HighResMIP scenarios on West African Precipitation found that the annual peak of precipitation in August appears to be underestimated by some of the models and the ensemble mean in whole West Africa (Felix *et al.* 2020). Faye and Akinsanola (2021) evaluated extreme precipitation indices over West Africa in CMIP6 models. They found that CMIP6 models reasonably reproduce the spatial patterns of the extreme precipitation indices over the entire region, although their performance is quite different between Sahel and Guinea coast sub regions. However, we cannot solve whole West African climate issue over only two regions Akinsanola *et al.* (2021). A main

problem of uncertainties in the studies is that only two climatic zones are investigated by the most studies. However, West Africa has at least three major climatic zones: The Sahel, savanna and Guinean regions (Kouassi *et al.* 2015). Each region has its specific agro-climatic characteristics and thus might be affected by climate change in a different way, so it is essential to characterize the strengths response of each climatic zone during the last decades. Only a few studies have investigated the three sub regions of West Africa and they only focused on the seasonal aspect of rainfall in West Africa, (Kumi and Abiodun. 2018). The annual cycle of rainfall was investigated by a few other studies, but again using only two sub regions (Sahel and Guinean Coast) and do not include the Savannah, (Gang *et al.*, 2016; Sow *et al.*, 2020).

The temporary evolution of annual cycle with consecutive dry and wet days (CDD and CWD) over each sub-region in West Africa highlighted with accuracy the response of different regions to climate influence. The dry and wet climatologic period can be identify by the process of these two precipitation events, the length of rainfall is also mainly link to these precipitations indices due to the process of onset and secession period. In this study we focused on the ability of CMIP5 and CMIP6 model to capture the annual duration process of CDD and CWD over Guinea , Savannah and Sahel zones in order to bring out the drought and flood risk of each Climatic zones over West Africa (Srivastava *et al.*, 2020). Previous studies have well emphasized rainfall feature over West Africa especially Guinea and Sahel zones have been most relevant, noted that a very big area and uncertainties are observed between Sahel and Guinea zones, this region is called Savannah, (Biasutti *et al.*, 2019; Marlon *et al.*, 2018). In addition to the Sahel and Guinea this study investigate the rainfall pattern over Savannah zone.

Thus, there is currently little information available on the future development particularly of changes in the intensity and duration of extreme events (heavy rains, droughts) over the three

subregions of West Africa, and the ability to reproduce them by climate model scenarios (CMIP5 and CMIP6). Consequently, this study examine the rainfall characteristics of six extremes precipitation indices (CDD, CWD, R10mm, R20mm, Rx5day and SDII) over the whole of West Africa during the monsoon period (JJAS) and the (CDD and CWD) annual cycle will be studied over the three subregions. Furthermore, there is need to understand the response of each climatic zone to the climate change. Thus this study is focused on how West African summer rainfall is influenced by climate change and it also assess the performance of CMIP5 and CMIP6 to capture the climate of the region that are the two last models of the project and by the way help improving future models. Therefore, the present study intends to provide more information on the Sahel, Savannah and Guinea because most of the last floods happened in the two last areas according to (Salome *et al.*, 2017; Pape *et al.*, 2020). Using both models on the same subregion will allow us to identify which of the two models is more suitable.

1.2 STATEMENT OF PROBLEM

West Africa is at risk of flooding and drought which can lead to famine and disease and displacement due to the effects of climate change Patrick (2022). Climate change is causing major changes in the precipitation characteristics of West Africa, Oyebande *et al.* (2015). A change in the frequency, intensity, duration and length of rainfall in the region is noted by other study (Sylla *et al.*, 2016). A variety of methods have been used to measure changes in precipitation properties in West Africa. This includes using satellite data, surface rain gauges and climate models. These impacts include increased frequency and intensity of extreme weather events, increased number of dry days and reduced annual precipitation totals, (Adegoke *et al.*, 2017). These changes have had major impacts on agriculture, water resources and human health in the region, leading to increased poverty, malnutrition and other negative impacts. In conclusion, climate change is

having a major impact on the precipitation characteristics of West Africa. It is important to understand the effects of these changes in order to develop strategies to mitigate the effects of climate change.

1.3 AIM AND OBJECTIVES

1.3.1 Aim

The aim of the study is to investigate the impact of climate change on rainfall characteristics over West Africa in near and far future from climate project of better certainty.

1.3.2 Objectives

Specific objectives of the research are to:

- (i) evaluate the selected data of CMIP5 and CMIP6 in their performance to reproduce the West African climate;
- (ii) determine the changes in rainfall characteristics in the near and far future over West Africa and;
- (iii) determine the change of rainfall evolution for better prediction over West Africa.

1.4 JUSTIFICATION

West Africa zone has been reported as one of the most vulnerable zones to climate change, so we must pay attention to this region in making development actions that start with research and operational activities. A lot of work has been done in West Africa however, some efforts need to be made in the area of climate change specifically in the sub-regions such as the Sahel, the Savannah, and also the Guinean zone. It is well known that precipitation reduction has a crucial effect on economic activities such as agriculture, energy production and food security over West Africa. Taking into account changing climate by natural or human activities, improvement of

precipitation efficiency should be one of the priorities in developing countries. Moreover, most of the socioeconomic issue in West Africa comes from precipitation reduction. This study will allow scientists to get recent information and it leads to understand how climate change affects rainfall in over Sahelian region in order to help making mitigation. Knowledge from this is important for policy making. The impact of climate change on rainfall characteristics is critic for some West African countries because their economy is mainly based to energy generation in using hydro-powered, they make rain-fed agriculture and fishing. The effects of climate change in West Africa are already being felt, with increased temperatures, decreased rainfall, and more extreme weather events. These changes are expected to worsen in the coming years, leading to further disruption of ecosystems and economies of the region. Studying West African climate change can provide valuable insights into the causes and effects of climate change in the region and it can also help to inform global efforts to address climate change.

1.5 CONTRIBUTION OF THE RESEARCH TO KNOWLEDGE

The results obtained from the research have been able to:

- i. improving knowledge regarding the current climate conditions in West Africa by studying factors such as rainfall fluctuations, extreme weather events, and changes in precipitation patterns across both space and time;
- ii. future climate projections based on shared socioeconomic pathways, policymakers and the government can gain valuable insights into the potential climate trends expected to occur in West Africa, enabling them to make informed decisions and develop appropriate strategies, and
- iii. develop suitable policies that address both adaptation and mitigation in West Africa posed by climate change.

CHAPTER TWO

LITERATURE REVIEW

2.1 WEST AFRICAN CLIMATE SYSTEM

The West African Climate system is linked to some climate drivers like monsoon system, tropical easterly Jet, West African westerly Jet, African Easterly Jet, temperature, Intertropical Convergence Zone (ITCZ).

2.1.1 West Africa Topography

The Atlas Mountains, which span 8 million square kilometers and 17 nations, are home to a variety of landforms, including the alluvial valleys of Senegal and Ghana, the lowlands and sands of the Sahel, and the undulating hills of Togo. The rough peaks of Niger and Guinea are higher than 1,800 meters, (Christophe *et al.*, 2009). The fourth part of Africa is made up of West Africa, which has a variety of ecosystems, bioclimatic regions, and habitats ranging from rainforests to deserts. West Africa can be separated internally based on its physical characteristics. According to (Dominique *et al.*, 2016), relief alone is not the cause of West Africa's significant regional diversity. Generally speaking, West Africa is low and flat, this distinguishes it from the other significant regions of Africa. Except for the mountainous regions of the Fouta Djallon, the Guinea Highlands, the Jos Plateau, and the Air Mountains, the relief also contributes nothing to break up the latitudinal and zonal patterns of the climate and the vegetation. Britannica (2023).

2.1.2 African Climate

There is only one rainy season that lasts for one to six months throughout the majority of West Africa, from the sub-Saharan region to the wet coastal nations. The southern region of the coastal nation from Liberia to Nigeria is the only place where there are two rainy seasons, one long and

one brief. The movement of tropical fronts the meeting point of two air masses, one hot and humid and the other cool and dry has an impact on the climate. Each year, this front moves one to two months later than the position of the sun, moving north and south. Above the Sahara Desert in winter (December to March), there is an anticyclonic high pressure system. It feeds harmattan, a dusty, dry wind that blows from the northeast rather consistently, drying the terrain down to the coast. In the summer, low pressure systems take the role of anticyclones, bringing warm, humid winds from the Atlantic to the southwest (Gulf of Guinea) (Arbonnier., 2000; Zwarts *et al.*, 2009). In general, the dry season lengthens and yearly precipitation declines as latitude rises. In contrast, precipitation increases at southern latitudes and the dry season often lasts just four months (December to March). Together with latitude, maximum temperature and temperature range also rise. Temperature differences are minimal in the wet south, but range from 0°C to nearly 45°C in the dry north (Church. 1966). The climate in West Africa is controlled by the interaction of two air masses, the influence of which varies throughout the year with the north-south movement of the Convergent Tropical Zone (ITCZ), (Nicholson *et al.*, 2018). From November to February, hot, dry continental air masses originating from a high pressure system in the Sahara create dust storms across much of West Africa. In summer, moist equatorial air masses form over the Atlantic Ocean to bring annual monsoon rains (Nicholson *et al.*, 2013). Adefisan and Abatan (2015) studied the agroclimatic zoning of Nigeria based on rainfall characteristics and the index of drought propensity. They analyzed the start and end dates, duration of the rainy season, and amount of rainfall. The research region has been divided into three main climate zones based on studies of the features of rainfall and the index of drought-proneness. The research revealed that the contours for rainfall onset dates (ROD), rainfall cessation dates (RCD), and length of rainy season (LRS) in the first zone, Guinea, are constrained and have a strong gradient, but the contours for the Sahel

zone, are open and have a mild gradient. Savannah, has a scattered contour due to an uneven grade, placing it between Sahel and Guinea zones. The four climate zones over Nigeria, according to their result, are humid, sub-humid humid, sub-humid dry, and semi-arid.

Sanogo *et al.* (2015) conducted a study on the characteristics of West Africa's rainfall recovery, analyzing its spatial and temporal elements. They employed various techniques, such as precipitation indexes and two definitions, to identify the start and end of the rainy season. The study revealed patterns of daily rainfall frequency, intensity, and changes in the monsoon season length. Furthermore, they observed a correlation between ARC2 and monthly rain gage data from June to September. Utilizing the Standard Precipitation Index (SPI-12) to assess regional rainfall variations, an increase in total rainfall was noted over the Guinean coast with more intense wet spells. Additionally, a current trend was also detected with some stations along the Guinea Coast revealing no trend at all. Nevertheless, there was a consistent rise and extension of rains over the second rainy season observed on the Guinea Coast which were much less significant than other findings from the study.

2.1.3 Tropical Easterly Jet

The Tropical Easterly Jet (Jet Stream) is a meteorological term for upper-level easterly winds that begin in late June and continue through early September. This powerful air current forms in the upper atmosphere during monsoons and stretches from Southeast Asia to Africa. The tropical easterly jet (TEJ) developed rapidly after the subtropical jet stream (STJ) moved to the northern Himalayas (early June). The Tropical Eastern Jet flows east-west across the Indian Peninsula and North Africa. The formation of the TEJ results in a reversal of the upper air circulation pattern (high pressure to low pressure) and a rapid onset of monsoons. Recent observations suggest that the magnitude and duration of ocean warming has a direct impact on monsoon rainfall, recent

observations have revealed that the intensity and duration of heating of ocean has a direct bearing on the amount of rainfall in West Africa by the monsoons. This tropical jet stream affects the formation and duration of Indian and African summer monsoons. When the summer temperature of air over ocean remains high for a sufficiently long time, it helps in strengthening the easterly jet and results in heavy rainfall, (Hastenrath and Stefan 1985).

2.1.4 West African Westerly Jet

The West African westerly jet (WAWJ) is a low-level (925 hPa) jet centered near 10°N, directed from the eastern Atlantic onto the West African coast. It persists from June to September, with maximum velocities exceeding 5.5 m/s in August. It is clearly distinguished from the West African monsoon (WAM) flow and it plays a dominant role in Sahel rainfall in August on decadal timescales. Despite these findings, the relationship of the WAWJ and the West African precipitation is not well known on seasonal and diurnal timescales. The jet plays a critical role by advecting moisture from the East Atlantic into the Sahelian region. Furthermore, the associated moisture flux of the jet is usually significantly greater than that of the southerly flow of the WAM during this period (Liu *et al.*, 2020).

2.1.5 West African Monsoon

The West African monsoon, characterized by alternating southwest winds and surface harmattan, occurs between 9° and 20° north latitude. While northeasterly winds are always found farther north, southwesterly winds are only found farther south. Rainfall is irregular during high sunshine periods from June to August, and it remains mostly dry at 20°N throughout the year. Droughts farther south are less severe and shorter, persisting for only about half a year at 12°N and disappearing completely at 8°N. Additionally, a milder drought occurs further south during the months of high solar radiation when the southwest monsoon is at its strongest. Similar to the Java

monsoon drought, the current dry spell is attributed to the arrival of parched surface air from anticyclones that originate beyond the Southern Hemisphere's equator. Nevertheless, this phenomenon departs from the equator much like the monsoon "break-in" experienced in southern India (Smith *et al.*, 2023). Berthou *et al.* (2019) studied the improved climatological characteristics of precipitation over West Africa at convection-permitting scales confirmed that the region's climate is distinct and difficult to replicate using standard resolution climate models because a significant portion of precipitation originates from organized deep convection. They revealed a rise in mean precipitation, which improved the mature phase of the West African monsoon but degraded the early and late phases. It also revealed a better depiction of wet and dry spells. The findings revealed a decreasing mean bias over the Sahelian region in JAS, from 10 to 30% to typically less than 10%, as well as an improvement in the frequency and severity of wet days. Nonetheless, they confirmed that CP4A continues to highlight the need for more model advancements.

2.1.6 Sea Surface Temperature (SST) impact on West Africa Climate

With rising mean temperatures, there has been a simultaneous increase in mean precipitation. This comes as no surprise, as higher temperatures lead to greater evaporation, resulting in a need for more precipitation to maintain balance (IPCC, 2014). West Africa faces fluctuating precipitation levels on both short-term and long-term time scales. Additionally, severe droughts ravaged the region in the 1970s and 1980s, caused by the impact of sea surface temperature (SST) effects, as evidenced by (Almazroui *et al.*, 2017). Due to the connection between precipitation and temperature, there are notable variations in precipitation worldwide. As temperature increases, so does the amount of water vapor in the atmosphere, which alters the way precipitation is dispersed over time and space, according to (Bucchignani *et al.*, 2018). The augmentation in temperature

augments the quantity of water vapor, thus impacting the distribution of precipitation, creating a unique pattern of precipitation around the world (Barkhordarian *et al.*, 2018). In the study of Climate Change across West Africa: Current Patterns and Future Projections, by Sylla *et al.* (2016), in addition to the CORDEX multi-GCMs/multi-RCMs projections, they utilized a variety of observation products. First, the findings demonstrated that the area has warmed recently in response to an increase in anthropogenic GHG forcing. The future temperature increase over West Africa will be between 1.5 and 6.5 °C, according to projected climate change from the multimodel CORDEX experiments. Additionally, it demonstrates that future precipitation variations can vary between 30 and 30% in comparison to the reference period, highlighting the fact that anticipated precipitation over the region is subject to significant uncertainty. They assert that in addition to these anticipated climate changes, recent literature has focused on other significant aspects of climate change over West Africa, such as the shortening of the rainy season and the growing season, the intensification of extreme events prior to the mature monsoon season, and the extension of torrid.

Over time, significant increases were found in the near-surface temperature anomaly when comparing 1995-2010 and 1979-1994, (Grant *et al.*, 2011). Noticing a rise in mean surface temperatures annually and seasonally, investigations of African temperature trends have been conducted, the findings show that temperatures in Northern Africa have surged in the current century (Morice *et al.*, 2021). More severe and frequent weather events, including but not limited to storms, floods, and heat waves, could be the potential outcomes of rising temperatures. The effects of droughts spread even further and reach the realms of health and food production, primarily in West Africa. Insufficient access to food, malnutrition, and increased susceptibility to infectious diseases are some of the ramifications. Economic consequences, such as reduced

agriculture productivity, escalated food prices, and livestock loss, are also likely outcomes of droughts. These assertions have been substantiated by various sources, including (Ngcamu *et al.*, 2020 and John *et al.*, 2020).

2.1.7 African Easterly Jet (AEJ)

The African Easterly Jet (AEJ) is an important feature of the atmospheric circulation over North Africa and the tropical Atlantic during summertime, it is characterized by strong winds blowing from east to west at an altitude of around 3-5 km, it also plays a crucial role in the climate of West Africa, as it transports heat and moisture from the equatorial regions towards the Sahara desert (Bercos *et al.*, 2021).

It is part of a complex system that includes Saharan mineral dust aerosols and West African precipitation, the formation of the AEJ is closely linked to the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ), which is a band of low pressure that encircles the Earth near the equator. During the summer months, the ITCZ moves northwards, causing a pressure gradient between the equator and the Sahara desert. This pressure gradient creates the AEJ, which is further strengthened by the temperature difference between the warm land surface and the cooler ocean surface (Reij, and Smale. 2009). As the AEJ blows across the Sahel region, it picks up moisture from the Gulf of Guinea and transports it towards the Sahara desert, where it can cause rainfall (Emily *et al.*, 2020). The topography can also influence the AEJ, with flattened topography causing it to disappear and weaken the monsoonal flow (Hamilton *et al.*, 2020). The AEJ is one of the phenomena driving regional as well as global atmospheric circulation, and it generates African easterly waves (AEWs), (Joshua *et al.*, 2021). African Sahel rainfall trends traits, mechanisms, and causes was investigated by Biasutti *et al.*, (2018), they found that Sahel rainfall is dynamically linked to the global Hadley cell and to the regional monsoon circulation; however, their review is

only focused on regional and continental trends in seasonal accumulation, the timing of the rainy season, and the mean intensity of daily rainfall. They took note of the relationship between the advance of the ITD and the warming of the Desert as well as how the rain band continues to remain south of the ITD. The findings pointed to rising rainfall totals in the middle and eastern Sahel but falling totals in the westernmost regions, as well as a concentrated rainy season with heavier, more frequent rains, drier conditions at first and wetter ones toward the end of the growing season.

Despite its importance, the AEJ remains a challenging phenomenon to study due to its location and variability. The Sahel region is sparsely populated and lacks the infrastructure for extensive meteorological observations, while the AEJ itself can vary in strength and location from year to year, (Hosten *et al.*, 2018).

To overcome these challenges, researchers have turned to remote sensing techniques such as satellite imagery and computer models. These tools can provide valuable insights into the behavior of the AEJ and its impact on the climate of West Africa.

2.2 IMPORTANCE OF THE WEST AFRICAN MONSOON RAINFALL

Local cloud formation is greatly impacted by the humidity and dust pathways associated with the West African Monsoon (WAM) system, which is the main supplier of rainfall to the agricultural region of West Africa (Niang *et al.*, 2020). While monsoons are typically associated with destructive rainstorms, they play a vital role in crop production (Krishnamurti *et al.*, 2023). Therefore, it is essential to comprehend the transport mechanisms associated with WAM.

Every summer, the West African Monsoon blesses the region with rain thanks to a change in wind direction. The northeasterly flow is replaced by a southwesterly flow that brings moist air from the Atlantic Ocean and Gulf of Guinea. The impact of this weather pattern is critical to the people's

lives in West Africa; it delivers vital water for crops, livestock, and other livelihoods and also provides a regular source of income. The (WAM) heavily influences the weather patterns in the western Sahel climate, Bart *et al.* (2010); Sylla *et al.* (2013), the region depends on the monsoon season to bring the water that sustains life, especially agriculture. Devoid of this season, the area would be barren and inhospitable. The farmers in West Africa find the monsoon season to be indispensable as it irrigates their crops effectively. Absent the monsoon, the agricultural output would take a major hit in the region. The West African Monsoon is crucial for the region's sustenance, as it provides water for crops, livestock, and other forms of life. Its replenishing effect on groundwater reserves and grazing lands is particularly essential. Without it, the water supply and livestock of the region would suffer. The region's biodiversity relies heavily on the monsoon, with Joseph *et al.*, (2023) stating that the farther land separates from the sea, the lesser the monsoon's impact. Not only is it for supporting the ecosystem of the area, but it is also a significant draw for tourists, providing an income for many. Without this weather pattern, the region would suffer greatly. The West African zonal wind (Figure2.1) has been drawing by (Hourdin *et al.*, 2010).

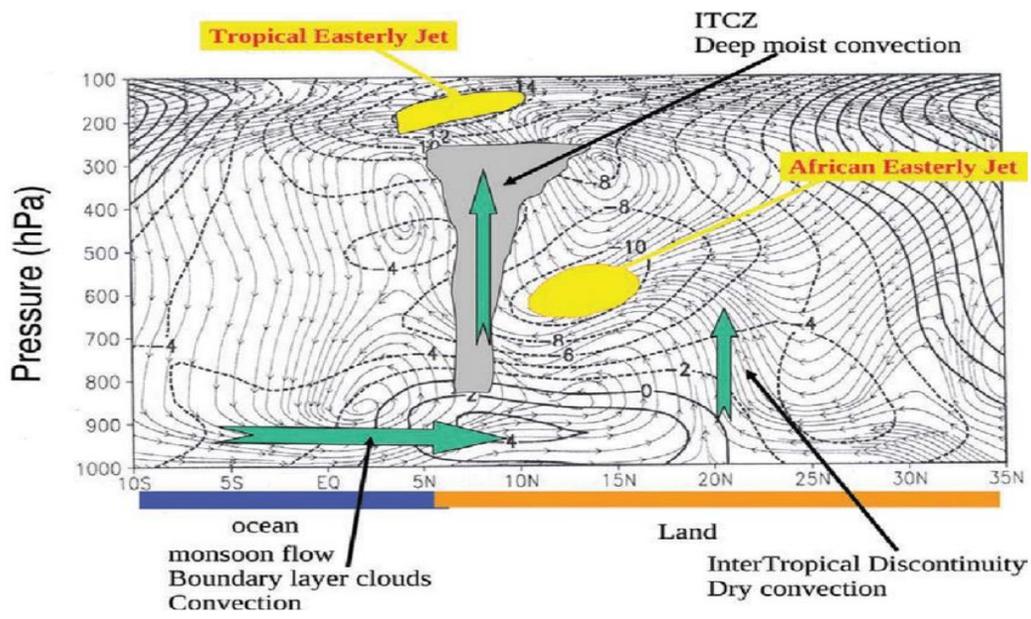


Figure 2.1: Mean Meridional Circulation (stream lines) and associated mean Zonal Wind (m/s) over West Africa during the summer season adopted from Hourdin *et al.*, (2010)

2.2.1 Socioeconomic potential of West African Rainfall

Rain is vital to the survival of countless species, including humans. Its importance is particularly evident in West Africa, where it is a key factor in the region's economy. Rainfall plays an important role in agriculture, water resources and other economic sectors, making it an integral part of the socio-economic development of the region (Takimoto *et al.*, 2008).

Rainwater is vital to agriculture in West Africa. It is the primary water source for plants, allowing them to grow and thrive. Rainfall also helps replenish groundwater and soil moisture, both of which are essential for healthy plants. Without sufficient rainfall, crop yields and the agricultural sector in the region will suffer. Rainfall is also critical to the region's water resources. It helps replenish groundwater and surface water, both of which are necessary for human consumption and other uses, and supports agricultural production that is critical to economic growth. It also helps reduce air pollution, a major problem in many parts of the region. Precipitation is beneficial to the region's socio-economic development, plays an important role in agriculture, water resources, and the economy, and is an integral part of the region's development. However, we need to calibrate precipitation according to Chagnaud *et al.* (2022) and increases in the annual maximum of daily precipitation are more likely due to stronger storm intensities. Without sufficient rainfall, water resources will become scarce and water supplies in the region will suffer. Rainfall also plays an important role in the region's economy.

2.2.2 Importance of climate modeling

Climate modeling is the process of using computer-based models to simulate the behavior of the Earth's climate system. It is a powerful tool for understanding the complex interactions between the atmosphere, oceans and land surfaces, and can help us understand the past, present and future of Earth's climate. Climate models are used to study the impact of natural and anthropogenic variability on our climate Sylla *et al.* (2015), they are used to study the effects of global warming, extreme weather conditions and other climate-related phenomena. Climate models can also provide insight into the impacts of climate change on ecosystems, agriculture and other human activities (Malhi *et al.*, 2020). They can help us understand how climate change affects water, food and energy supplies, and how it affects public health (Sarah *et al.*, 2020). Climate models are limited by the accuracy of the data used to create them. They are also limited by the complexity of the climate system itself, which is difficult to accurately model in a computer simulation.

Climate models are also limited by the computing power available to run them. Climate models can be used to assess the potential impacts of various climate change mitigation strategies (Fawzy *et al.*, 2020). Climate models can also be used to evaluate the potential impacts of proposed policies and actions, and to assess the effectiveness of existing policies and actions.

2.3 MODELING OF WEST AFRICAN MONSOON

Dosio *et al.* (2021), have referenced Ashfaq *et al.* (2020), who investigated the ICTP-RegCM CORE runs and discovered that the monsoon season was beginning later, mainly in the Sahel. They argued that this delayed start was due to a reduction in convective pre-monsoon precipitation, which was caused by a higher land boundary layer and a lack of moisture supply as winds were blowing primarily from dry areas.

Omotosho *et al.* (2000) study, they created some empirical methods for predicting the commencement and cessation, as well as the monthly and seasonal amounts of rainfall at Kano based on the features of the West African flow regime. It becomes clear that the characteristics (heat and moisture properties) of this air would unquestionably determine rainfall and its variations over the sub-region when they used the potential temperature for both dry and saturated processes and discovered that it is primarily the surface and near-surface air that ascends to form the clouds that produce the precipitation. They pointed out the limitations of using simply surface data. To confirm this limitation, Leonard *et al.* (2010) provided studies of 21st-century precipitation trends over West Africa. He simulated anomalies of precipitation, normalized rainfall, and did the GHG-forced simulated time series of the Sahel. He discovered that El Nino events increased vertical thermal stability due to a warming troposphere and deteriorated vegetation cover, which increased albedo and decreased evapotranspiration. He cited that it is difficult to accurately replicate Sahel rainfall trends because several physical forces fight to drive the trend either higher or downward. Similar to how monsoon onset and retreat, as well as interactions between the land, vegetation, and atmosphere, affect seasonal precipitation anomalies, these processes should be more accurately approximated with the considerably greater resolution of the regional model.

2.3.1 Modeling the West African precipitation using global and regional models

Emiola *et al.* (2013) investigated the inter-annual variability of precipitation and temperature in West Africa through running several CORDEX simulations. They highlighted that prior research had suggested that the differences in the annual cycles of RCMs are mainly ascribed to their different abilities of reproducing features needed for initiating and upholding WAM precipitation, including the monsoon flow, Tropical Easterly Jet (TEJ), African Easterly Waves (AEWs), and African Easterly Jet (AEJ) Diallo *et al.* (2012); Sylla *et al.* (2013), used Hovmoller diagrams of

monthly precipitation, derived from GPCP and UDEL measurements, to study the annual cycle of monthly precipitation and temperature. Their results showed that the overall annual cycle of precipitation across West Africa is relatively uniform with a peak shifting to September in majority of RCMs as well as their multi-model ensemble mean; yet there are also marked double-peaked annual cycles and some intermediate values. Lastly, all RCMs were found to perform well on average for modeling mean rainfall across different regions. Akinsanola *et al.* (2021) investigated how well sixteen Coupled Model Intercomparison Project Phase6 (CMIP6) models could replicate current precipitation extremes over Eastern Africa in both the MAM and SON rainy seasons. They used nine extreme rainfall measures to compare the findings of the models with two gridded observation data sources (TRMM and GPCP). Their analysis showed that, overall, the CMIP6 models (including their ensemble mean) tended to overestimate, underestimate, or accurately measure total wet day precipitation, consecutive wet days, very wet days, and maximum 5-day precipitation over the area for both seasons. Moreover, the CMIP6 still exhibited the same drizzling bias as earlier research on CMIP5 determined Flato *et al.* (2013; Herold *et al.* 2016; and Zhang *et al.* (2018). Additionally, their examination revealed that certain lower-resolution and moderate-resolution models performed better than higher-resolution models for specific indices.

Simulating West African precipitation with global and regional models has both advantages and disadvantages (Heiko *et al.*, 2011). Global models provide an overview of the region's climate and can be used with regional models, but are limited by their coarse resolution and are not able to take into account the influence of local topography and other factors on precipitation. Regional models are more accurate at predicting local weather patterns, but they are also more computationally intensive and require more data to run. By combining global and regional models, researchers can better understand precipitation patterns in the region. However, it is important to understand the

limitations of each model type and the data sources used to inform them to ensure predictive accuracy. Data from various sources were used to process the West African precipitation model.

Satellite data are used to provide an overview of the region's climate, while ground stations provide more detailed information about local weather patterns. Reanalysis datasets are also used to provide estimates of precipitation and other weather variables.

Data from these sources are used to process global and regional models and provide more accurate estimates of precipitation in the region. However, these data sources have their own limitations, such as limited spatial coverage and temporal resolution, which can lead to inaccurate models.

2.3.2 Modeling the West African rainfall using CMIP6

Climate models are essential tools for predicting future climate changes. CMIP6, the sixth phase of the Coupled Model Intercomparison Project, is the latest generation of climate models and is used to simulate global climate patterns. CMIP6 is specifically designed to simulate West African rainfall and its associated climatic variability, CMIP6 models are constantly updated with new data and information, making them more accurate and reliable. CMIP6 models are also useful for understanding the impacts of climate change on the region. Climate change is one of the biggest challenges facing West Africa today. CMIP6 models are a valuable tool for understanding and predicting the impacts of climate change on the region. CMIP6 models are an essential tool for understanding and predicting West African rainfall patterns. By using CMIP6, researchers can gain a better understanding of how West African rainfall will change in the future and how to best prepare for and adapt to these changes. By understanding how climate change will affect West African rainfall, researchers can better prepare for future and adapt to these changes, helping to create a more resilient and sustainable West Africa. Characterization of long period return values

of excessive daily precipitation in the CMIP6 models was examined by (Wehner *et al.*, 2020). For the future change predictions he generated and compared the 20-year return values for the extreme daily temperature and precipitation indices from the CMIP5 and CMIP6 climate models. The outcome suggested that the yearly Rx1day variations predicted by CMIP5 and CMIP6 are meaningfully different. He claimed that the Clausius-Clapeyron (C-C) connection, which has a coefficient of around 7% per degree (C) of local warming, governs the saturated atmospheric conditions that cause excessive precipitation (Allen *et al.*, 2002). They cast doubt on the CMIP6's additional contribution to boosting confidence in predictions of changes in extreme precipitation.

The Evaluation of CMIP6 Precipitation Simulations Across Different Climate Zones: Uncertainty and Model Intercomparison, Farhad *et al.* (2021) assessed the performance of precipitation estimates from 12 CMIP6 models by comparing them to observation data from the GPCP (Global Precipitation Climatology Centre) at a common 1° spatial resolution and at various temporal scales over Iran's climatic regions. They discovered that the rainiest region had a significant underestimating, and they discovered that all models typically exhibit some degree of underestimation throughout the summer. According to their findings, there are considerable differences in place and time between the accuracy of precipitation estimates. The CMIP6 models are the most accurate in simulating the climatological characteristics of precipitation and its spatiotemporal fluctuations over the arid and hyper-arid regions of the country. They provided information on the models that are appropriate for various climate zones, such MRI-ESM2-0 and CNRM-CM6-1 for humid zones (HadGEM3-GC31-LL, BCC-CSM2-MR, and CanESM5 for arid and hyper arid zones). Nana *et al.* (2021) conducted a study to examine Summer Monsoon Extreme Precipitation Events over West Africa with CMIP6 models. Three observational datasets (GPCP, CHIRPS, and TAMSAT) were used to verify the model simulations during the JJA monsoon

season. Statistical techniques such as RMSE and RSD were utilized to assess model accuracy and results showed similarities in pattern and rainfall magnitude between actual observations and models; however, significant discrepancies were observed when comparing the simulations. By analyzing African precipitation, Dosio *et al.* (2021) used advanced global models like CMIP5 and CMIP6 and various precipitation indices, such as RR1, RX1day, SDII, SM, and CDD. To further understand their findings, they used spatial representation, the annual cycle of the monthly average, and box-and-whiskers plots. After a thorough examination of their results, they discovered that there were variations across different regions including West Africa, Central Africa, and the Ethiopian Highlands. For example, SDII increased in certain areas while all ensembles predicted a significant decrease in the number of wet days across most of western Sahel during JJA. Moreover, global models forecasted an increase in SM coverage across SAH and a portion of ETH with CMIP6 covering about 95% of the land area. However, regional models exhibited a strong reduction instead. Conclusively, all ensembles indicated a notable decline in the number of rainy days over an area from 50% (CMIP6) to 100% (CORE), leading to extended periods without rain.

2.4. SIMULATING THE CLIMATE INDEX DURING SUMMER PERIOD

West African climate is known for its hot and humid summers. Simulating this climate accurately is a challenge due to its complexity and variety of conditions. The study discuss the different elements that go into simulating the West African climate during the summer period. In order to accurately simulate the West African climate and rainfall characteristics, it is important to use historical data and computer models to take into account the various factors that can affect the climate. Other techniques, such as using satellite imagery, radar data, and numerical weather prediction models, can be used to create a more accurate simulation, Kerry *et al.* (2020); Cook *et*

al. (2020) said that future simulations are generated by increasing atmospheric CO₂. Akinsanola, Ogunjobi, *et al.* (2015) examined the West African summer monsoon precipitation of CORDEX Africa by analyzing the monthly rainfall mean of four models, namely TRMM, CCLM, RCA, and REMO. They used the standardized Precipitation Index during the months of June, July, and August (JJA) as well as the inter-seasonal variance of mean monthly precipitation for the Guinea Coast, Savannah, and Sahel regions. Upon assessment, they noted that based on the TRMM precipitation model, the region receiving the highest amount of rainfall was located in the coastal part which extends from the southwestern part of Liberia down to the southeastern part of West Africa. Conversely, moderate to low levels of rainfall was observed above the latitude of 10° within the same period based on the time-latitude cross-section of monthly mean rainfall.

It is important to use a variety of techniques in order to accurately simulate the climate. Each technique has its own advantages and disadvantages, and it is important to understand the strengths and weaknesses of each technique in order to create an accurate simulation of the West African climate during the summer period. Accurately simulating the West African climate is important for a variety of reasons. Accurate simulations can help inform decision-making, such as when to plant crops or when to irrigate fields. Accurate simulations can also help with forecasting, such as predicting the intensity and duration of a storm. Accurately simulating the West African climate is a challenging task, but it is an important one. It is essential in order to make informed decisions and understand the impacts of climate change. Felix *et al.* (2020) study evaluated the Performance of CMIP6 HighResMIP on West African Precipitation from 1950-2014. They analyzed how two regions, the Sahel (15°N to 30°N) and the coast of Guinea (0°N to 15°N)) experienced June-September precipitation events using seven consortiums. While all models captured similar general patterns, some models slightly underestimated annual maximums of 200 mm/month

observed in August at both coastlines of Guinea and Sahel, as well as 100 mm/month in West Africa. To gauge agreement between the simulated data and observational data, Taylor plots were employed in their analysis.

2.5 GAPS IN LITERATURE

The literature review is beneficial because it gives a comprehensive view of the topic, which can provide ideas for future research and decisions. Despite all the studies there are some gaps in the literature.

2.5.1 Gaps in CMIP5 and CMIP6 models

Among several studies over West Africa, only a few studies focused on the model comparison (CMIP5 and CMIP6), Biasutti, (2017) did a similar study but over the world. The study will examine the differences between these two phases, the improvements made in CMIP6, and the benefits of using the latest models for climate research (Collins *et al.*, 2020). A comparison between CMIP5 and CMIP6 is useful and necessary for understanding the improvements made in the latest phase of the Coupled Model Intercomparison Project (Flato *et al.*, 2013). It is good to know whether the CMIP6 model can provide a more comprehensive view of the Earth's climate system and allow for more accurate predictions of future climate change (Eyring *et al.*, 2016). The literature review lacks information on the performance of CMIP6 models in predicting rainfall in West Africa. It is critical to explore this gap in order to gain an understanding of how accurate the model and its representation are. Furthermore, the literature review did not provide information on the impact of CMIP6 models on local weather patterns in West Africa and the three subregions. This is important because it can help identify some areas like West African three subregions where the model may need improvement.

2.5.2 Gaps in CMIP6 scenarios

Some previous studies investigated the CMIP5 scenarios over West Africa like Kumi *et al.* (2017) and found an increasing of temperature. The literature review lacks information on the potential impact of the CMIP6 scenario on precipitation in West Africa. This is an important gap because it can shed light on how scenarios will affect the West African subregions.

Furthermore, the literature review did not provide information on possible changes in local weather patterns in West Africa resulting from the CMIP6 scenario. This is important because it can help identify areas where the model may need improvement.

CHAPTER THREE

DATA AND METHODS

3.1. DESCRIPTION OF THE STUDY AREAS

West Africa lies between 0°N –30°N latitude and 20°W–20°E longitude and includes 15 countries. There are three main agro-ecological zones in this region (Figure3.1), namely the Guinea zone (4-8°N), Savannah (8-12°N) and the Sahel (12-16°N) (Omosho and Abiodun, 2007). The climate of the region is mainly determined by the West African Monsoon (WAM), which accounts for about 70% of the annual precipitation, and is characterized by local highlands such as the Guinea Highlands (11°N, 10°W), the Jos Plateau (10°N, 9°E) and the Cameroon Mountains (5°N, 12°E). The WAM is a large-scale circulation characterized by reversals in winds in the lower atmosphere of the Atlantic Ocean, transporting moisture inland (Kwesi *et al.*, 2020).

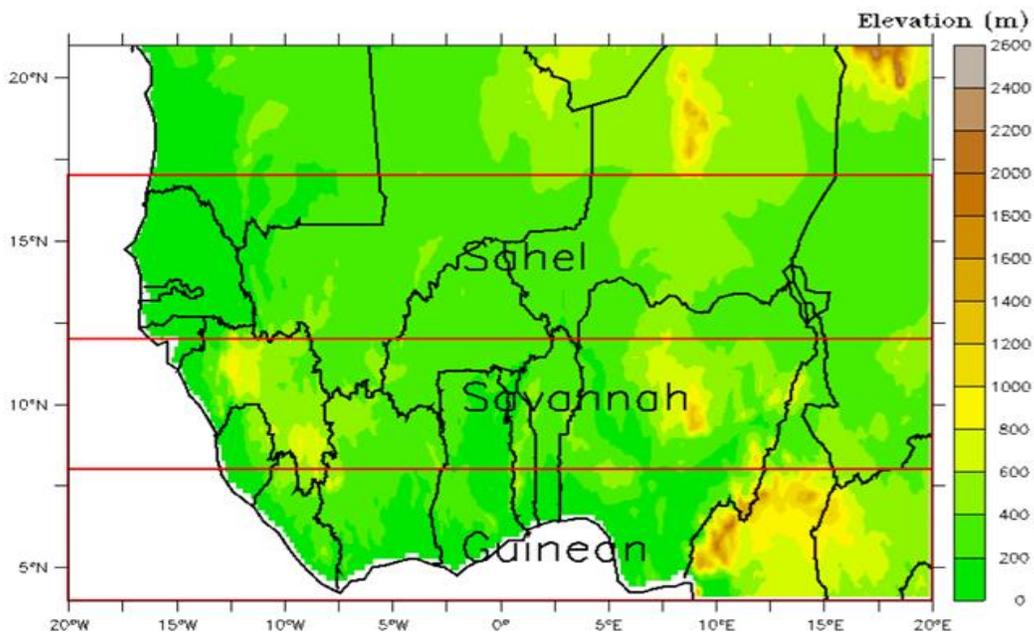


Figure 3.1: Topographic map of West Africa with its three zones demarcated by red lines, Dark brown areas denote mountainous regions. Adopted from (Omotosho and Abiodun, 2007)

3.2 OBSERVATIONS AND MODELS

The study used daily precipitation data from 1983 to 2012 from the archives of Coupled Model Intercomparison version 5 (CMIP5), version 6 (CMIP6) and two observed datasets Global Precipitation Climatology Center (GPCC) and Climate Hazard group Infrared Precipitation with Station data (CHIRPS) over West Africa. The period from 1983 to 2012 was chosen as it represents a significant span of time to capture long-term climate trends and variability while also aligning with the availability of comprehensive observational data and the historical period covered by the CMIP5 and CMIP6 models (Flato *et al.*, 2013; Eyring *et al.*, 2016; Ayugi *et al.*, 2021). This period was used to evaluate the performance of both CMIP5 and CMIP6 outputs over West Africa in simulating daily precipitation amount, trend and variability over a climatic period. The second set of datasets used was daily precipitation data from 2021 to 2050 for near and from 2071 to 2100 for far future climate using CMIP6 output data. Some precipitation indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) such as Dry days, Wet days, and Heavy precipitation were used to explore precipitation trends and variations over West Africa in near and far future climates. Annual cycle of rainfall and the seasonal (JJAS) amount were also used to identify the change of rainfall characteristics over West Africa. The study area was divided into three sub regions in order to closely identify the rainfall characteristics over each sub region and the entire West Africa.

The GPCC Full Data Daily Version 2020 at 1.0° used in this study has been downloaded from Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data. https://10.5676/DWD_GPCC/FD_D_V2020_100. The GPCC also utilizes cutting-edge technology to analyze and interpret data, it is continuously innovating and developing new technologies to better understand the global water cycle. It is also helping to identify areas of the world that are most

vulnerable to the effects of climate change. The GPCC is a valuable resource for researchers, policymakers, and the public. Its data and insights are helping to inform decisions on how to best manage our water resources and adapt to the changing climate.

The performances between observed data and models were evaluated by using some statistical parameters like Bias, correlation coefficient and standard deviation.

The Global Precipitation Climatology Centre (GPCC): operated by DWD under the auspices of the World Meteorological Organization (WMO) The Global Precipitation Climatology Centre (GPCC) provides global precipitation analyses for monitoring and research of the earth's climate. The GPCC daily data is one of the favourite observed data used by previous study, (Akinsanola *et al.*, 2016).

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a 30 year quasi-global rainfall dataset. CHIRPS incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring. The Climate Hazard Group Infrared Precipitation with Station data (CHIRPS) is Quasi-global daily satellite and observation based precipitation estimates over land, and getting from <https://catalogue.ceda.ac.uk/uuid/4e53c2aee3fe44e7aa107c163696d2e7>. The data set runs from 1981 to the near present.

3.2.1 The Coupled Model Inter-comparison CMIP5 and CMIP6 models

The Coupled Model Inter-comparison Project (CMIP) is a set of climate models used to study past and future climate changes. CMIP5 and CMIP6 are two of the most recent versions of the project. CMIP5 was released in 2013 and CMIP6 was released in 2018, CMIP6 has an improved model of the ocean-atmosphere system, which is expected to give more accurate predictions of future trends.

Comparing IPCC AR5 and AR6 warming projections

Projected likely (AR5) and very likely (AR6) warming between the 1850-1900 and 2081-2100 periods.

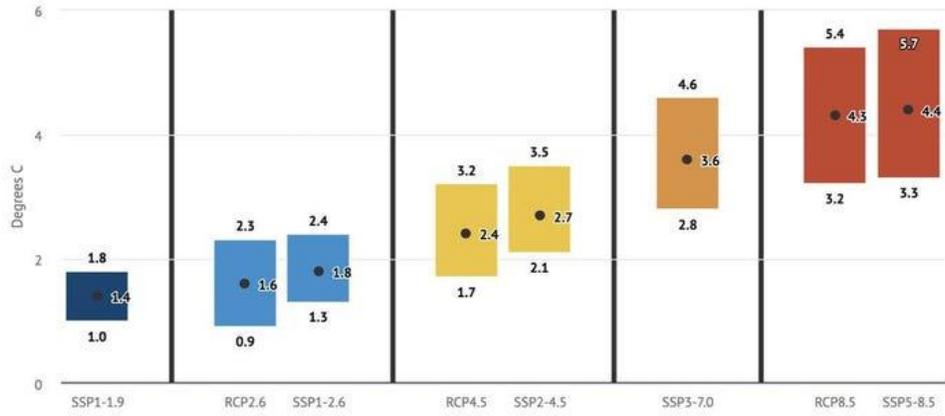


Figure 3.2: CMIP5 and CMIP6 models scenarios representation

CMIP5 and CMIP6 differ significantly as the latter centers on future scenarios. CMIP5 predictions rely on four GHG concentration pathways and 2100 radiative forcing values, as outlined by (Vuuren and Riahi, 2011). In contrast, CMIP6 utilizes socioeconomic pathways (SSPs) within the framework of the CMIP5 scenarios. All the CMIP5 and CMIP6 data were downloaded from <http://esgf-node.llnl.gov/cmip5> , and <http://esgf-node.llnl.gov/cmip6> respectively.

3.3 MODEL SETUP FOR THE SIMULATION

3.3.1 CMIP Model configuration

Six models output were selected from CMIP5 (CanESM2; CMCC-CESM; CNRM-CM5; IPSL-CM5A2; FGOALS-s2 and MIROC5) and their corresponding ones from CMIP6 Historical data to achieve the first objective. These specific models were chosen for analysis over West Africa due to their diverse representation of physical processes, historical performance, and availability of key variables relevant to West African climate dynamics such as precipitation, temperature, and circulation patterns (Wang *et al.*, 2019; Voldoire *et al.*, 2019; Oudar *et al.*, 2020; Jiang *et al.*, 2020; Sellar *et al.*, 2020). These models collectively provide a robust ensemble to assess future climate projections and capture uncertainties associated with different modeling approaches. The same six models data is used for three Shared Socioeconomic Pathways (SSP) scenarios from CMIP6 to determine the near and far future trends of West African Precipitation, which are SSP1-2.6, SSP2-4.5 and SSP5-8.5. These scenarios incorporate SSP1-2.6, SSP2-4.5, and SSP5-8.5, which represent different emission levels (Figure3.2). The CMIP6 scenarios provide an important tool for understanding the impacts of different emissions scenarios and how they could affect the climate system. These scenarios can be used to develop strategies and policies to reduce emissions and help limit global warming. By understanding the impacts of different emissions scenarios, we can make informed decisions about our future.

SSP1-2.6 is a low-emissions scenario that aims to limit global warming to 1.5°C above pre-industrial levels. This scenario is favorable because it allows us to discern the implications of a low-carbon future and the implications for the climate system.

SSP2-4.5 is an intermediate emissions scenario that aims to limit global warming to 2°C above pre-industrial levels. It is useful for scientists because it allows us to understand the impact of higher emissions in the future and how this influences the climate system.

SSP5-8.5 is a high emissions scenario that aims to limit global warming to 3°C above pre-industrial levels. The scenario can be used to develop strategies and conduct to reduce emissions and help limit global warming.

3.3.2 Model representation

The models CMIP5 and CMIP6 are tabulated in the Table3.1

Table3.1 Information of the six climate models

S/No	Model	Institute	Resolution (°lon×°lat)	References
1	CanESM5	Canadian Earth System Model and Analysis	2.81×2.81	Swart et al. (2019)
2	CMCC-CM2	Centro Euro-Mediterraneo per I Cambiamenti Climatici	0.748 × 0.75	Scoccimarro et al. (2020)
3	CNRM-CM6-1	Centre National de Recherches Météorologiques	1.40 ×1.41	Voltaire et al. (2018)
4	FGOALS-g3	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University, China	2.81 ×2.81	He et al. (2019)
5	IPSL-CM6A-LR	Institute Pierre-Simon Laplace	2.50 ×1.26	Boucher et al. (2018)
6	MIROC6	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies,	1.40 ×1.40	Tatebe et al. (2019)
Information of the six CMIP5 climate models used in this study				
1	CanESM2	Canadian Earth System Model and Analysis	2.81 ×2.81	Arora et al. (2011)
2	CMCC-CESM	Centro Euro-Mediterraneo per I Cambiamenti Climatici	3.44 × 3.75	Marcello Vichi et al. (2011)
3	CNRM-CM5	Centre National de Recherches Météorologiques	1.40 ×1.40	Voltaire et al. (2013)
4	FGOALS-g2	LASG–Center for Earth System Science (CESS)	2.81 ×2.81	Li et al. (2013)
5	IPSL-CM5A2	Institute Pierre-Simon Laplace	1.80 ×3.75	Dufresne et al. (2013)
6	MIROC5	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.40 ×1.40	Watanabe et al. (2010)
Observations data				
1	GPCC	Global Precipitation Climatologic Center	1° × 1°	Ziese et al., (2020)
2	CHIRPS	Climate Hazard Group Infrared Precipitation with Satellite data	0.5° × 0.5°	Sousa et al., (2020)

The models data are selected based on previous study Farhad *et al.*, (2021) assessed the performance of precipitation estimates from 12 CMIP6 models by comparing them to observation data from the GPCC (Global Precipitation Climatology Centre) at a common 1° spatial resolution and at various temporal scales over Iran's climatic regions. They discovered that the rainiest region had a significant underestimating, and they discovered that all models typically exhibit some degree of underestimation throughout the summer. According to their findings, there are considerable differences in place and time between the accuracy of precipitation estimates. The CMIP6 models are the most accurate in simulating the climatological characteristics of precipitation and its spatiotemporal fluctuations over the arid and hyper-arid regions of the country. They provided information on the models that are appropriate for various climate zones, such MRI-ESM2-0 and CNRM-CM6-1 for humid zones (HadGEM3-GC31-LL, BCC-CSM2-MR, and CanESM5 for arid and hyper arid zones)

3.3.3 Model Evaluation and processing Methods

First of all, the models (CMIP5 and CMIP6) and observations data (GPCC and CHIRPS) in Table3.1 have been processing over the period (1983 – 2012) for present analysis due to the time constraint of the two models, all the data has been regridded to 1° × 1°, and the summer period has been used (June – July – August – September) to simulate West African Precipitation characteristics. The ETCCDI has been used to process six Extremes Precipitation indices (CDD, CWD, R10mm, R20mm, Rx5days and SDII).

Second, the three CMIP6 scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5) have been processed over two times period (2021 – 2050) for near future trends and (2071 – 2100) for far future trends. Then nine Extremes Precipitation indices have been used (CDD, CWD, R10mm, R20mm, Rx5days, SDII, R75p, R90p and R95p) from ETCCDI as tabulated in Table3.2.

Table 3.2 Precipitation extreme indices

S/No	Extreme indices	Name	Definition	Units
1	SDII	Simple daily intensity	Let PR_{wj} be the daily precipitation amount on wet days, $PR \geq 1$ mm in period j . If W represents number of wet days in j , then: $SDII_j = (\sum_{w=1}^W PR_{wj})/W$	mm/day
2	CDD	Consecutive dry days	Let PR_{ij} be the daily precipitation amount on day i in period j . Count the largest number of consecutive days where $PR_{ij} < 1$ mm	days
3	CWD	Consecutive wet days	Let PR_{ij} be the daily precipitation amount on day i in period j . Count the largest number of consecutive days where $PR_{ij} > 1$ mm	days
4	R10mm	Heavy precipitation days	Let PR_{ij} be the daily precipitation amount on day i in period j . Count the number of days where $PR_{ij} > 10$ mm	days
5	R20mm	Very heavy precipitation days	Let PR_{ij} be the daily precipitation amount on day i in period j . Count the number of days where $PR_{ij} > 20$ mm	days
6	Rx5day	Maximum 5 days precipitation	Let PR_{kj} be the precipitation amount for the 5-day interval ending k , period j . Then maximum 5 day values for period j are: $RX5day_j = \max (PR_{kj})$	mm
7	R75p	75 th percentile	Number of moderate wet days— $Rd > 75$ th percentile for days with $Rd \geq 1$ mm	days
8	R90p	90 th percentile	Number of wet days— $Rd > 90$ th percentile for days with $Rd \geq 1$ mm	days
9	R95p	95 th percentile	Number of very wet days— $Rd > 95$ th percentile for days with $Rd \geq 1$ mm	days

After, the monthly average was computed for the annual cycle of (CDD and CWD) over West Africa and its three zones (Guinea, Savannah and Sahel).

Finally, a time series analysis have been used to simulate the annual dynamic of the precipitation over West Africa with all the data set.

3.4 Presentation of the Precipitation indices used in the study

Six precipitations extremes indices have been used to evaluate CMIP5 and CMIP6 performance and nine precipitations indices to determine the near and far future impacts of Climate Change on West African precipitations characteristics. All the indices are represented in Table3.2.

Some statistics operator used in this study:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N \|y(i) - \hat{y}(i)\|^2}{N}}; \quad (3.1)$$

$$MBE = \frac{1}{N} \sum_{i=1}^N (Pi - Oi); \quad (3.2)$$

$$STD = \sqrt{\frac{\sum_{i=1}^n (Xi - \bar{X})^2}{N-1}} \quad (3.3)$$

Where: N = number of data points; $y(i)$ = i-th measurement; $\hat{y}(i)$ = Corresponding prediction

Pi and Oi = The i-th forecast and observation, respectively;

Xi = Value in the data distribution; \bar{X} = Sample mean.

Standard deviation is calculated by first finding the mean (average) of the data set. Then, each data point is subtracted from the mean, and the result is squared. This is done for each data point, and the sum of the squares is divided by the number of data points.

The result is the variance, which is then square rooted to obtain the standard deviation. This calculation provides a measure of the spread or variability of the data points in the set.

The root mean square error (RMSE), standard deviation (STD) and mean bias error (MBE) are all important metrics for measuring the accuracy of a model or estimator. They provide a measure of how close the predictions are to the true values and can be used to compare different models or estimators. These metrics can also be used to identify areas of improvement in a model or estimator. By analysing the errors, it is possible to identify patterns in the errors and to adjust the model or estimator accordingly.

The amount of course is important to the overall water cycle and soil rehydration, quantity is a product of accumulation or intensity times duration. For example, short-duration, high-intensity rainfall may have the same amount as long-duration, low-intensity rainfall.

However, intensity and duration can have a significant impact on whether precipitation infiltrates or becomes surface runoff. Higher precipitation intensity produces larger raindrops with more impact energy, so higher intensity storms can damage fragile vegetation and bare ground. High-intensity storms can actually move soil particles, cause soil crusting, or start the soil erosion process. High-intensity storms can also overwhelm the soil's ability to infiltrate precipitation at the same rate, resulting in excess infiltration runoff.

The duration refers to the length of time rainfall occurs. Rainfall for a short duration may affect tender seedlings, but it will not likely have much effect on soil erosion and runoff. Rainfall of longer duration can significantly affect infiltration, runoff, and soil erosion processes.

Frequency, or more specifically return period, refers to how often precipitation occurs in a particular amount or intensity and duration. For example, precipitation cycles are called 100-year 1-hour rainfall or 100-year 24-hour rainfall to define the probability of a specific amount occurring during a particular time period.

The seasonal distribution of precipitation refers to the year's seasons with different amounts of precipitation. Seasonal distribution determines when surface runoff or deep infiltration is most likely to occur, or when irrigation is required. Because seasonal patterns of precipitation vary in different parts of the country.

Taylor diagrams (Figure4.1 and Figure4.2) are used in climate science to evaluate how well patterns match each other in terms of their correlation, their root-mean-square difference, and the

ratio of their variances NCAR, (2022). They are primarily used to evaluate models designed to study climate and other aspects of Earth's environment. The diagram provides a concise statistical summary of the model's performance compared to observations KEYVAN, (2020). It is useful for comparing multiple models or datasets and identifying which ones perform better than others. The Taylor Diagram was developed by Karl E. Taylor and has been frequently used by meteorologists and atmospheric scientists.

Mathematical Relationships

The Taylor Diagram draws the following three statistical metrics on a single plot: standard deviation, CRMSE, and correlation. The equation below relates these three:

$$E' = \sigma_o^2 + \sigma_s^2 - 2\sigma_o\sigma_s\rho \quad (3.4)$$

Where

E' : Centered root mean squared error

σ_o : Standard deviation of observed values

σ_s : Standard deviation of simulated values

ρ : Correlation coefficient

This relationship can be easily derived using the definition of CRMSE, which is:

$$E' = \left\{ \frac{1}{N} \sum_{n=1}^N [(O_n - \bar{O}) - (S_n - \bar{S})]^2 \right\}^{\frac{1}{2}} \quad (3.5)$$

Where

\bar{S} : Mean of the simulated time series
 \bar{O} : Mean of the observed time series
 O_n : Simulated time series
 S_n : Observed time series

We can expand this equation to the following:

$$\sum_{n=1}^N (O_n - \bar{O})^2 + \sum_{n=1}^N (S_n - \bar{S})^2 - \sum_{n=1}^N 2(O_n - \bar{O})(S_n - \bar{S}) \quad (3.6)$$

The first two components of the equation are standard deviations of observed and simulated time series. To understand the third component of the equation, we need to recall the mathematical definition of correlation.

$$\rho = \frac{\frac{1}{N} \sum_{n=1}^N (O_n - \bar{O})(S_n - \bar{S})}{\sigma_O \sigma_S} \quad (3.7)$$

If we multiply both sides of the above equation by standard deviation of observed and simulated, we see that the third components of the two equation are actually the same. The Taylor Diagram uses polar coordinates to visualize all of these components.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 ANALYSIS OF THE CHARACTERISTICS OF THE WEST AFRICA PRECIPITATION WITH CMIP5 AND CMIP6

The characteristics of rainfall are the amount, the intensity, the duration, the frequency or return period, and the seasonal distribution. All the characteristics were investigated in this study.

4.1.1 Seasonal average (JJAS) of the WA rainfall with CMIP5 and CMIP6

A comprehensive analysis of monthly precipitation and monsoon period (JJAS) were used to evaluate rainfall pattern over West Africa. It shows two types of drought in the Sahel. The first is associated with increased surface atmospheric circulation in the northern tropical Atlantic and warmer sea surface temperatures in the Gulf of Guinea. The second is related to positive sea level air pressure and easterly circulation anomalies as noted by (Niang *et al.* 2014).

These methods tend to compensate for significant variability and differences between each model.

4.1.2 Annual cycle of Consecutive dry day

The annual cycle of rainfall is an important component of regional climate. Rainfall and snow are key elements in the Earth's water cycle, which is vital to all life on Earth. Anthropogenic climate change is predicted to cause spatial and temporal shifts in precipitation patterns, which may be apparent in changes to the annual cycle of precipitation. The study of annual cycles in precipitation is also important in helping to understand the relationship between rainfall processes. The seasonal shift of the annual cycle of rainfall can influence the orographic nature of rainfall distribution and timing in a region, (Juan *et al.* 2019).

The study of consecutive dry days over a region can provide valuable information about extreme precipitation and seasonal droughts. It can also help predict burned areas and the threshold rainfall value for burning. Additionally, it can contribute empirical evidence to understanding variations in consecutive dry days in a specific region. A study has shown that changes in dry-day frequency play a key role in changing regional climate, particularly in a warming climate. Machine learning algorithms have also been used to predict monthly dry days with high accuracy, (Shabbir *et al.* 2022).

The study of consecutive wet days over a region can provide insights into precipitation patterns and their potential impacts. For example, one study found that extreme precipitation occurring on consecutive days may substantially increase the risk of related impacts. Another study assessed the potential impact of global warming on consecutive dry/wet days over West Africa. Other studies have analyzed annual and seasonal variations of precipitation characteristics defined by the duration of maximum consecutive wet days, as well as projected future climate change scenarios for regions such as the coastal Savannah agroecological zone. Understanding characteristics of consecutive wet days can help with measures to mitigate risks associated with extreme precipitation and seasonal droughts, (Duan *et al.* 2017).

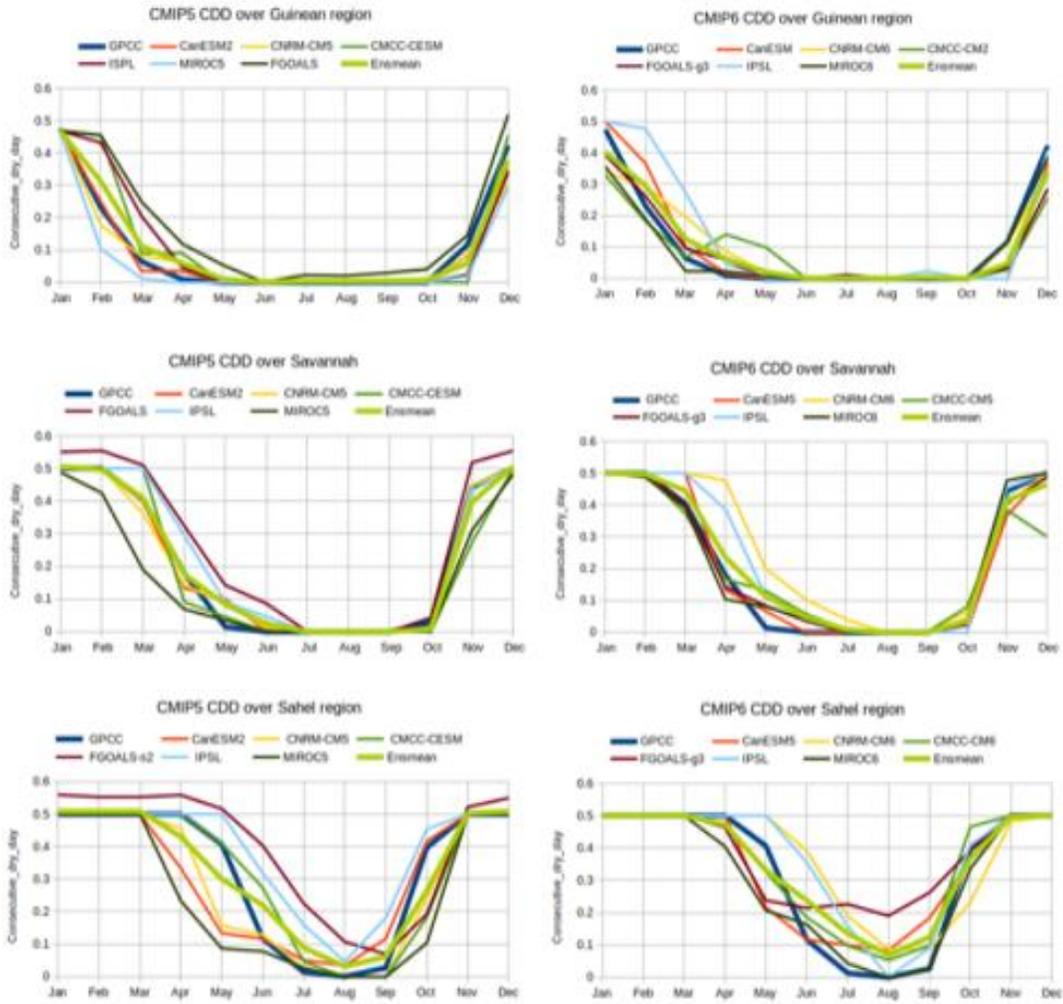


Figure 4.1: Annual cycle of consecutive dry days in each zone of West Africa with CMIP5 (left), CMIP6 (right) and their Ensmean with observational dataset (GPCC) from 1983 to 2012

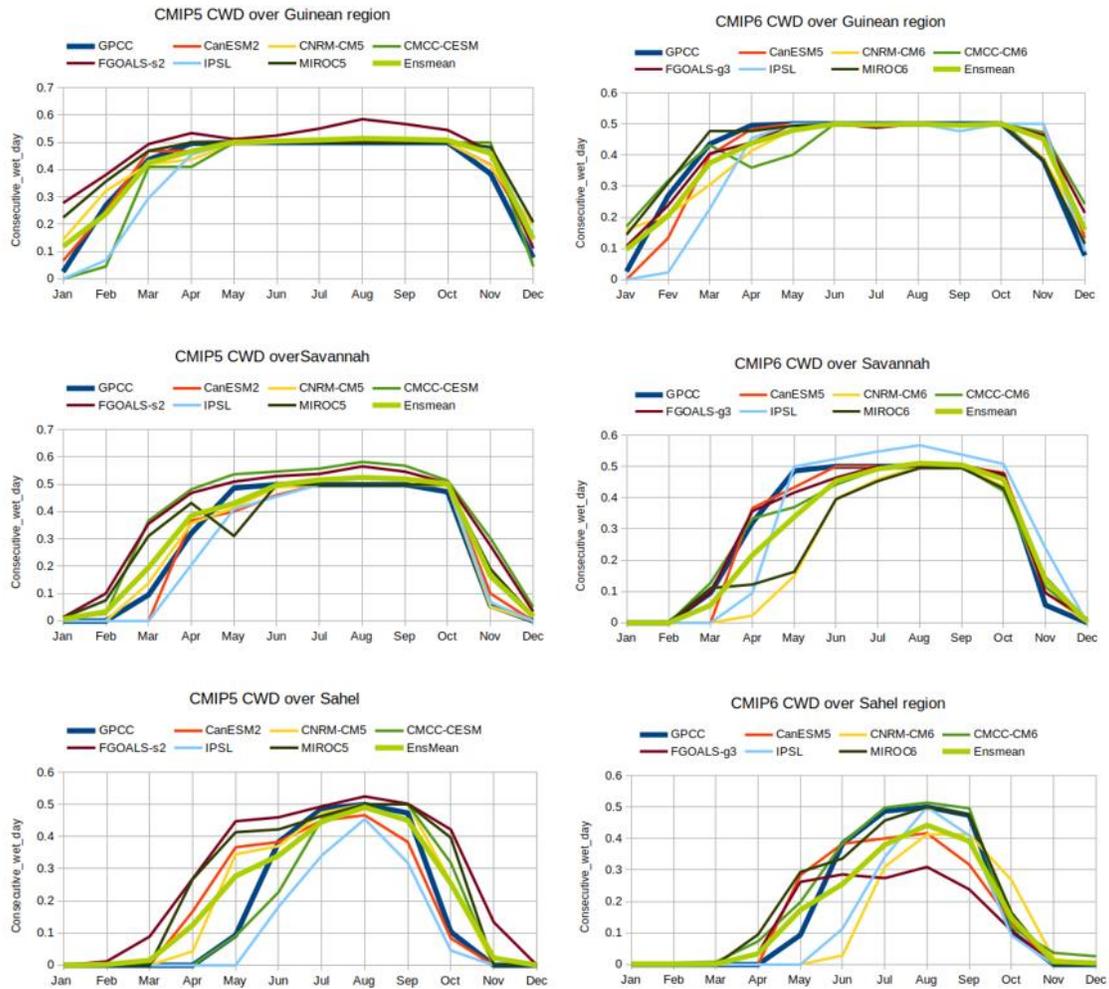


Figure 4.2: Same as (Figure4.1), but for consecutive wet day (CWD), annual cycle of observational dataset (GPCC), CMIP5 (left), CMIP6 (right) and their Ensmean from 1983 to 2012

:

The length of dry day (Figure4.1) is relatively higher in CMIP6 model than CMIP5 and shrinking from Sahel zone (north of W.A) to Guinea zone (south of W.A), this shrinkage is mainly link to monsoon activity over West Africa. The length of consecutive dry days (CDD) in Guinea Coast is spread from November to February in CMIP5 while in CMIP6 model most of the simulated data are strongly correlated to observe data and show a dry length from November to March. However, the FGOALS-s2 in CMIP5 overestimate the dry days over Guinea region extending from November to the end of May. A significant enlargement of the length of CDD event is observed over Savannah region spreading from October to the end of April in CMIP5 model and from October to early June in CMIP6 model, while satellite dataset GPCP recorded a length of dry day period from October to May. The most significant enlargement of consecutive dry days (CDD) is represented over Sahel region (Figure4.1), there is no significant activities of rainfall. A simple peak is observed in August during the wet period (CWD) (Figure4.2) for all the CMIP6 output models and their Ensmean in agreement with observed data. However, this wet spell is highly overestimated by CMCC-CM6 in CMIP6 model while it is overestimate by FGOALS-s2 in CMIP5 model over Sahelian zone. The annual cycle of wet days over Guinea Coast is longer and shows two peaks (June and September) in similarity with previous study Sow *et al.*, (2020). The intensity of wet days (Figure4.2) is strongly overestimate by CMCC-CESM and FGOALS-s2 in CMIP5 model while it is overestimate by MIROC6 in CMIP6 model. The Savannah region bring great uncertainties between models for representing feature rainfall due to the presence of many climatic drivers (Monsoon, ITCZ), the Savannah area located between Guinea Coast and Sahel regions is subject to climate disasters (flood, drought). The succession of these two disasters over West Africa is mostly common in Savannah region because of the delay of the wet period and the sudden onset of dry period which effect many activities like agriculture, fishing and energy generation.

4.2 Spatial distribution of precipitations indices with CMIP5 and CMIP6 models

The Expert Team on Climate Change Detection and Indices ETCCDI is a set of internationally recognized indices that highlight changes in the frequency, duration and intensity of extreme climate events based on daily temperature and precipitation measurements Donat *et al.*, (2013); Sillmann *et al.*, (2013a); Sillmann *et al.*, (2013b). Several researchers worldwide have applied the ETCCDI climate index to analyze possible changes in past extreme precipitation events (Brown *et al.*, (2010); Sillmann *et al.*, (2013a); Donat *et al.*, (2016); Iacovone *et al.*, (2020); Cerón *et al.*, (2021); Regoto *et al.*, (2021); Faye and Akinsanola, (2022) and using climate models to predict future climate Sillmann *et al.*, (2013b); Thibeault and Seth, (2014); Xu *et al.*, (2019); Avila-Diaz *et al.*, (2020); Gouveia *et al.*, (2022).

The calculated indices allow assessment of the intensity (R75p, R90p, R95p, RX5day and SDII), frequency (R10mm and R20mm,) and duration (CDD and CWD) of extreme precipitation climatic events, which were chosen because they represent the important extreme events Debortoli *et al.*, (2017). Furthermore, these indices have been widely used to study observed and modeled climate variability around the world Sillmann *et al.*, (2013a) Sillmann *et al.*, (2013b); Avila-Diaz *et al.*, (2020); Faye and Akinsanola, 2022; Wilson *et al.*, (2022).

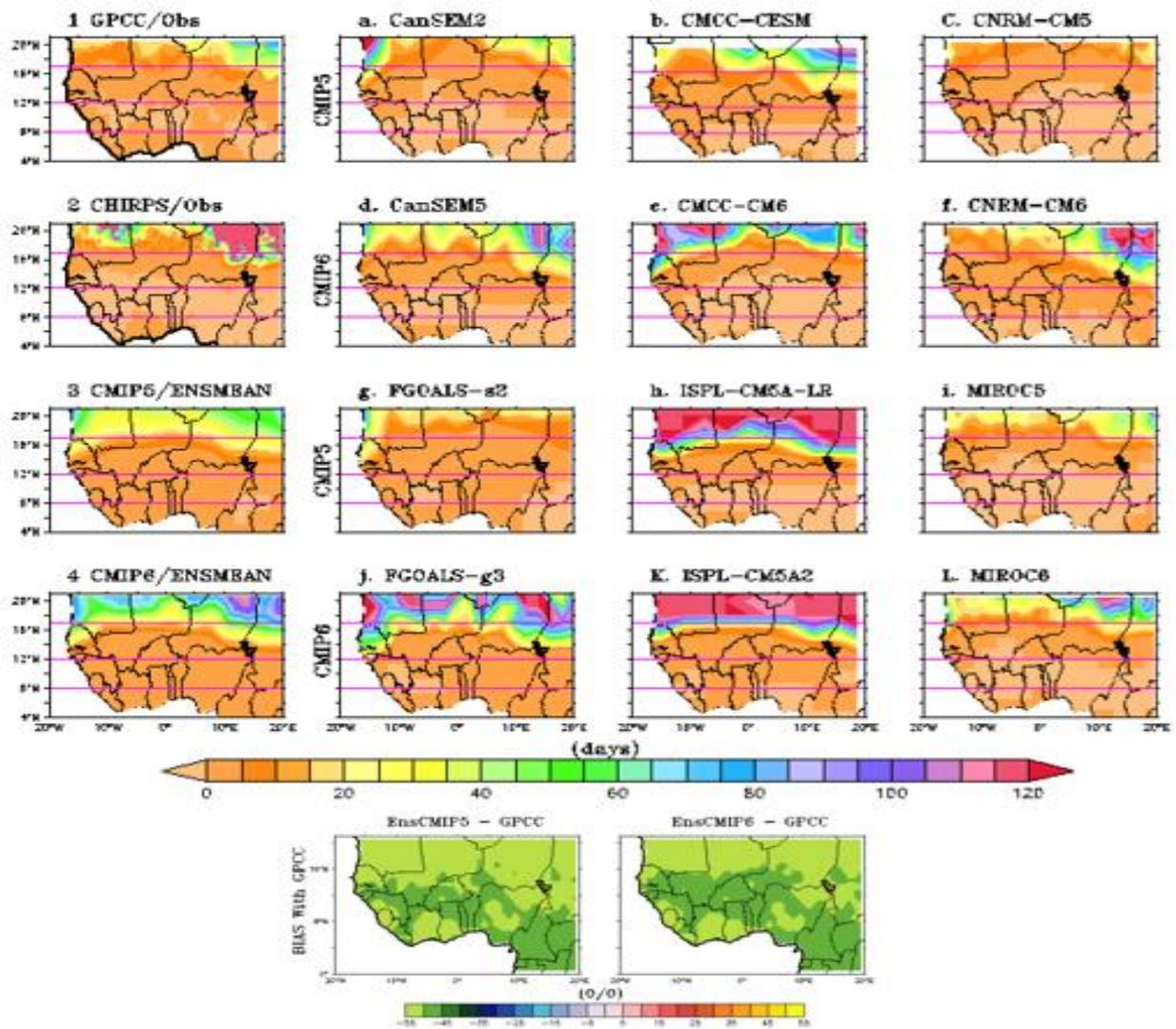


Figure.4.3: Consecutive dry day (CDD) with observed dataset GPCC, CHIRPS (1, 2); Ensmean CMIP5 and CMIP6 (3, 4); CMIP5 (a, b, c, g, h and i) CMIP6 (d, e, f, j, k and L) from 1983 to 2012 and bias with GPCC dataset in the bottom

Spatiotemporal representation of consecutive dry days refers to the analysis of the spatial and temporal variability of consecutive dry days (CDD) within a given region. CDD is defined as the largest number of consecutive days with daily precipitation amount less than 1 mm, within a year, Panadiotis *et al.*, (2010). Researchers use various indices such as CDD, consecutive wet days (CWD), maximum precipitation, and precipitation events to detect and explain spatiotemporal patterns in palaeoclimate change Sebastian *et al.*, (2019). The study of consecutive dry days is important for understanding climate variability and its impact on ecosystems. The calculated indices allow assessment of the intensity (RX5day and SDII), frequency (R10mm and R20mm,) and duration (CDD and CWD) of extreme precipitation climatic events, which were chosen because they represent the important extreme events of Precipitation Debortoli *et al.*, (2017).

On the (Figure4.3), all the models and observed data showed a moderate dry days over southern part of West Africa. However, some models such as CanESM, CNRM-CM, FGOALS, and MIROC from CMIP5 and CMIP6 underestimate the width of Consecutive dry days in the northern part of West Africa compared to the observed data while, CMCC and IPSL from CMIP5 and CMIP6 are extended the width and length of crucial dry days. Their Ensmean underestimated the CDD event with a negative bias.

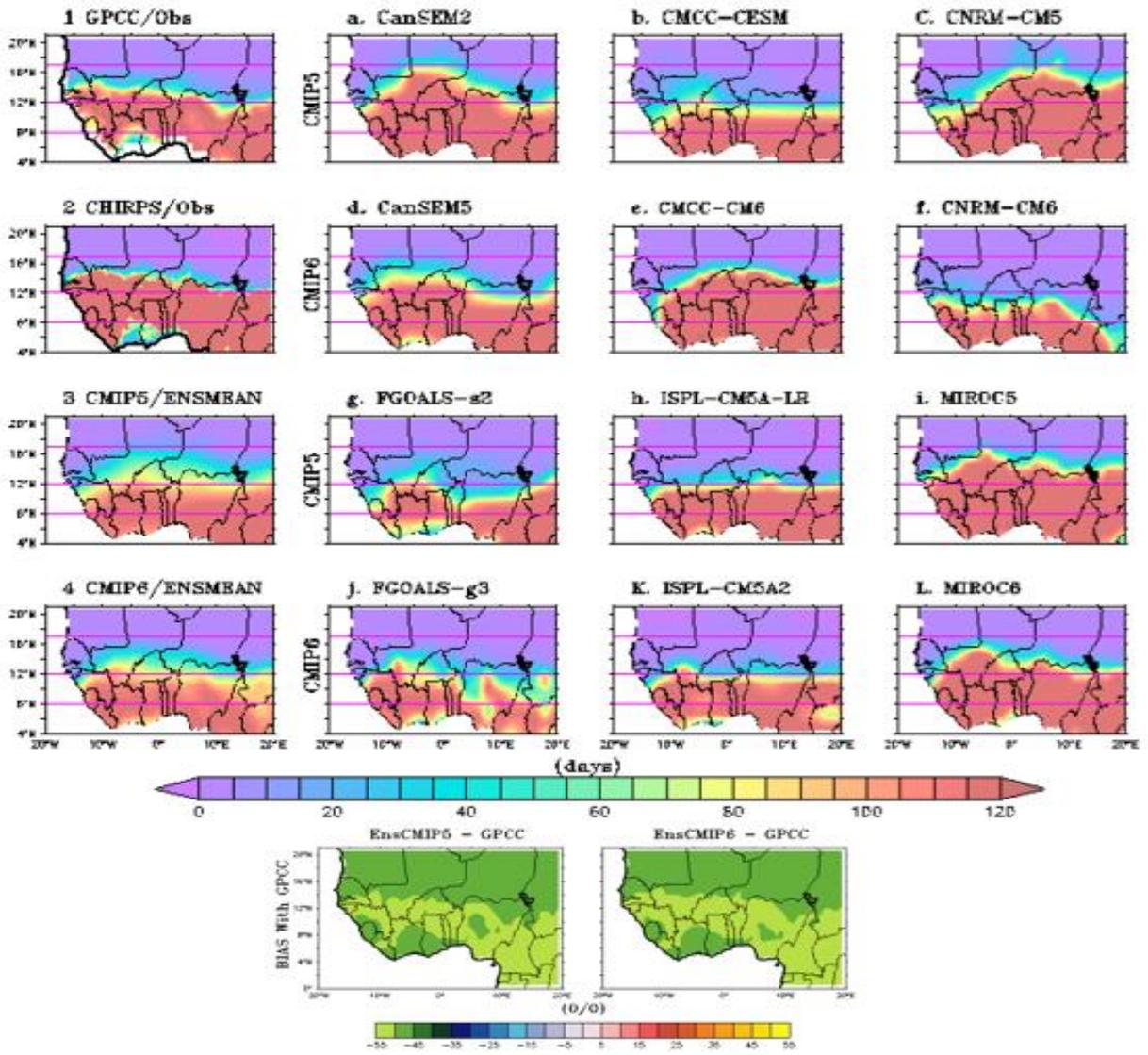


Figure 4.4: Same as (Figure 4.3) but, for Consecutive Wet day (CWD)

The spatiotemporal representation of consecutive wet days is a measure used to analyze precipitation patterns over time and space. It is often represented by the consecutive wet days (CWD) index, which measures the number of days with precipitation above a certain threshold that occur consecutively in a given location Imran *et al.*, (2023). This index can be used to identify trends in precipitation patterns and to assess the risk of flooding or other water-related hazards.

In contrast with the dry days, the consecutive wet days (CWD) (Figure4.4) showed during this last thirty years a significant wet period to Guinea and Savannah than Sahel zone. This wet period is more highlighted by observation data (GPCC) than some models such as FGOALS and IPSL from CMIP5 and CMIP6. The CMIP5 and CMIP6 Ensemble mean have shown a negative bias with GPCC consecutive wet days means that they underestimated the CWD activities over the three subregions and over all West Africa.

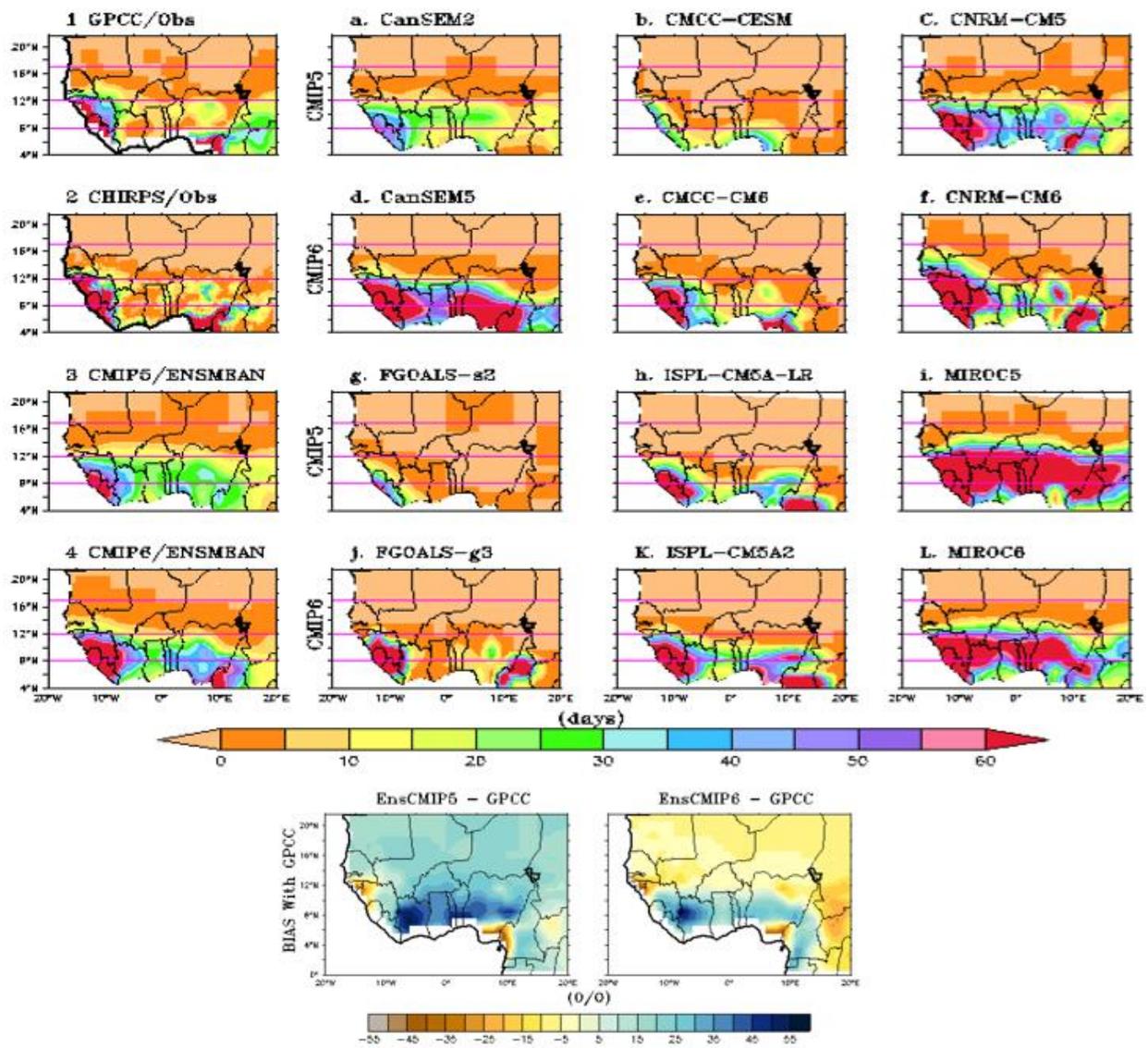


Figure 4.5: Same as (Figure 4.3) but, for Heavy Rainfall (R10mm)

The spatial representation of heavy rainfall is important for understanding the patterns and trends of extreme rainfall events. Studying the synchrony and interdependency of heavy rainfall occurrences can help understand the underlying physical mechanisms Frederik *et al.*, (2021). Investigating the spatiotemporal variations of extreme rainfall can also help understand teleconnections between a given location or climate pattern and extreme rainfall. Spatial analysis of trends in extreme precipitation can highlight regions with increasing, stationary, and decreasing extreme rainfall through time. Rainfall is a variable that presents high spatial and temporal variability, so spatiotemporal analysis is crucial for climate modeling. A spatiotemporal classification method for massive-ensemble rainfall datasets has been proposed to aid in this research. Only the southern region over West Africa is concerned by Heavy precipitation (Figure4.5) from 0N to 15N. All the six models from CMIP6 match well with observed data compared to their correspondent in CMIP5. All the models with observation showed a heavy precipitation activity across the eastern and western area of Guinea coast and Savannah region. However, the MIROC5 and MIROC6 from (CMIP5 and CMIP6) respectively, and CanESM5 from CMIP6 extend the R10mm activity over the central region of Guinea coast and Savannah in West Africa. The northern region of West Africa showed a positive bias with CMIP5 Ensemble mean while it showed with CMIP6 Ensemble mean a negative bias with the (GPCC) R10mm event.

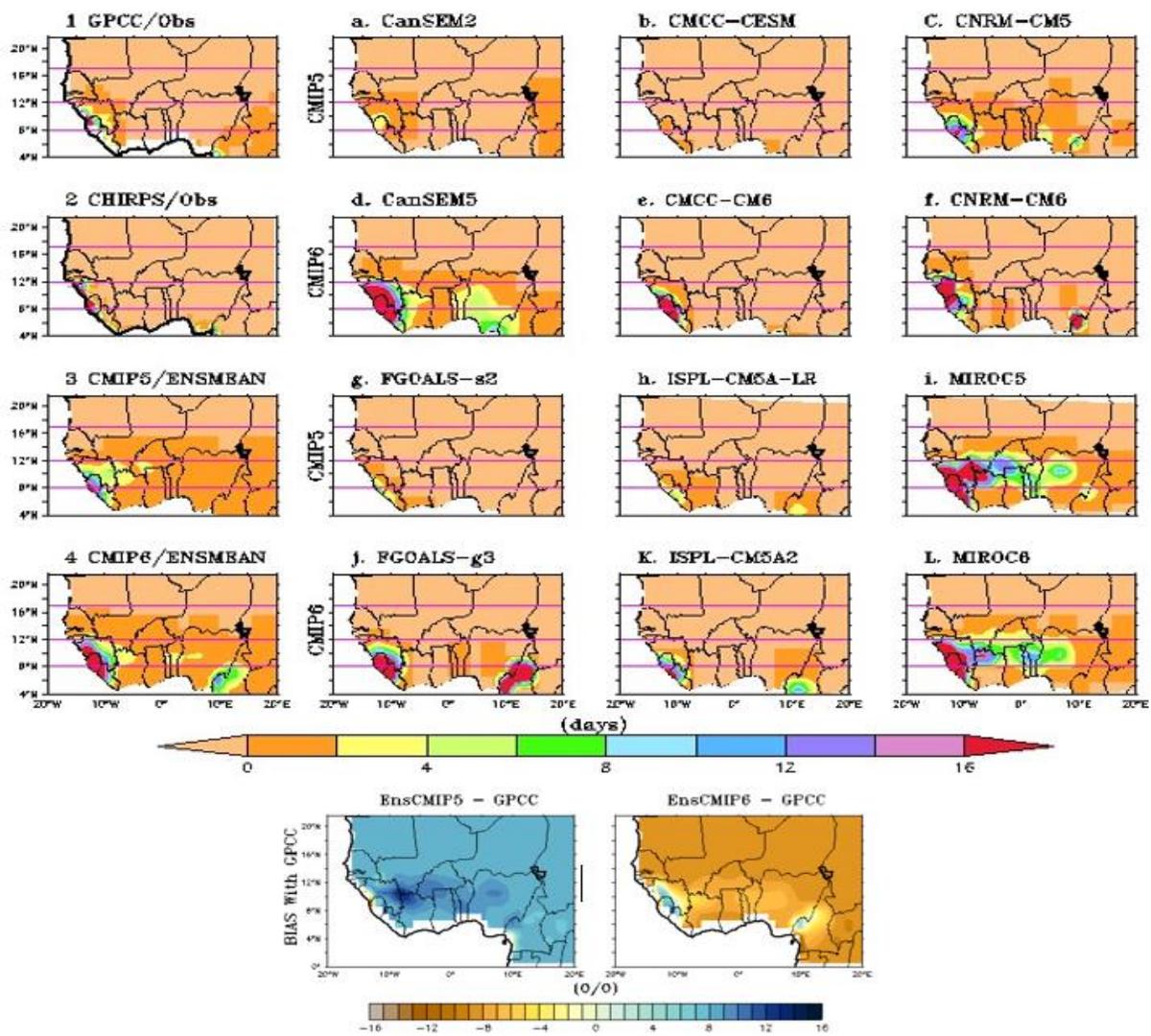


Figure 4.6: Same as (Figure 4.3) but, for Very Heavy Rainfall (R20mm)

The very heavy precipitation lies in understanding the patterns and trends of extreme precipitation over time and space. Extreme precipitation can cause significant damage, so it is important to study its spatiotemporal variability to better predict and prepare for future events Dingkui *et al.*, (2022). Spatiotemporal analysis can also help identify regions that are more vulnerable to extreme rainfall and landslides Fagnant *et al.*, (2020). Factors such as elevation, relative humidity, and wind direction play a crucial role in determining precipitation patterns. The representation of R20mm is important because it helps to identify the patterns and trends of extreme precipitation over time and space. This information can be used to predict and prepare for future events, as well as to identify regions that are more vulnerable to extreme rainfall and landslides, Weizheng *et al.*, (2022). By comparing to observational GPCC data in this simulation (Figure4.6), five models overestimate the Very Heavy Rainfall characteristic including four from CMIP6 output data such as CanESM5, CNRM-CM6, MIROC6, FGOALS and MIROC5 from CMIP5. We observe that only some few locations especially the western area over Guinea region and the southeastern part of Nigeria are concerning by the R20mm activity. We observed a positive bias with CMIP5 Ensemble mean while the CMIP6 Ensemble mean showed a negative bias with the GPCC R20mm event.

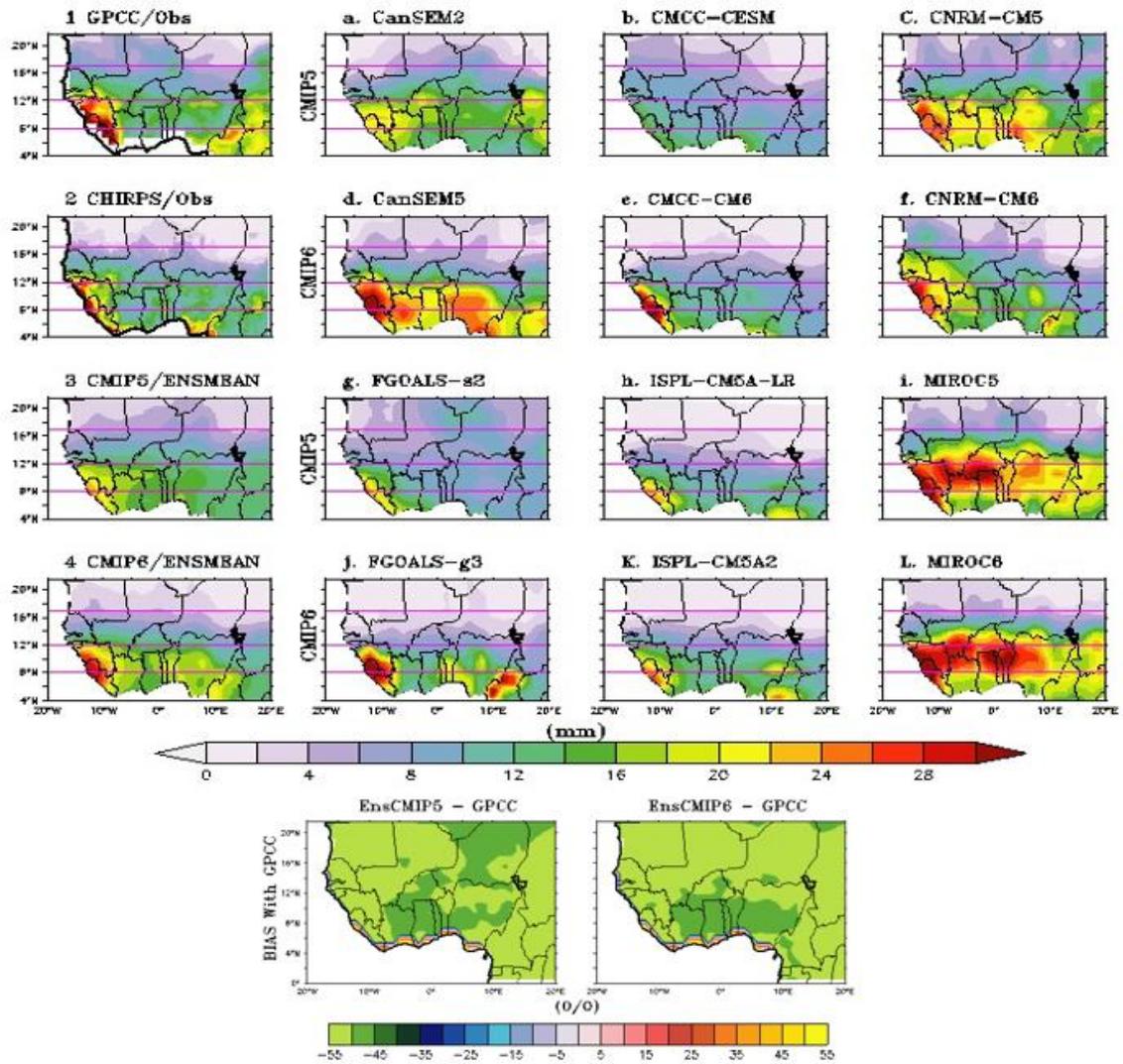


Figure 4.7: Same as (Figure 4.3) but, for highest 5 days Precipitation amount (Rx5days)

Spatiotemporal analysis of precipitation data can also be used to develop quantitative precipitation forecasts, which are important for atmospheric forecast models Dawit *et al.*, (2020). Studies have been conducted to characterize spatiotemporal trends in extreme precipitation and highlight regions with increasing or decreasing rainfall Fagnant *et al.*, (2020). Precipitation prediction is a relevant challenge in weather and climate research, making exploratory metrics like spatiotemporal analysis an important tool for understanding this phenomenon. Understanding spatiotemporal trends in extreme precipitation can provide several benefits. Firstly, it can help identify regions that are experiencing increasing or decreasing extreme rainfall, which is important for developing effective adaptation and mitigation strategies. Secondly, it can aid in understanding the mechanisms behind changes in extreme precipitation events, which is crucial for predicting future trends and their potential impacts. Thirdly, studying spatiotemporal variations of extreme rainfall can improve the accuracy of extreme rainfall prediction models. Overall, understanding spatiotemporal trends in extreme precipitation is essential for mitigating the negative impacts of climate change and ensuring sustainable development, Derya *et al.*, (2022). Similarly, with the CWD in (Figure4.4), the most activity with highest 5 days precipitation is collected in Guinea zone and Savannah region over West Africa (Figure4.7). The lowest value of (Rx5day) is represented beyond 15N over West Africa for all the calculated and GPCP dataset except for CMCC-CESM, FGOALS-s2 and ISPL-CM5A-LR from CMIP5 and ISPL-CM5A2 from CMIP6, which underestimate the width of Rx5day and show a crucial decreasing over the central area of Guinea coast and Savannah zones. The study gave a negative bias with both Ensmean with GPCP except the southern area in Guinean zone.

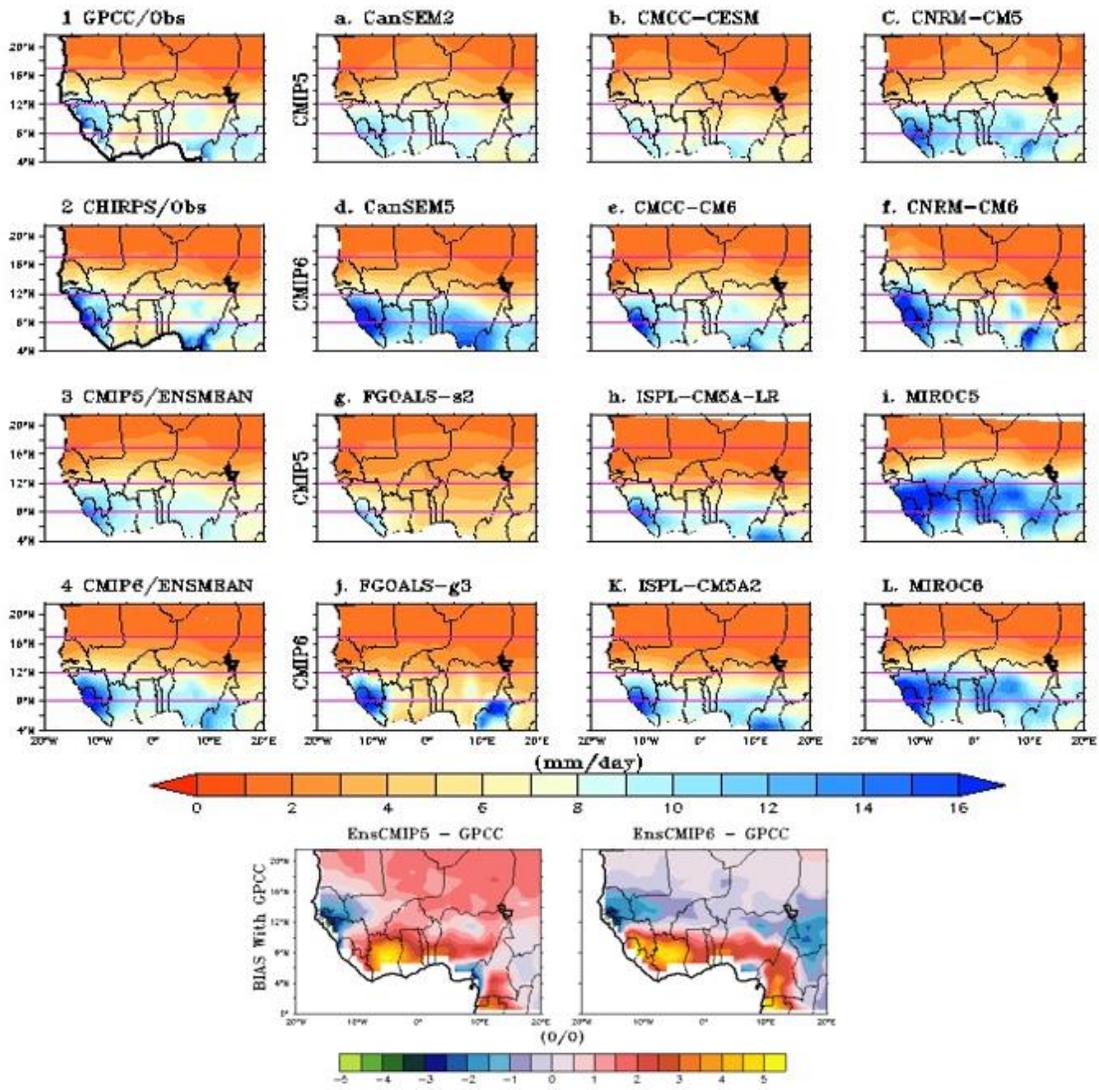


Figure 4.8: Same as (Figure 4.3) but, for Simple Daily Intensity (SDII)

The representation of simple daily intensity of rainfall is important for various reasons. It can help in deriving intensity-duration-frequency (IDF) curves, which are graphical representations of the probability that a given average rainfall intensity will be exceeded over a certain duration. Simple precipitation intensity indices can also be used to estimate the duration, frequency, and intensity of precipitation extreme episodes Sun *et al.*, (2019). Daily rainfall data can be used to derive indices that represent extreme precipitation events and detect changes in climate patterns.

The Simple Daily Intensity Index (SDII) curves are graphical representations of the probability that a given average rainfall intensity will be exceeded over a certain duration, for a given location and return period Francesco *et al.*, (2014). The curves describe the relationship between rainfall intensity, duration, and return period (or its inverse). The mathematical expressions used to derive IDF curves can be theoretical or empirically fitted to observed rainfall data Koutsoyiannis *et al.*, (1998). An IDF curve is a graphical representation of the exceedance probability that a given rainfall intensity will occur for different durations and return periods.

The (SDII) extreme event of precipitation is well captured by observation GPCC data and all the models (Figure4.8); the highest values of Simple Daily Intensity (SDII) are found over Guinea coast and Savannah. However, the FGOALS-s2 from CMIP5 underestimated the spatial distribution of SDII event in comparison with GPCC over the Centre-south of West Africa and the Northern area up to 12°N across West Africa. In contrast, the SDII event is overestimate under the simulation of CanESM5, MIROC6 from CMIP6 and MIROC5 from CMIP5, which display the greater intensity between 14mm to 16mm over the Centre area of Guinea and Savannah zones. The SDII Ensemble mean bias is widely high in CMIP5 than CMIP6 over most of West African areas.

Function deduced from the Gumbel distribution and the opposite Gumbel distribution, for a given duration t :

(Equation 4)

$$I(p) = \mu + \sigma \ln \left(\ln \left(1 - \frac{1}{p} \right) \right) \Rightarrow F(I) = \exp \left(-\exp \left(-\frac{I - \mu}{\sigma} \right) \right) = 1 - \frac{1}{p}$$

(Equation 5)

$$I(p) = \mu + \sigma \ln(\ln p) \Rightarrow F(I) = 1 - \exp \left(-\exp \left(\frac{I - \mu}{\sigma} \right) \right) = 1 - \frac{1}{p}$$

It is used to model the distribution of the maximum (or the minimum) of a number of samples of various distributions. By calculating $1/p$, we can estimate the return period associated with a given threshold. For instance, if $p = 0.05$ (or $1/0.05 = 20$), it implies that the associated extreme event is expected to occur once every 20 years on average.

With μ representing the location parameter, σ representing the scale parameter, and p representing the probability or return period associated with a specific threshold value.

4.3 Statistic diagram to represent (RMSE), (STD) and Correlation Coefficient

The Taylor diagram has been used to represent the three statistical values over the three zones of West Africa.

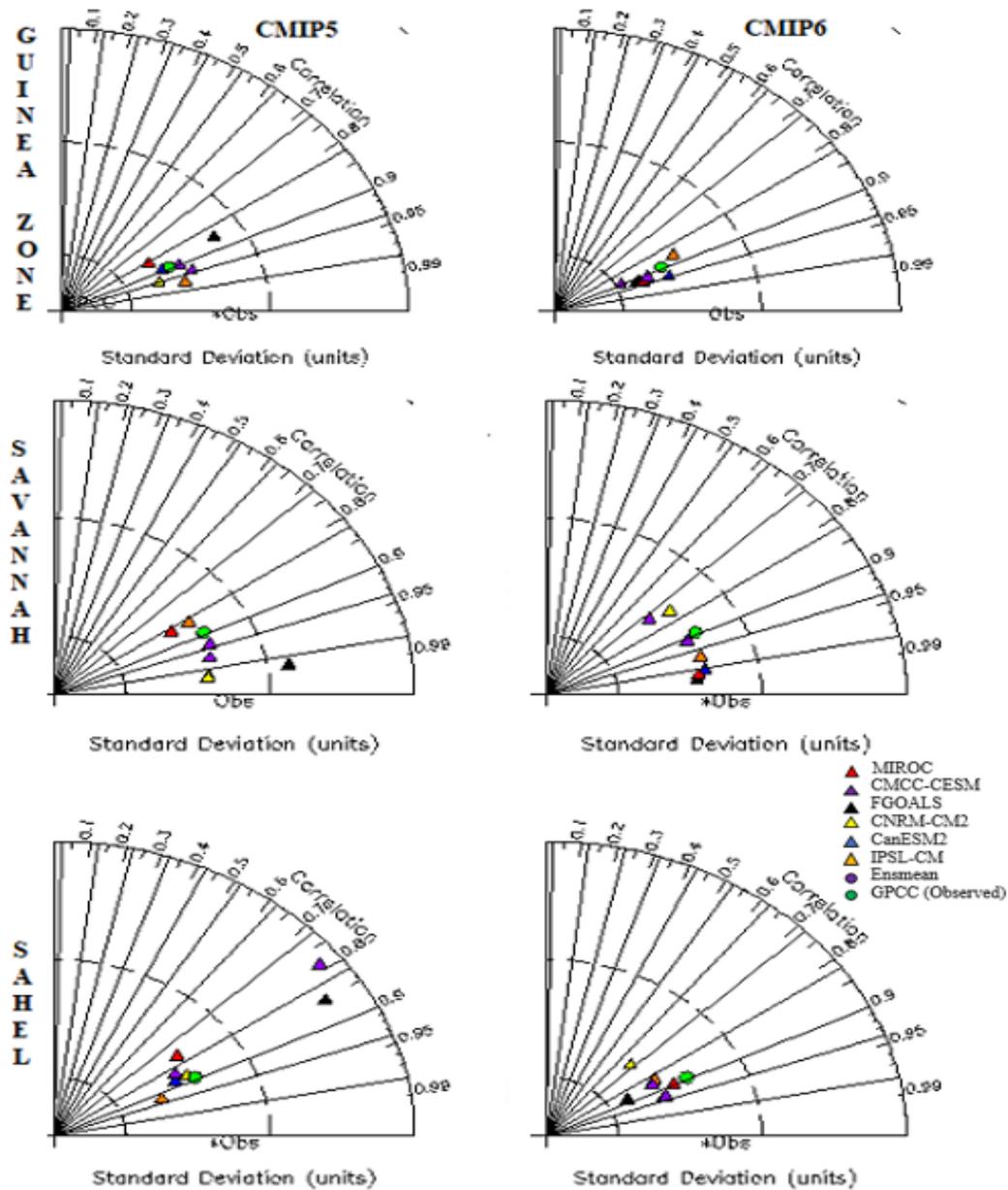


Figure 4.9: Taylor diagram with consecutive dry day (CDD) with CMIP5 (left), CMIP6 (right) simulation of six models estimated with (GPCC) observed data over each sub-region in West Africa, Guinea region on (top), Savannah in the (middle) and Sahel at (bottom)

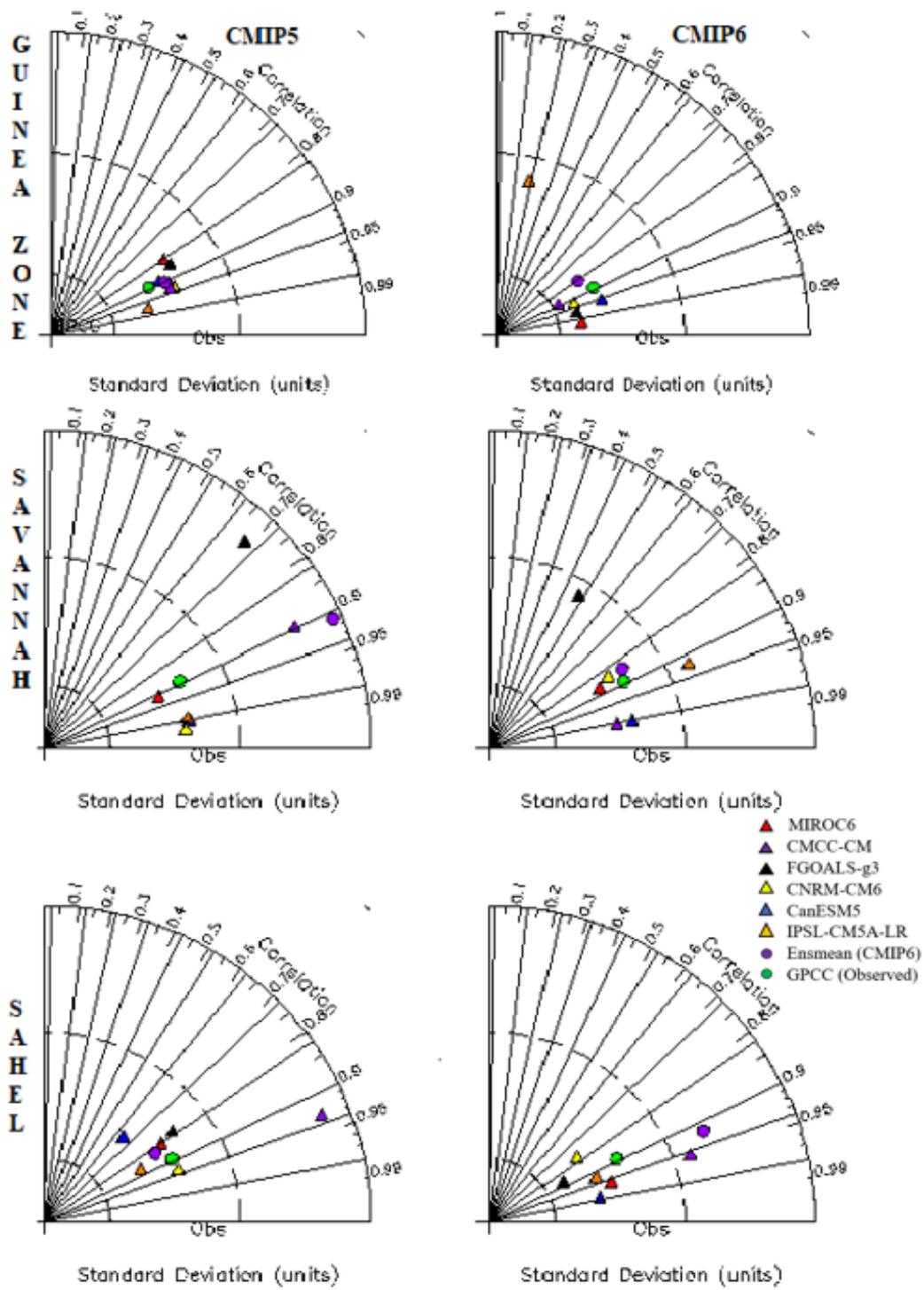


Figure 4.10: Same as (Figure 4.9), but for consecutive wet day (CWD)

The evaluation of model performance is a widely discussed and yet extremely controversial topic in hydrology, atmospheric science, and environmental studies.

There are several studies and databases available on the variability of rainfall time series in West Africa. Some of these studies include such as an analysis of rainfall data from some West African countries with Falaye *et al.*, (2022) found a change in rainfall frequency, precipitation in West Africa has changed over time. According to a study, seasonal rainfall amounts have partially recovered in recent decades, but rainy season characteristics have changed: rainfall is more intense and less frequent, Biasutti, (2019). Another study suggests that future changes to the West African summer monsoon (WASM) will result in less rainfall over the western Sahel region and more rainfall over the central-eastern region, Allada *et al.*, (2020).

The annual cycle of rainfall average of the ensemble CMIP6 model (Figure4.11) fit better with GPCC observed data than the ensemble CMIP5 model over each subregion in West Africa. The global Circulation models gives a good resolution over a big area as observed with the all West Africa. This dynamic has changed over a small area like Sahel, Savannah and Guinea zone. This figure (Figure4.11) shows that while GPCC gave the highest value of annual rainfall for September over Guinea zone, the two models have pointed July for this value.

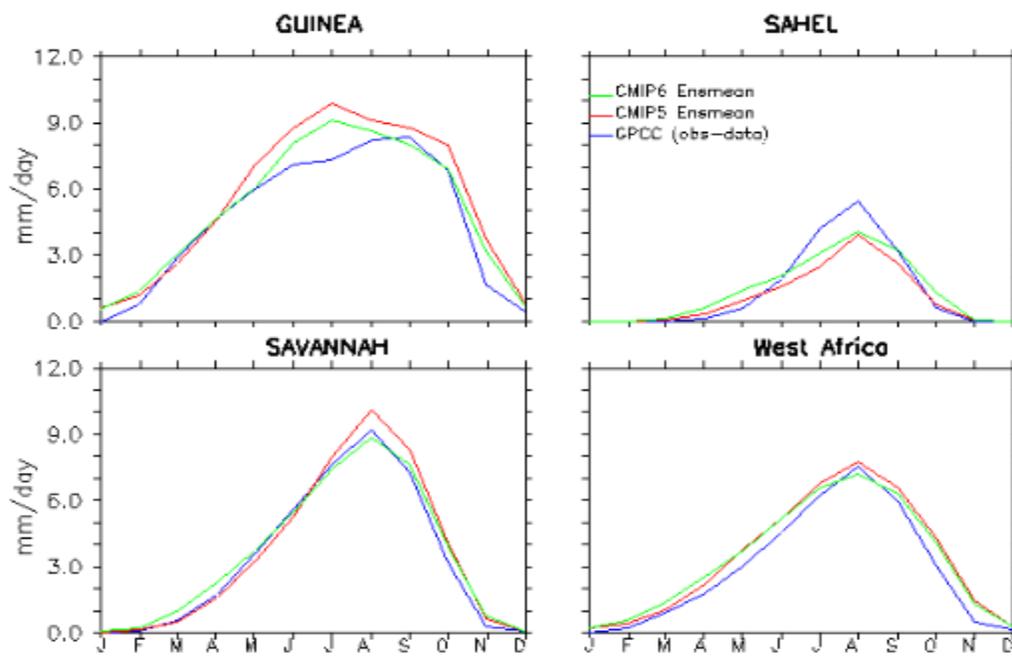


Figure 4.11: Time series analysis over West Africa and its three subregions (Guinea, Savannah and Sahel) from 1983 to 2012 for Ensemble CMIP5 in (red), CMIP6 in (green) and GPCC observed data in (blue)

West Africa is a region of considerable climatic variability, with seasonal differences in temperature and precipitation. Precipitation is the main source of water in the region, and it is essential for agriculture and livelihoods. The seasonal average of precipitation over West Africa is an important indicator of the region's climate and its impact on the environment and people.

The seasonal average of precipitation in West Africa varies greatly, with the highest values occurring in the wet season. During this season, the average precipitation is highest in the coastal areas and decreases towards the interior. The seasonal average of precipitation over West Africa is an important factor in the region's water availability and agricultural productivity. The wet season brings with it an abundance of water, which is essential for crop growth and yields. In contrast, the dry season is characterized by little or no precipitation, resulting in reduced crop yields and increased vulnerability to drought. The seasonal average of precipitation is thus a key factor in the region's agricultural productivity. Climate change is having an increasingly significant impact on the seasonal average of precipitation over West Africa. Warmer temperatures are resulting in more extreme weather events, such as prolonged periods of drought and heavy rainfall. This is resulting in changes to the seasonal average of precipitation, with an increase in the number of dry days and a decrease in the number of wet days, Ayoade *et al.*, (2001)

All the three scenarios models output (Figure4.12) are showing a significant rainfall amount over Savannah and Guinea zones. However, it decreases significantly in near and far future projection over the Sahel.

4.4 CMIP6 scenarios to simulate near and far future trends over West Africa

4.4.1 Seasonal average of Ensmean of six output model from CMIP6

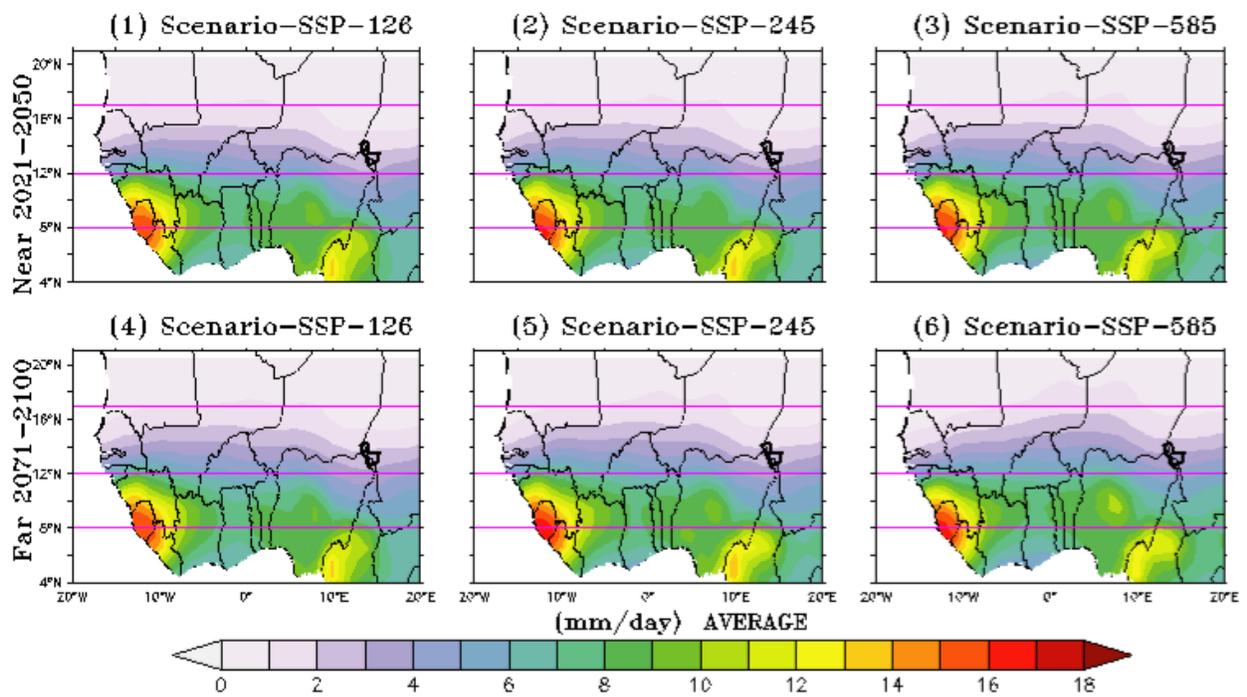


Figure 4.12: Average of monsoon period (JJAS) for near (2021 – 2050) on the top and far future period (2071-2100) on the bottom, ssp1-2.6 at left, ssp2-4.5 at the middle and ssp5-8.5 at right

4.4.2 Standard deviation of Ensmean of six output model from CMIP6

The standard extreme precipitation indices used in studies vary, but they generally measure aspects of precipitation frequency, duration, and intensity. Some examples of these indices include the amount of daily precipitation above a certain threshold, the number of consecutive dry days, and the maximum 5-day precipitation amount Lisa *et al.*, (2019); Myhre *et al.*, (2019). Other studies use different sets of extreme precipitation indices to assess trends in extreme precipitation events over time Asher *et al.*, (2020); Gentilucci *et al.*, (2020)

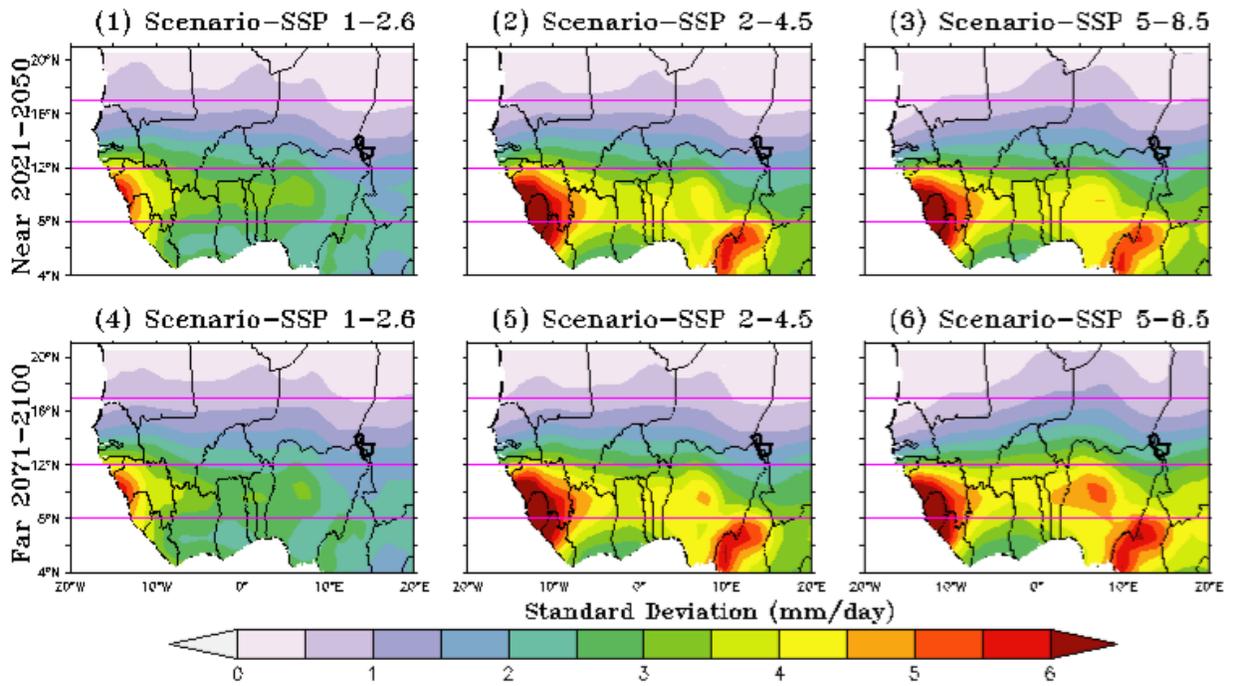


Figure 4.13: Standard Deviation of monsoon period (JJAS) for near and far future trends for the Ensmean of all the six dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

Standard deviation is a measure of the spread or dispersion of a set of data values. The importance of standard deviation in West African rainfall lies in its ability to provide a measure of the amount of variability in the amount of rainfall between regions, this allows for better forecasting. Standard deviation is an important measure used to quantify the variability of rainfall in West Africa. It is used to determine the degree of risk associated with agricultural investments, and to determine the amount of water available for irrigation. It is also used to compare the variability of rainfall between different years, or even between different countries in West Africa. This can help inform decisions about how to best manage the agricultural sector in the region.

A large deviation is displaying (Figure 4.13) over Savannah and Guinea zones under the ssp2-4.5 and ssp5-8.5 for near and far future projection due to the time and spatial distribution. The standard distribution under the ssp1-2.6 still moderate except the coastal area of Guinea Conakry and Liberia which showed a high distribution due to the sea surface temperature and monsoon flow.

4.4.3 Biases in the simulated precipitation seasonal average

Bias simulation of West African rainfall is a method of estimating the amount of rainfall in the region by simulating the data with a computer model. This method is used to improve the accuracy of the rainfall estimates and to reduce the uncertainty associated with the estimates. According to Gonzalez *et al.*, (2009) Bias simulation of West African rainfall can provide a more accurate picture of the amount of rainfall in the region. This can be useful for making decisions about water resources management and agricultural production, as well as for predicting the potential impacts of climate change, Kang *et al.*, (2013).

Methods Used in Bias Simulation of West African Rainfall: It is typically done using a computer model. This model is used to simulate the data and to estimate the amount of rainfall in

the region. The model can be used to improve the accuracy of the estimates and to reduce the uncertainty associated with the estimates. The model can also be used to assess the potential impacts of climate change on the region.

Challenges of Bias Simulation of West African Rainfall: One of the challenges of bias simulation of West African rainfall is the availability of data. In some cases, the data may be limited or incomplete, which can make it difficult to accurately simulate the data. This can lead to inaccurate estimates of the amount of rainfall in the region. Another challenge of bias simulation of West African rainfall is the complexity of the computer model. The model may be difficult to understand and may require a significant amount of time and effort to set up and run accurately. The bias simulation of West African rainfall is an important method of estimating the amount of rainfall in the region.

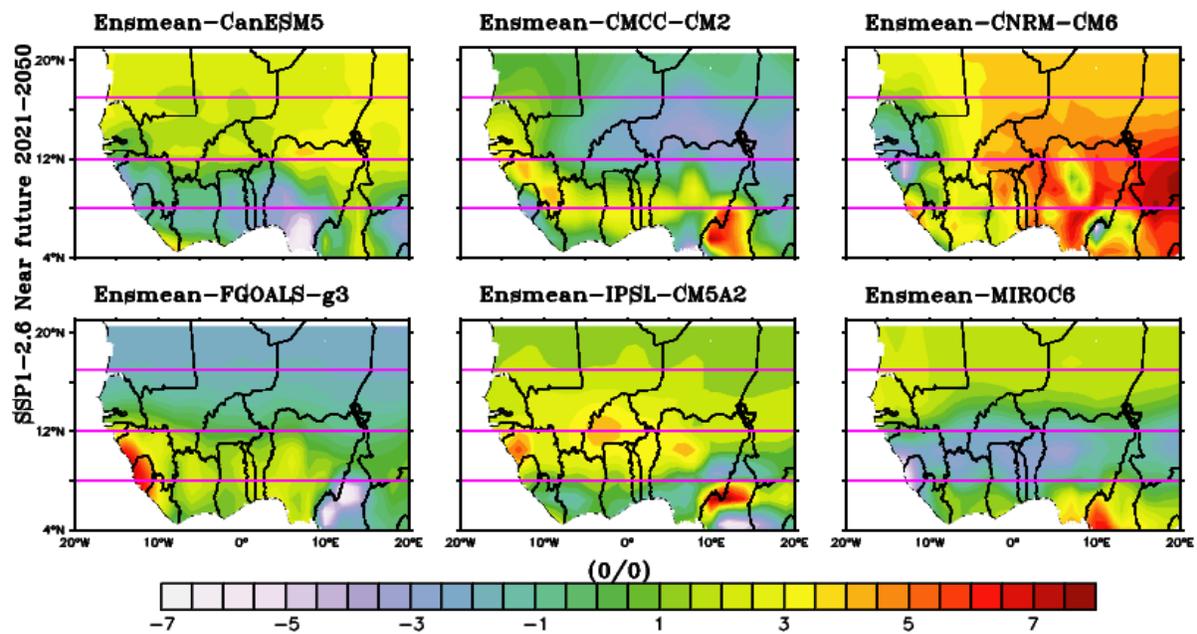


Figure 4.14: Seasonal average (JJAS) Bias between Ensmean SSP1-2.6 and individual output model for near future trends (2021 - 2050)

Comparing to the Ensmean, the monsoon rainfall is overestimate over the northern area of West Africa with the IPSL-CM5A2 and CanESM5 over the three zones (Guinea, Savannah and Sahel) with CNRM-CM6 for near future projection (Figure4.14). However, it is underestimate with MIROC6 in Savannah and it is also underestimate for all the Sahel zone with FGOALS-g3 and CMCC-CM2. The positive bias observed in the Sahel and Savannah zones across most models, except CMCC-CM2 and FGOALS-g3, suggests a tendency for these models to overestimate future climate conditions in these regions under the ssp1-2.6 scenario. This overestimation could have implications for the projected impacts of climate change on these areas, such as increased precipitation or temperatures, which may need to be reevaluated based on the performance of these two models. It may be influenced by various factors, such as inadequate representation of land-atmosphere interactions, uncertainties in regional-scale processes, or biases in simulating atmospheric circulation patterns.

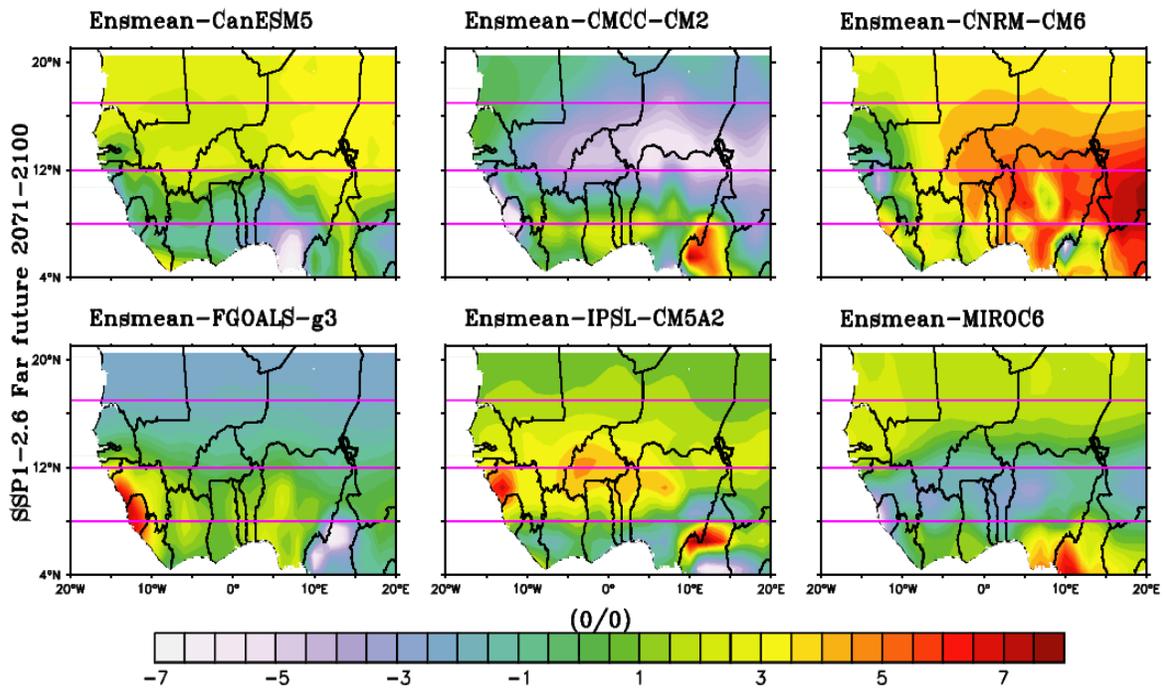


Figure 4.15: Seasonal average (JJAS) Bias between Ensmean SSP1-2.6 and individual output model for far future trends (2071 - 2100)

Comparing to the Ensmean, the rainfall process is overestimate over the Sahel area of West Africa with IPSL-CM5A2 and CanESM5, over the three zones (Guinea, Savannah and Sahel) with CNRM-CM6 except the coastal zone of Senegal and Guinea Conakry for near future projection (figure4.15). However, it is underestimate in Savannah with MIROC6 and it is also underestimate for all the Sahel zone with FGOALS-g3 and CMCC-CM2. Understanding these specific factors is crucial for improving regional climate projections in these vulnerable regions and ensuring accurate assessments of potential impacts, such as changes in precipitation patterns, temperature extremes, and ecosystem dynamics.

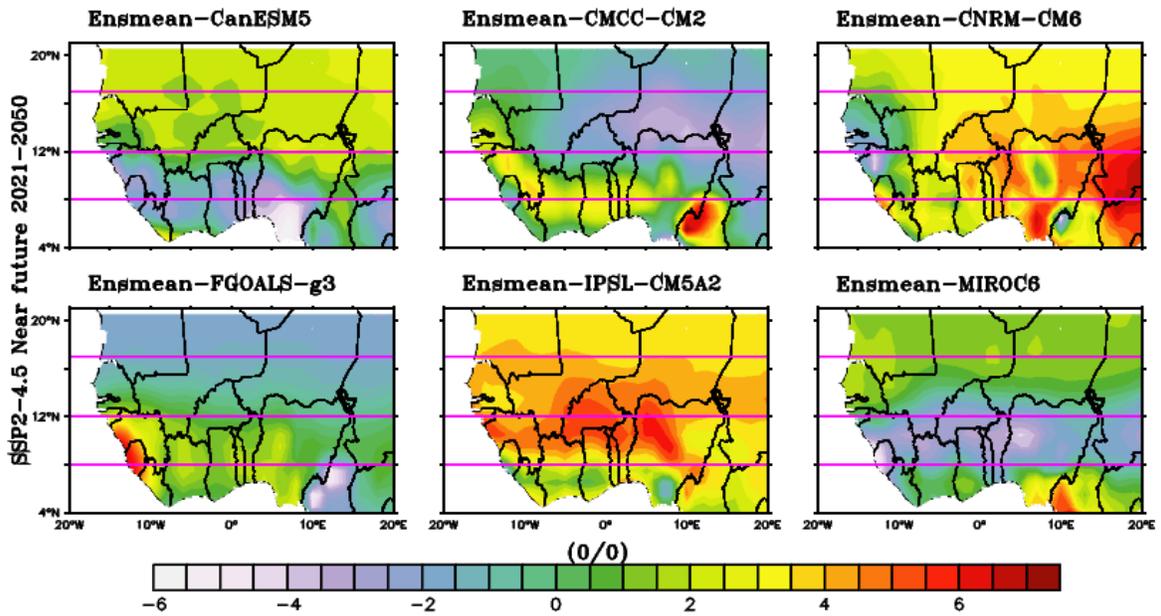


Figure 4.16: Seasonal average (JJAS) Bias between Ensmean SSP2-4.5 and individual output model for near future trends (2021 - 2050)

The (Figure4.16) showed for the far future projection the same process and displayed a significant positive bias with IPSL-CM5A2 and CNRM-CN6, a negative bias is collected in Sahel zone with CMCC-CM2 and FGOALS-g3. The CanESM5 and MIROC6 also contained a negative bias over central Savannah. The significant positive bias observed with IPSL-CM5A2 and CNRM-CN6 in the near future period indicates a tendency for these models to overestimate climate conditions under the SSP2-4.5 scenario. This overestimation could lead to potential impacts such as increased rainfall or higher temperatures, which may have implications for the Sahel zone. Conversely, the negative bias seen in the Sahel zone with CMCC-CM2 and FGOALS-g3 suggests an underestimation of future climate conditions in terms of precipitation or temperature. Additionally, CanESM5 and MIROC6 exhibited a negative bias over the central Savannah, implying a potential underestimation of future rainfall or cooler temperatures in this region. These biases highlight the need for further investigation into model-specific processes, such as representation of regional-scale atmospheric circulation, land surface processes, and feedback mechanisms, to enhance the accuracy of regional climate projections and better understand the potential impacts of climate change.

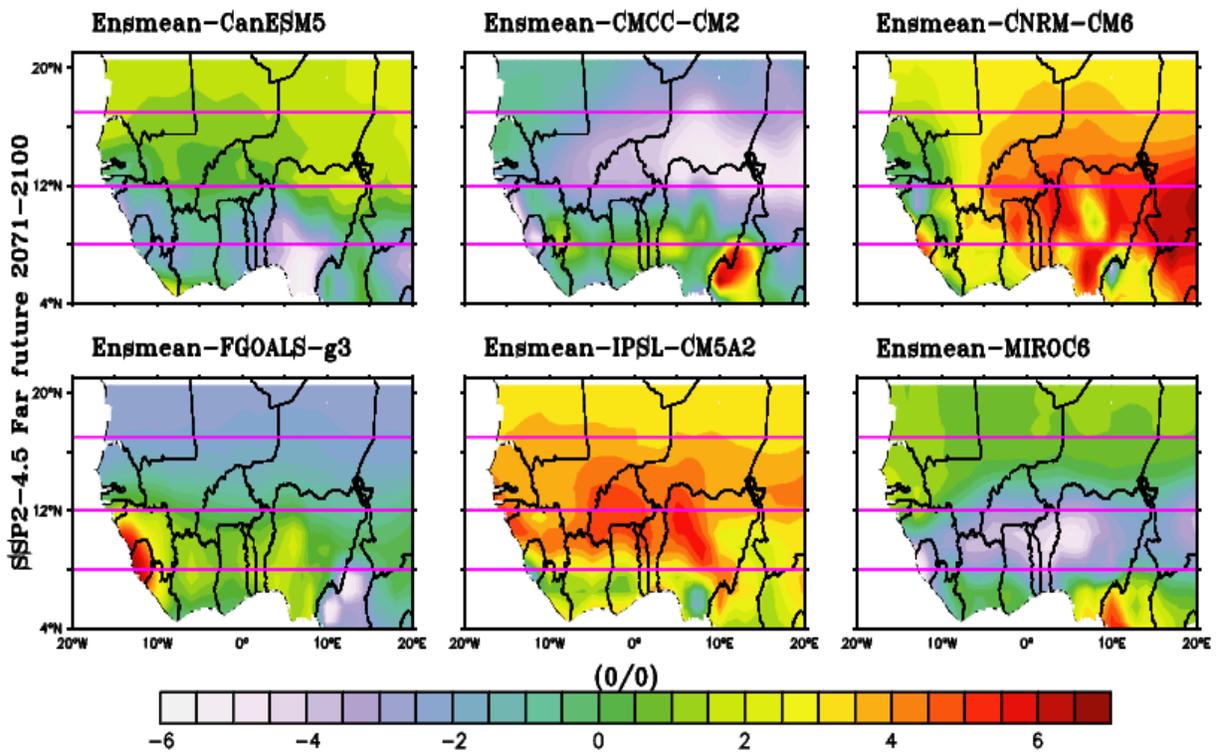


Figure 4.17: Seasonal average (JJAS) Bias between Ensmean SSP2-4.5 and individual output model for far future trends (2071 - 2100)

As the SSP1-2.6 for the period (2071 – 2100), the far future projection of SSP2-4.5 (Figure4.17) collected positive bias over the three zones of West Africa under the CNRM-CM6 and IPSL-CM4A2. A negative bias is collected in Sahel zone with CMCC-CM2 and FGOALS-g3, while a negative bias is collected over Savannah and Guinea zone for CanESM5 and MIROC6. Means that the models CNRM-CM6 and IPSL-CM5A2 highly overestimate the rainfall process. This overestimation may have implications for the impacts of climate change in these regions. Conversely, the negative bias seen in the Sahel zone with CMCC-CM2 and FGOALS-g3 suggests an underestimation of future climate conditions, potentially leading to lower precipitation or cooler temperatures. Moreover, CanESM5 and MIROC6 exhibited a negative bias over the Savannah and Guinea zone, indicating a potential underestimation of future rainfall or cooler temperatures in these areas. These biases highlight the need to further examine model-specific processes and improve their representation of regional-scale climate dynamics and feedback mechanisms to enhance the accuracy of future climate projections for West Africa.

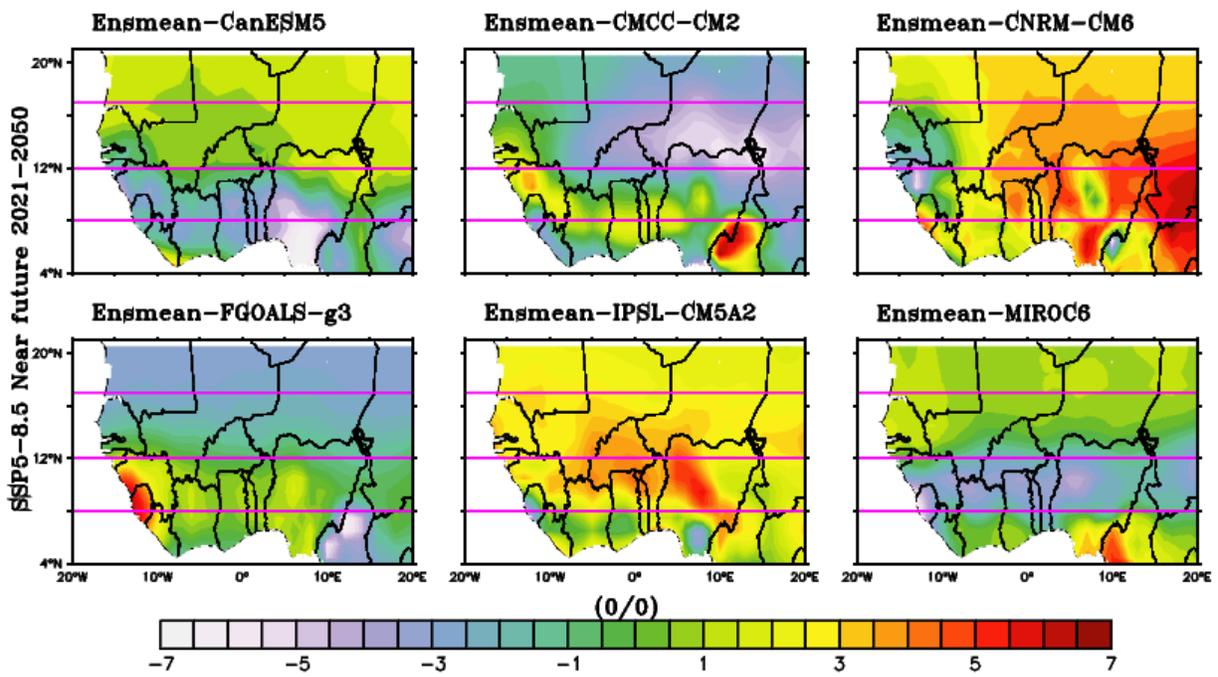


Figure 4.18: Seasonal average (JJAS) Bias between Ensmean SSP5-8.5 and individual output model for near future trends (2021 - 2050)

The same characteristics is observed. In the near future trends under the SSP5-8.5 scenario, the seasonal average bias reveals certain patterns (Figure 4.18). The underestimation of the seasonal average is observed in the central Savannah and south of Nigeria when using MIROC6 and CanESM5 models, indicating potential inaccuracies in predicting future climate conditions in these regions. Conversely, CNRM-CM6 and IPSL-CM5A2 models exhibit a greater positive bias across West Africa, suggesting an overestimation of future climate conditions, such as higher temperatures and increased rainfall, in this region. The CMCC-CM2 and FGOALS-g3 models, on the other hand, display different biases. The CMCC-CM2 model underestimates the seasonal average in the Sahel region, potentially indicating lower precipitation or cooler temperatures than projected. In contrast, it overestimates the seasonal average in the Guinea zone, suggesting higher precipitation or temperatures. These discrepancies emphasize the challenges in accurately capturing regional climate dynamics within these models. Understanding the factors contributing to these biases requires investigating the representation of land-atmosphere interactions, atmospheric circulation patterns, and regional-scale processes within each model. Additionally, the performance of the MIROC6 and CanESM5 models in the central Savannah and south of Nigeria warrants further scrutiny to identify potential limitations in simulating regional climate trends.

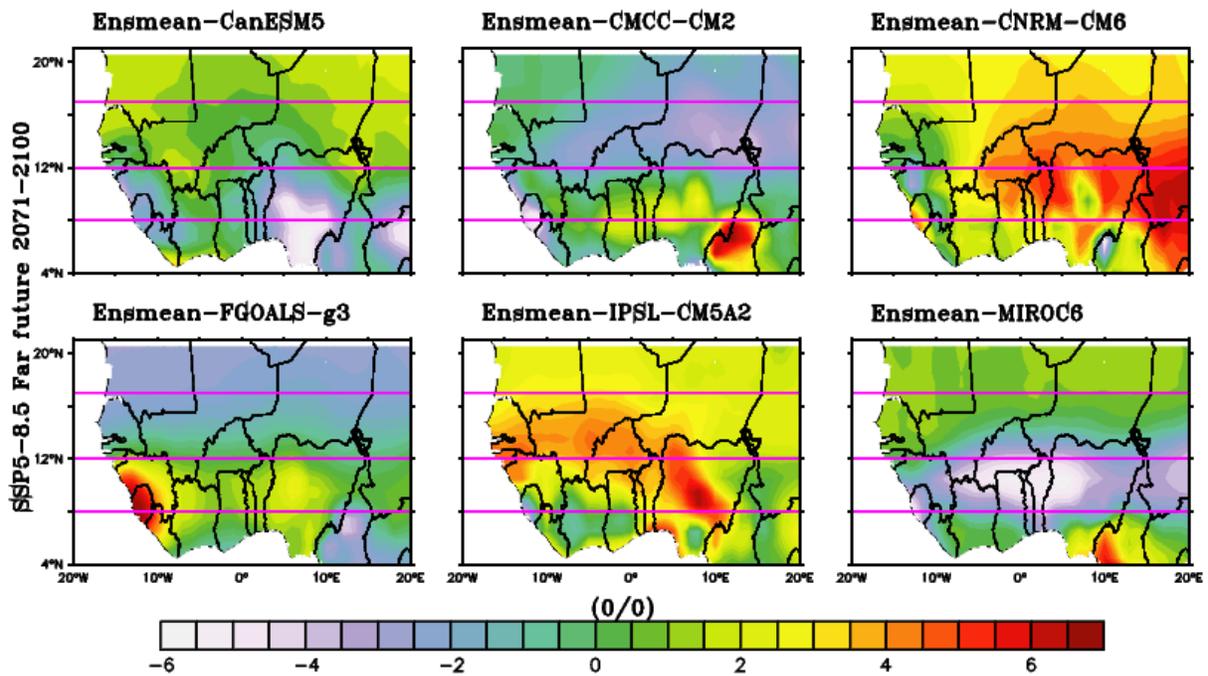


Figure 4.19: Seasonal average (JJAS) Bias between Ensmean SSP5-8.5 and individual output model for far future trends (2071 – 2100)

Based on the analysis of seasonal average bias between the Ensmean SSP5-8.5 and individual output models for the far future trends (2071-2100), it was observed that the Ensmean minus CNRM-CM6 and IPSL-CM5A2 models exhibited overestimation in the Sahel and Savannah zones. This suggests that these two models are projecting higher precipitation values or wetter conditions compared to the ensemble mean (Figure 4.19). On the other hand, the remaining models showed a negative bias, indicating that they are projecting drier conditions than the ensemble mean in these regions. These discrepancies could be attributed to variations in model parameterizations, initial conditions, or uncertainties in representing regional climate processes, all of which can influence the simulated precipitation patterns. The overestimation of precipitation by CNRM-CM6 and IPSL-CM5A2 models in the Sahel and Savannah zones may be due to their specific parameterizations or biases in representing regional climate processes, leading to an exaggerated projection of wetter conditions. The negative bias exhibited by other models suggests a potential underestimation of future precipitation in these regions, which could have significant implications for water resources, agriculture, and ecosystems, highlighting the need for further research and model improvements to enhance the accuracy of future climate projections in these vulnerable areas.

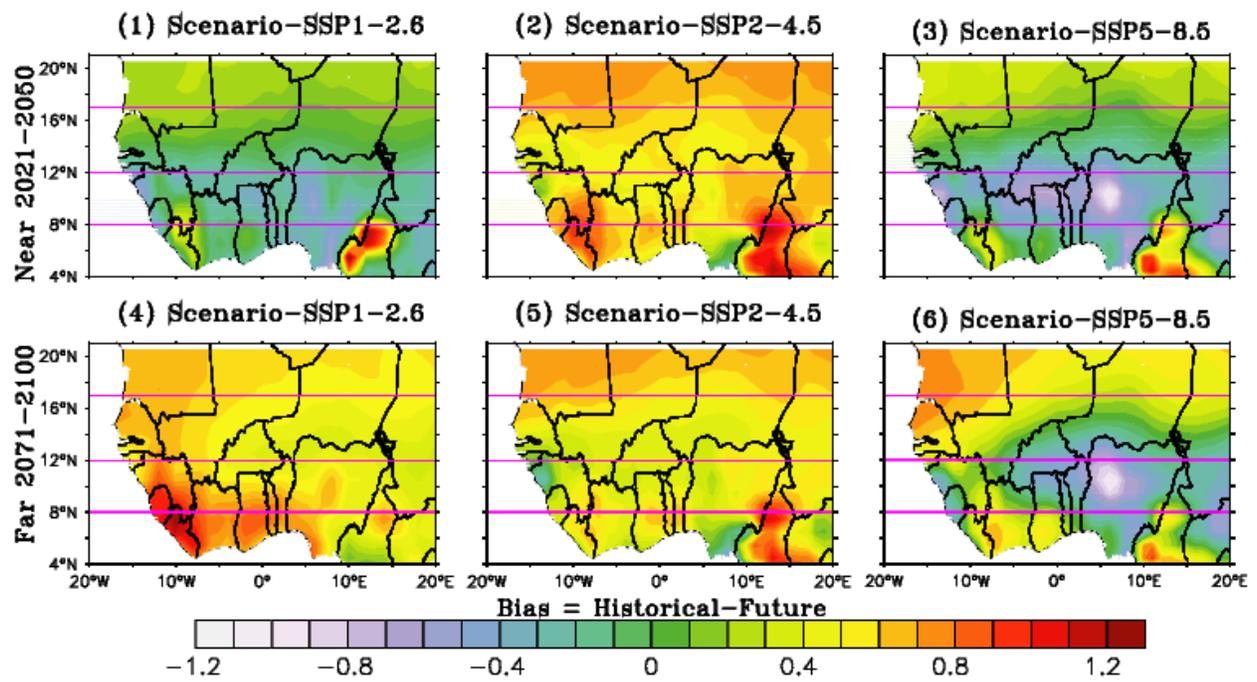


Figure 4.20: Bias plot between CMIP6 Historical and forecasting with (1), (2) and (3) for near period and (4), (5) and (6) for far period.

The simulation results indicate important insights into the climate projections for West Africa under different scenarios (Figure 4.20). Firstly, in the near future, the ssp1-2.6 scenario exhibits a negative bias across the Sahel, Savannah, and Guinea zones, suggesting that the actual climate conditions may be more favorable than predicted by this scenario. However, an interesting exception is observed in Cameroon, where a positive bias is projected, indicating that the climate conditions may be more challenging than anticipated. For the far future under ssp1-2.6, a consistent positive bias is projected across the entire West Africa region. This implies that the climate conditions may become more severe and unfavorable compared to the historical data, affecting various zones. Moving on to the ssp2-4.5 scenario, a positive bias is seen in the near and far future projections for the three zones of West Africa. This suggests that under this scenario, the climate conditions are likely to be worse than the historical data indicates, impacting the Sahel, Savannah, and Guinea zones. Contrarily, the ssp5-8.5 scenario shows a similar pattern in both the near and far future projections. It indicates a negative bias over the Savannah zone and a positive bias over the Sahel and Guinea zones, particularly affecting countries like Cote d'Ivoire, Ghana, Liberia, and Cameroon. This scenario implies that the climate conditions in these regions may become more challenging and potentially lead to adverse impacts. These findings highlight the importance of considering different climate scenarios when assessing the future climate trends. It is crucial to recognize the varying impacts across different regions, as demonstrated by the differences observed in Cameroon compared to other parts of West Africa. These results underscore the complexities involved in climate change forecasting and the need for robust models to capture the regional variations accurately.

4.5. Precipitations Indices using CMIP6 Scenarios

The Shared Socioeconomic Pathways (SSPs) are used to provide a basis for integrated scenarios of emissions and land use, facilitate climate impact, and assess the potential effects of climate change on agriculture, food security, and development in West Africa Halvard *et al.*, (2019). The SSPs help researchers quantify future world developments and provide narrative descriptions of future world developments Lehtonen *et al.*, (2021). They can be used to project growth in various sectors such as energy use and resource intensity. By using the SSPs, researchers can better understand the potential impacts of climate change on West Africa's food security and other socioeconomic factors.

The recently developed Shared Socioeconomic Pathways (SSPs) allows researchers to study coupled human-nature dynamics in new and more complex ways. Despite their broad applicability and undeniable benefits, the role of SSPs in conducting social impact assessments is hampered by potential pitfalls in forecasting economic growth relative to prior scenarios. In particular, assuming economic convergence and no major growth disruptions, the historical growth paths of developing countries would be disrupted. As a result, the SSPs portfolio became too narrow and the lower bound of the growth forecast was too optimistic. This is not a small problem, as the resulting impact assessments may underestimate the full human and material costs of climate change, especially for the poorest and most vulnerable societies. How will climate change shape society in the coming decades? What steps can be taken to avoid the worst consequences? The recently developed Shared Socioeconomic Pathways (SSP) framework plays an integral role in the ongoing sixth assessment cycle of the Intergovernmental Panel on Climate Change (IPCC) and represents the most comprehensive study. Attempts to match climate change scenarios O'Neill *et al.*, (2014); Riahi *et al.*, (2017).

The Coupled Model Intercomparison Project (CMIP6) is an international collaboration of climate scientists using climate models to study the impacts of climate change.

4.5.1 Consecutive dry day indices

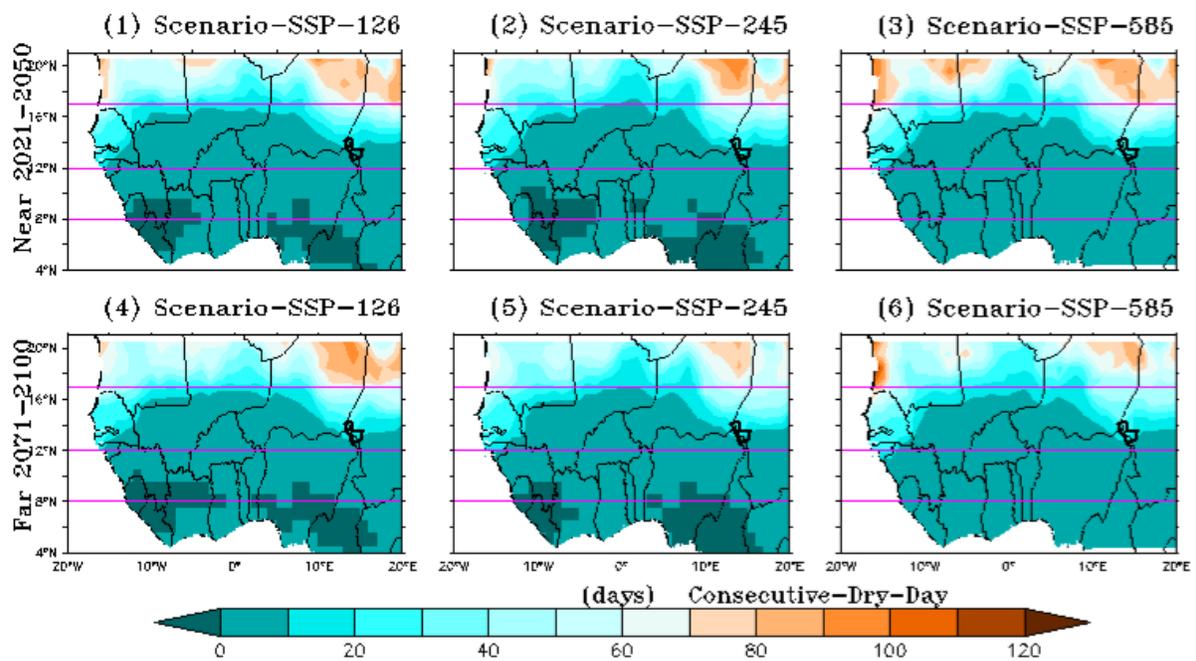


Figure 4.21: Consecutive Dry Day of (JJAS) for near and far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

The dry season is characterized by little or no precipitation, especially in the interior and northern area of West Africa Giannini *et al.*, (2003).

A significant dry days is recorded (Figure4.21) over the Sahara region with all the three scenarios models for near and far future period. While, the Guinea region and Savannah displayed a negligible dry period under the ssp-126 and ssp-245 for near and far future especially on Guinea Conakry, Cote d'Ivoire and Liberia Nigeria and Cameroon. The coastal area of Mauritania and northern area of Mali, Niger and Tchad recorded highest significant dry days with the Ensemble scenarios for both near and far future periods, means that the Sahel is expecting drought risks in the near and long term periods.

4.5.2 Consecutive wet day indices

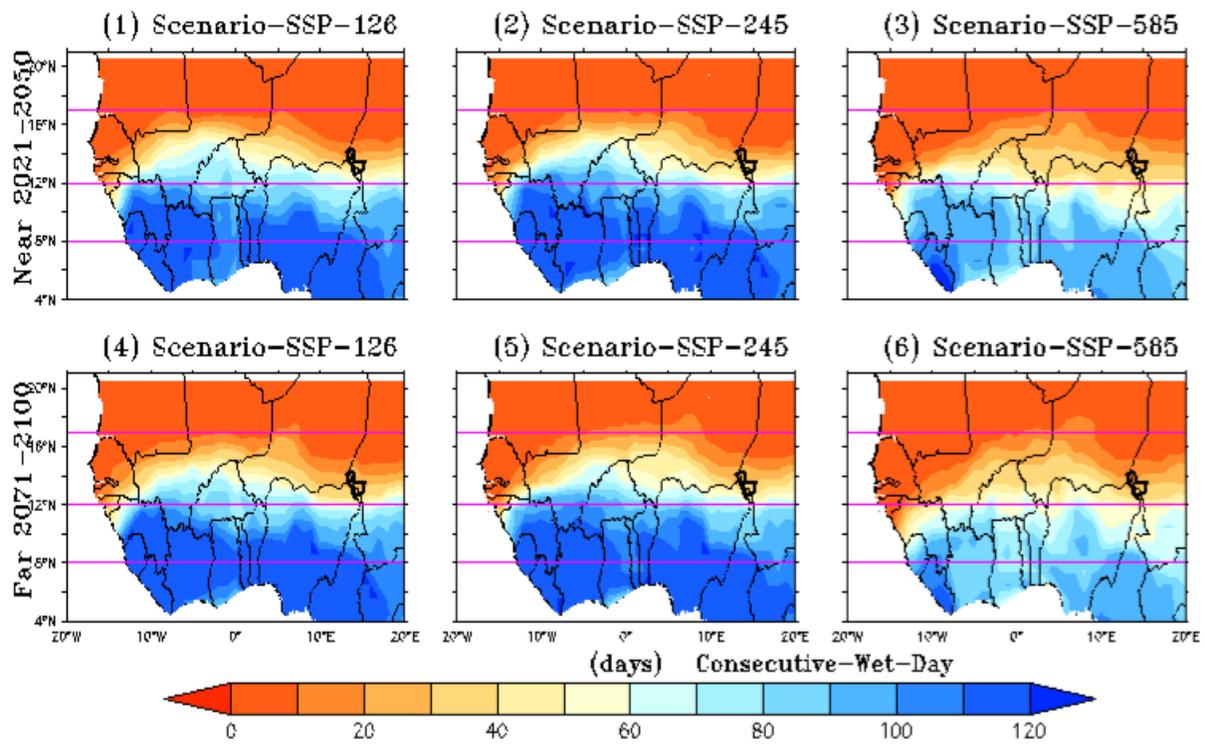


Figure 4.22: Consecutive Wet Day of (JJAS) for near and far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

The spatial distribution of the CWD index over West Africa is influenced by a number of factors, including topography, latitude, and prevailing wind patterns. Generally, areas closer to the equator receive higher amounts of rainfall and have a greater number of consecutive wet days than areas farther to the equator. In West Africa, the coastal areas of the Gulf of Guinea, which includes countries such as Ghana, Togo, Benin, and Nigeria, receive the highest amounts of rainfall and have the highest number of consecutive wet days. This is due to the proximity of these areas to the Atlantic Ocean and the influence of the West African monsoon, which brings moist air and rainfall to the region. In contrast, the Sahel region of West Africa, which includes countries such as Senegal, Mauritania, Mali, Burkina Faso, Niger, and Chad, receives lower amounts of rainfall and has fewer consecutive wet days. This is due to the influence of the dry Harmattan winds that blow across the region from the Sahara Desert. There is a great activity with the Consecutive Wet Day (CWD) over Savannah and Guinea regions with the scenarios SSP1-2.6 and SSP2-4.5 for near and far future period (Figure4.22). However, the SSP5-8.5 scenario showed a moderate wet day with both near and far future projection over Savannah and Guinea zones except the coastal Southwest area of West Africa (Sierra Leone and Liberia) which collected significant wet day period. It is important to note that the spatial distribution of the CWD index can change over time in response to changes in climate patterns. The spatial distribution of the CWD index is affected by the changes in rainfall patterns and amounts over West Africa, this spatial distribution of the CWD index reflects the complex interactions between climate patterns and regional geography, and provides important insights into the variability of rainfall and wetness over the region.

As the map shows, both scenarios project warming trends and mostly positive changes in annual precipitation across much of West Africa. While most of the changes are small and insignificant,

a wetter future is projected for Niger and Chad, while the SSP5-8.5 scenario suggests a likely drier trend in western West Africa, Niang *et al.*, (2014)

4.5.3 Heavy rainfall indices (R10mm)

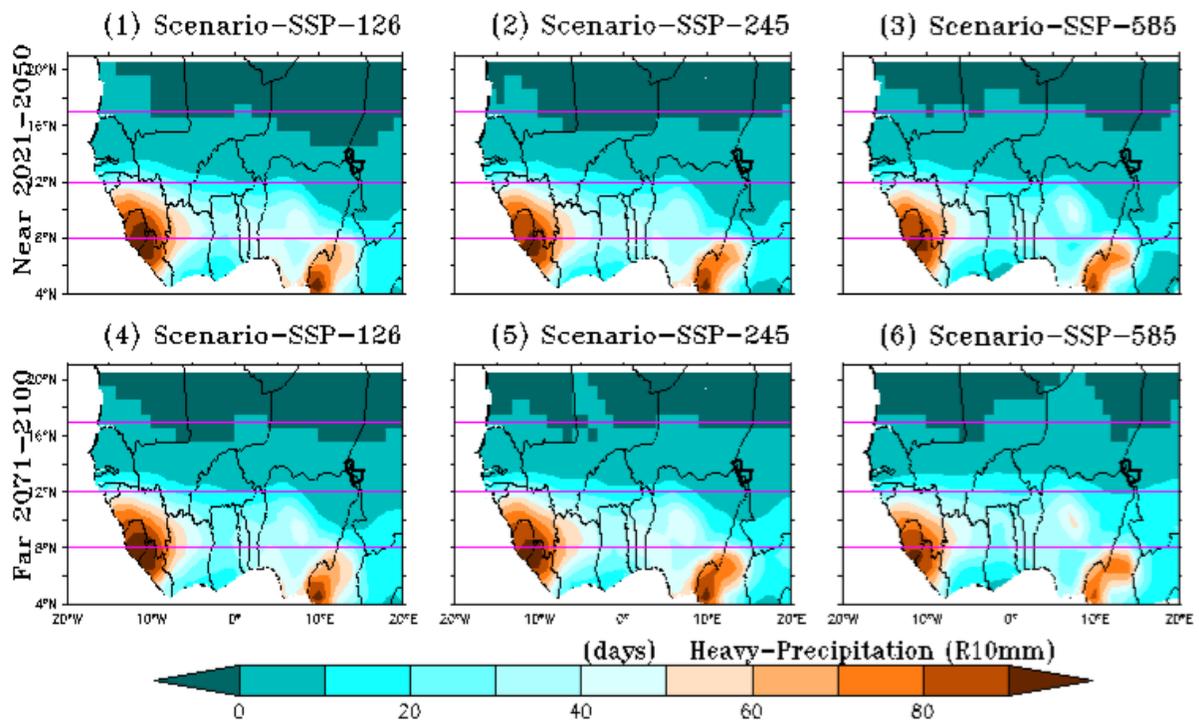


Figure 4.23: Heavy Precipitation of (JJAS) for near and far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

The heavy rainfall amount (R10mm) over West Africa is an important climatic phenomenon that has significant implications for the region. The coastal area (Figure 4.23) of West Africa recorded the significant activities of R10mm indices under all the scenarios both in near and far future projection. However, a nonsignificant heavy rainfall is observed over Sahel zone with SSP1-2.6, SSP2-4.5 and SSP5-8.5. The Guinea and Savannah zones, which include countries such as Guinea Conakry, Sierra Leone, Liberia, and Cameroon, have displayed a higher amount of rainfall, ranging from 60mm/day to 90mm/day. This indicates that these areas are more vulnerable to flooding, landslides, and other climate-related hazards Rowell *et al.*, (2015); Adedoyin *et al.*, (2020). The amount of rainfall in the Sahel zone, on the other hand, is much smaller, ranging from 0mm to 15mm/day Hagos *et al.*, (2014).

This is due to the fact that the Sahel zone is located in a semi-arid region and experiences a long period of drought and low rainfall. Climate change has made this situation worse, with rising temperatures and changing weather patterns exacerbating the already fragile ecosystem Adejuwon *et al.*, (2021). The heavy rainfall in the Guinea and Savannah zones can be attributed to several factors, including increased moisture from the Atlantic Ocean, changes in wind patterns, and the presence of low-pressure systems. These factors can be linked to global climate change and the intensification of the hydrological cycle.

4.5.4 Very heavy rainfall indices (R20mm)

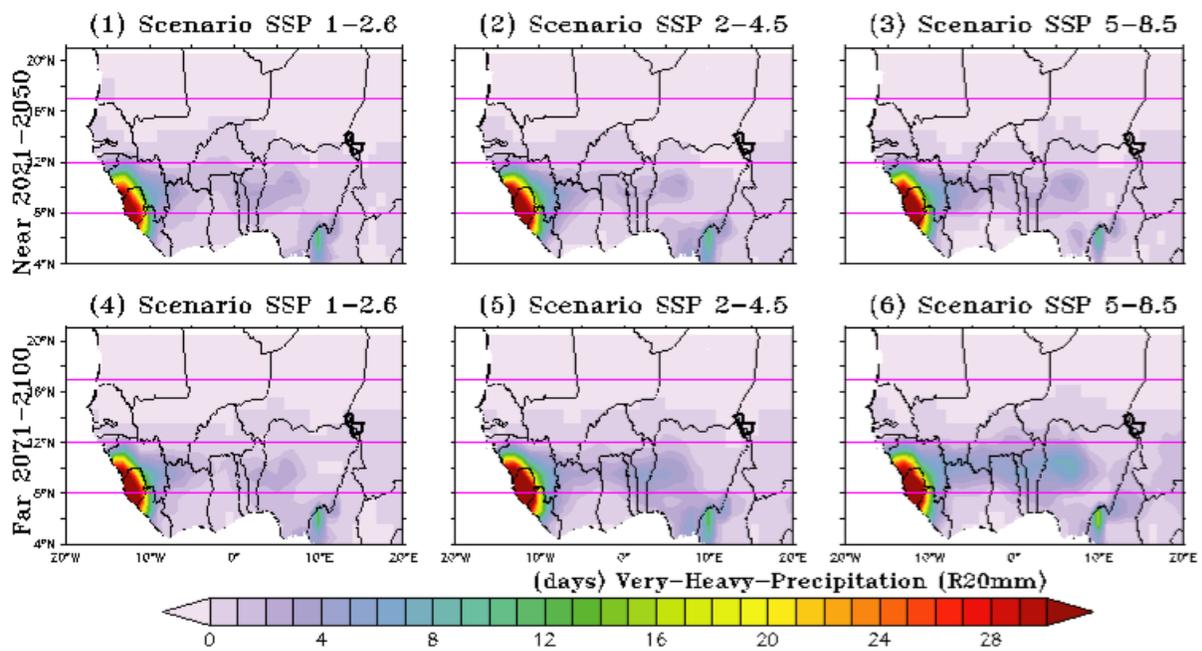


Figure 4.24: Very Heavy Precipitation of (JJAS) for near and far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-26, ssp2-45 and ssp5-85

The very heavy rainfall indices (R20mm) over West Africa have been shown to be influenced by a range of factors, including changes in sea surface temperatures and the position of the Inter-Tropical Convergence Zone (ITCZ) Giannini *et al.*, (2013); Fontaine *et al.*, (2011). The Guinea and Savannah zones, including Sierra Leone and Liberia (Figure4.24), have been identified as areas that are particularly vulnerable to very heavy rainfall Adedoyin *et al.*, (2020). The countries such as Guinea Conakry, Sierra Leone and Liberia recorded the most significant activities of R20mm indices followed by Cote D'Ivoire, Togo, Ghana, Benin and Nigeria which are expected to reproduce a moderate R20mm precipitation process over West African zones under all the three SSPs scenarios with both for the periods (2021 – 2050) and (2071 – 2100).

4.5.5 Highest 5 days precipitation indices (Rx5day)

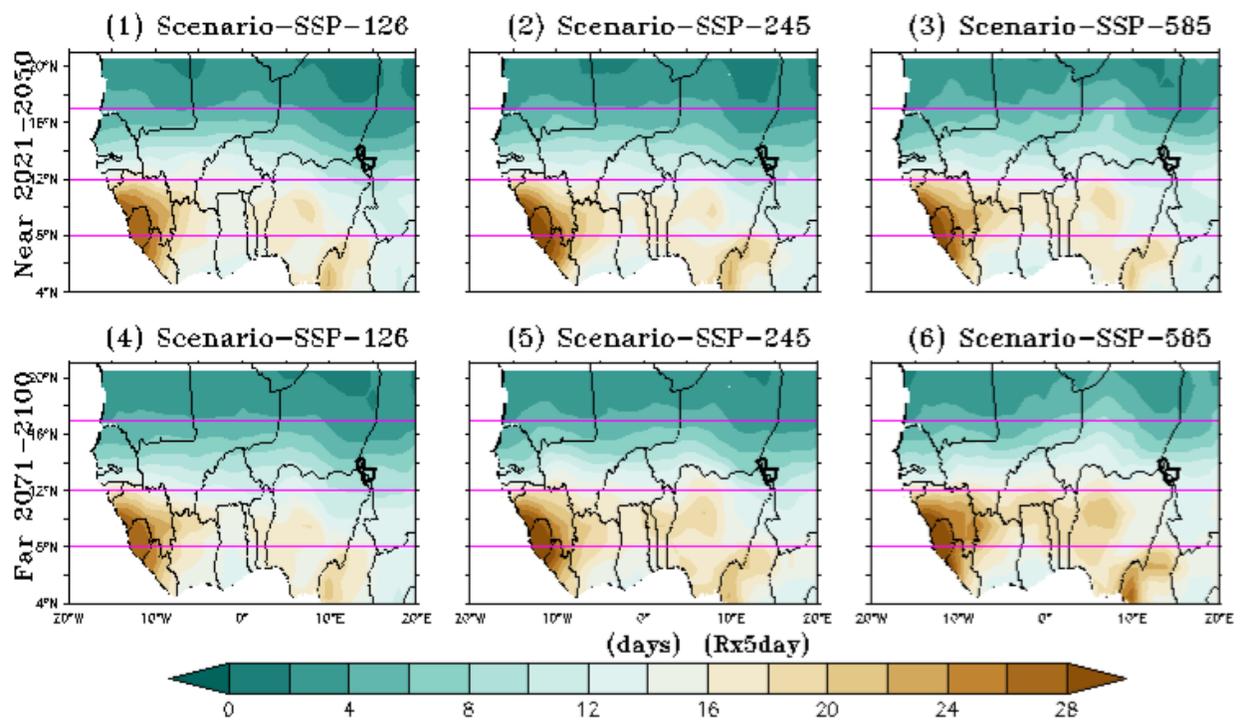


Figure 4.25; Highest 5 days precipitation of (JJAS) in near far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

The Rx5day indices showed the frequency of rainfall over an area (Figure4.25). The significant values of Rx5day extreme events over the Savannah and Guinea zones, particularly over Sierra Leone, Liberia, and Guinea Conakry, can be attributed to the region's distinct wet and dry seasons, with the wet season occurring from May to October. Climate change is also exacerbating the frequency and intensity of extreme weather events, including heavy rainfall and flooding, in this region. Human activities, such as deforestation, agriculture, and urbanization, could also be contributing to the observed pattern of extreme events.

4.5.6 Simple Daily intensity index (SDII)

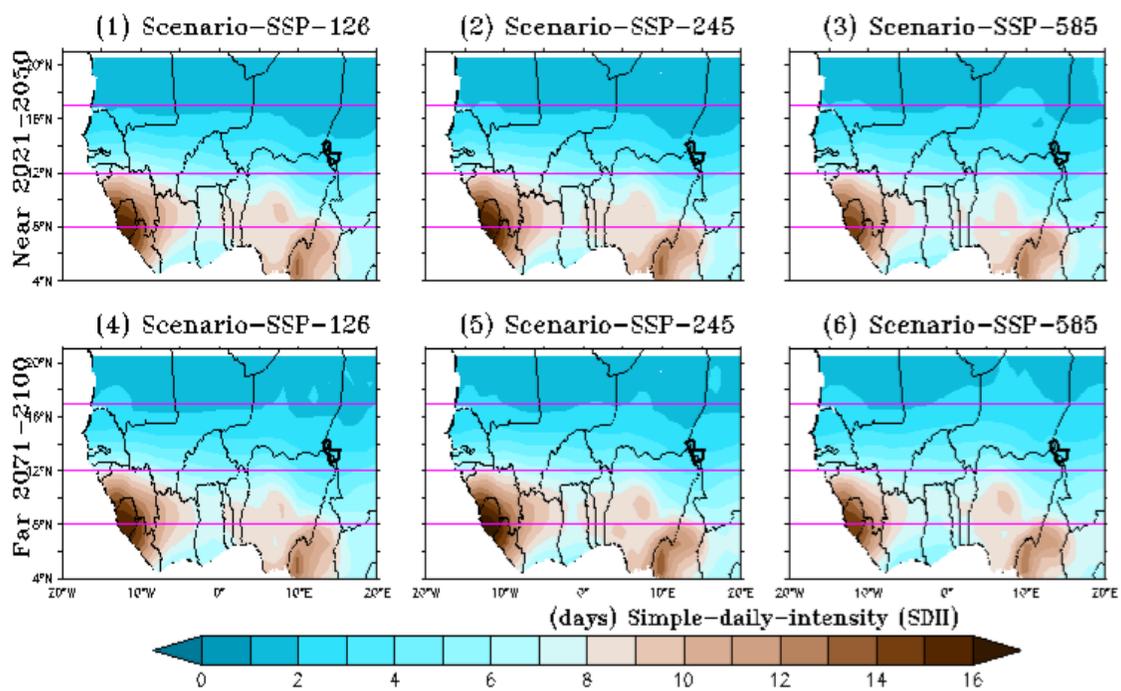


Figure 4.26: Simple daily intensity of (JJAS) in near far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

The simple daily intensity index (SDII) (Figure 4.26) gives the rainfall intensity. As represented with the Rx5day in (Figure 4.25), the SDII index in (Figure 4.26) is more significant over Savannah and Guinea zones especially in the Western and the Eastern areas. The Sahel zone recorded a moderate simple daily intensity index with three SSPs scenarios. The observed pattern of significant Simple Daily Intensity Index (SDII) extreme events over the Savannah and Guinea zones, particularly over Sierra Leone, Liberia, and Guinea Conakry, is likely due to a combination of factors. Firstly, the West African region experiences distinct wet and dry seasons, with the wet season typically occurring from May to October, which increases the likelihood of extreme rainfall events. Secondly, climate change is believed to be exacerbating the frequency and intensity of extreme weather events in this region. Rising temperatures, changes in atmospheric circulation patterns, and increased water vapour in the atmosphere can all contribute to more intense rainfall events. Additionally, human activities, such as deforestation, agriculture, and urbanization, can alter the landscape and contribute to the risk of extreme weather events. Deforestation can lead to increased runoff and soil erosion, while agriculture and urbanization can change the hydrological cycle. The observed pattern of significant SDII extreme events may also be related to the region's vulnerability and lack of preparedness for extreme weather events. Many communities in this area lack adequate infrastructure, such as drainage systems and flood control measures, making them more susceptible to the negative impacts of extreme weather events.

4.5.7. Simulation of 75th Percentile indices

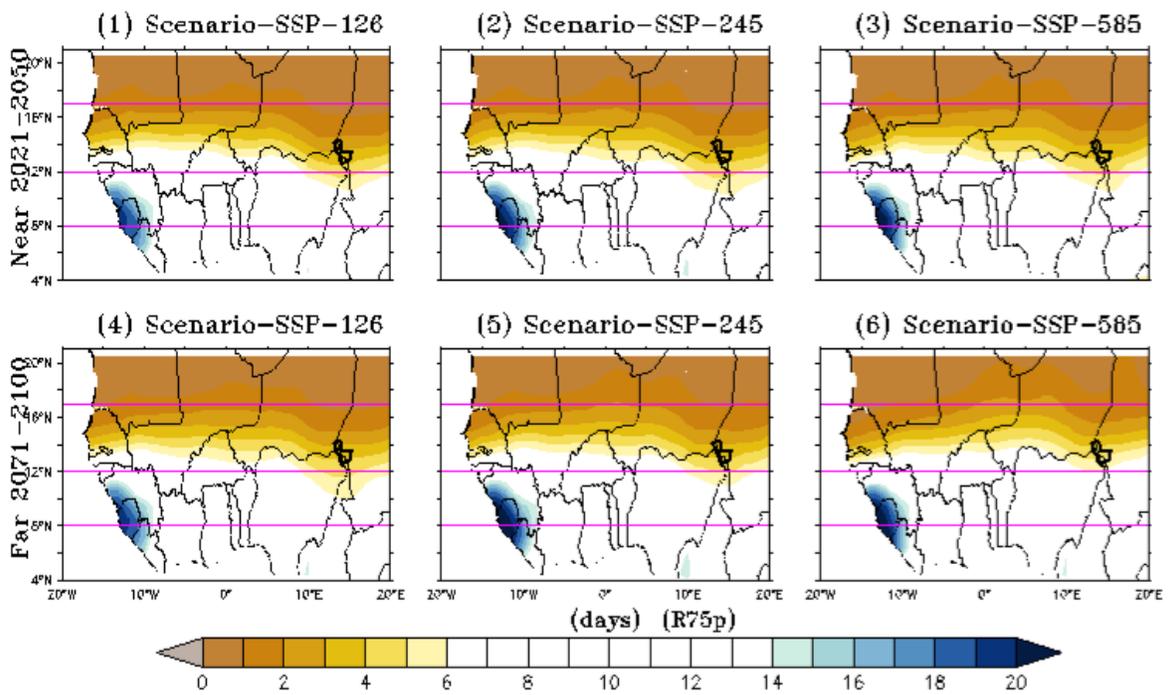


Figure 4.27: 75th percentile (JJAS) in near far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

The 75th, 90th and 95th percentile of West African rainfall used in this study are the amount of precipitation that falls in a particular area during the rainy season. They are the amount of rainfall that falls during the wet period that is greater than 75%, 90% and 95% respectively, of the total rainfall that falls in that area. This means that the 75th (90th or 95th) percentile of rainfall is higher than the average amount of precipitation that falls in the area, which is typically around 30-40 inches per year. The 75th (90th or 95th) percentile study of West African rainfall is important for understanding the amount of water that is available for agriculture and other activities. It also helps to determine the amount of water that is available for drinking and other uses. Knowing the 75th (90th or 95th) percentile of rainfall can help to predict the amount of water that will be available in the area in the future.

The 75th (90th or 95th) percentile of West African rainfall is measured using a variety of methods, including rain gauges, satellite imagery, and radar. Rain gauges measure the amount of precipitation that falls in a particular area, while satellite imagery and radar can be used to measure the amount of precipitation that is falling across a wider area. This information is then used to calculate the 75th percentile of rainfall for the region.

The 75th (90th or 95th) percentile of West African rainfall is also calculated using climate models. These models use historical data to predict the amount of rainfall that is likely to occur in a given year. It can affect the climate of the region, as changes in the amount of rainfall that falls in the area can lead to changes in the climate over time. The 75th (90th or 95th) percentile of West African rainfall can also have an impact on conservation efforts. Knowing the amount of rainfall that is likely to occur in a given year can help to identify areas that are most at risk of drought or flooding, and to target conservation efforts to these areas.

In West African rainfall, the percentile representation is used to quantify and rate heavy rainfall events. For example, some studies used the 90th or 95th percentile to represent extreme precipitation events Klutse *et al.*, (2021); Salack *et al.*, (2018), while others used the highest amounts of daily rainfall recorded during a typical rainy season Joël *et al.*, (2021). The ability to represent extreme precipitation in West African rainfall is highly dependent on the convective scheme used in regional climate models Berthou *et al.*, (2019).

Some moderate activities are recorded over Savannah and Guinea areas in West Africa with this 75th percentile (Figure 4.27), however, the most R75p is focussed over the coastal area of West Africa, especially over Guinea Conakry, Sierra Leone and Liberia under all the cmip6 scenarios with both near and far future projection.

4.5.8 Simulation of 90th Percentile indices

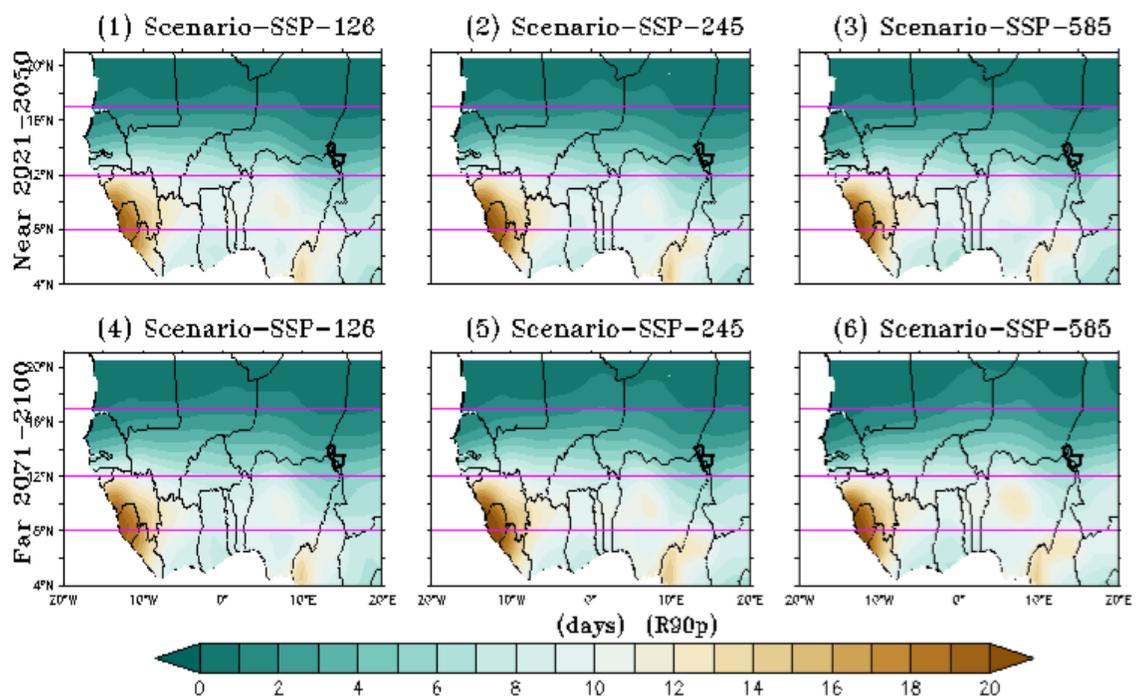


Figure 4.28: 90th percentile (JJAS) in near far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-26, ssp2-4.5 and ssp5-8.5

The 90th percentile is a statistical measure used to define extreme precipitation events. It is calculated by taking the 90th highest value of a given data set, which is then used as a benchmark for comparison. For example, if the 90th percentile for a given month is 20 inches (value on the graphic legend) (Figure4.28), then any precipitation event that exceeds this value would be considered as an extreme event. The 90th percentile is used to quantify the frequency and magnitude of extreme precipitation events. It is used to assess the risk of flooding and other potential disasters, and to help inform decisions about infrastructure and land use. The 90th percentile is also used to assess climate change impacts and to identify areas that are most vulnerable to extreme events.

The 90th percentile is calculated by taking the 90th highest value of a given data set. This value is then used as a benchmark for comparison. The data set used for the calculation is typically derived from historical records or climate models. Identifying extreme daily rainfall involves using data sets from either historical records or climate models. These precipitation events are those that surpass the gridded 90th percentile or any other pre-established thresholds by Ta *et al.*, (2016).

Understanding extreme precipitation events is crucial, and calculating the 90th percentile is essential in this endeavor. Having a comparison baseline and being able to evaluate the risk of flooding and disasters are crucial aspects of the 90th percentile's usefulness. However, this tool's limitations are worth noting since it is based on a single value and doesn't factor in the variability of extreme events. Better preparation and response to extreme precipitation events can be achieved through understanding the limitations of the 90th percentile, which does not account for the potential impacts of climate change resulting in a higher frequency and intensity of extreme events. Consequently, lives and livelihoods will be protected.

As mentioned in (Figure4.27) for the 75th percentile, the 90th percentile (Figure4.28) still significant over Guinea and Savannah especially over Guinea Conakry, Sierra Leone, Liberia and southern area of Nigeria. A moderate amount is collected in the central Guinea and Savannah, while a nonsignificant amount is observed in the Sahel zone.

4.5.9 Simulation of 95th Percentile indices

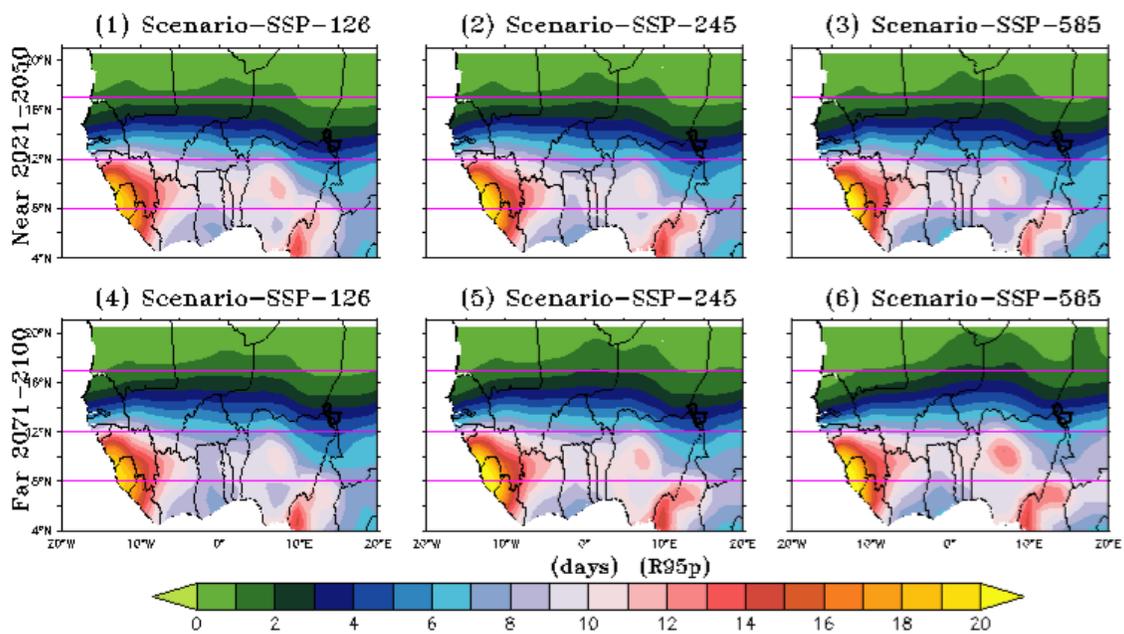


Figure 4.29: 95th percentile (JJAS) in near far future trends for the Ensmean of all the dataset from CMIP6 Scenarios ssp1-2.6, ssp2-4.5 and ssp5-8.5

Representing extreme precipitation events in West African rainfall with the 95th percentile. It extracts extreme values from observed data and defines a day with a lot of rain as very wet Salack *et al.*, (2018). Daily extreme precipitation events are also identified using this threshold. Moreover, studies reveal that there is a growing trend in the number of days with rainfall surpassing the 95th percentile and their impact on the overall precipitation Koffi *et al.*, (2022). Due to their significant impact on society and the economy in Africa, extreme weather events such as those associated with heavy rainfall are a major concern Francis *et al.*, (2019). When it comes to establishing trends in extreme rainfall over time, the 95th percentile is an important metric Kpanou *et al.*, (2021). The R95p extreme event over West Africa shows moderate values over the Savannah and Guinea zones, with significant values over Sierra Leone, Liberia, Guinea Conakry, Cameroon, and Nigeria, and nonsignificant values over the Sahel. This pattern can be attributed to the unique weather patterns of the region, with heavy rainfall events during the wet season contributing to extreme events. Climate change is exacerbating these extreme events, with increased temperature and water vapor in the atmosphere leading to more intense rainfall. Human activities such as deforestation and urbanization can also contribute to extreme events. The values from 10 to 20 inches (Figure4.29) are represented over Guinea and Savannah zones, especially Sierra Leone, Liberia, Southern Guinea Conakry and Western areas of Cameroon are exposed to the risk of flooding in the near and far future projection.

4.6 Annual cycle of CMIP6 scenarios and historical data over West Africa and its subregions

Over West Africa, rainfall patterns are examined and a determination is made on areas that are prone to drought or flooding. This is done with the assistance of a time series analysis that is conducted to detect both the yearly cycle and the seasonal changes in rainfall.

Across various studies and articles, different aspects of time series analysis for West African rainfall annual cycle have been explored. The characteristics of the mean seasonal cycle of rainfall were studied Janicot *et al.*, (2011) as well as the exact timing of the diurnal cycle of warm season rainfall Zhang *et al.*, (2016). Uncertainties have also been identified in the annual cycle of rainfall characteristics Sow *et al.*, (2020). Climatology, annual cycle, and interannual variability of rainfall have been assessed in order to provide valuable insight into West African rainfall patterns Emiola *et al.*, (2014). Furthermore, Ilori *et al.*, (2020) conducted an analysis of future temperature and rainfall data in West Africa to detect any changes and trends. These studies all serve to increase understanding of West African rainfall patterns and ultimately contribute to better resource management in the region.

The uncertainties associated with the annual cycle of West African rainfall include amplitude, timing, and duration. A study on daily rainfall over West Africa reported that satellite products possess high regional and seasonal skills at a 10-day scale but are sensitive to the passage of African easterly waves Imoleayo *et al.*, (2022). The Sahelian countries are highly vulnerable to intraseasonal and multidecadal variability of the West African Monsoon, which can lead to changes in annual rainfall amounts Monerie *et al.*, (2020).

4.6.1 Near and far future annual cycle over West Africa and its subregions

The Guinea zone, which includes Sierra Leone, Liberia, Cote d'Ivoire, and parts of Guinea, experiences a bimodal rainfall pattern with two peaks, one in June and the other in September Nicholson *et al.*, (2013). This pattern is likely due to the interaction between the Intertropical Convergence Zone (ITCZ) and the West African Monsoon (WAM), which creates two distinct rainy seasons. In contrast, the Sahel and Savannah zones, which include parts of Mali, Niger,

Nigeria, and Chad, experience a unimodal rainfall pattern with a single peak in August Nicholson *et al.*, (2017). The length of the rainy season also varies between the three zones, with the Guinea zone having a longer rainy season compared to the Sahel and Savannah zones. The length of the rainy season in the Guinea zone is approximately six months, starting from April and ending in September or October Giannini *et al.*, (2003). In contrast, the rainy season in the Sahel and Savannah zones is shorter, lasting for about four months, from June to September Sylla *et al.*, (2016).

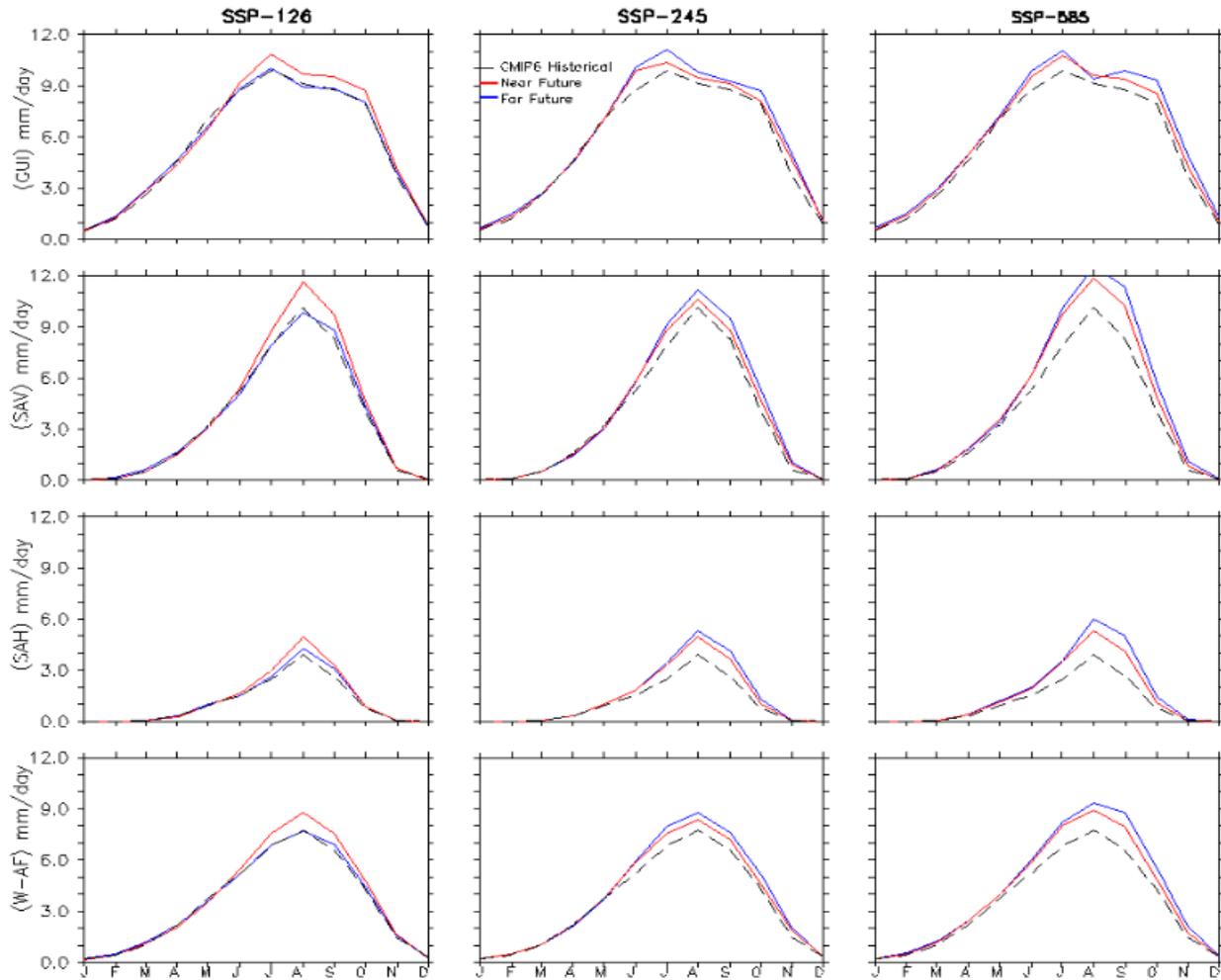


Figure 4.30: Annual cycle of monthly average with cmip6 historical in (dash) (1985-2014), near (2021-2050) in (red) and far future trends (2071-2100) in (blue) using ssp1-2.6, ssp2-4.5 and ssp5-8.5 over West Africa and his three subregions (Guinea, Savannah and Sahel)

This temporary representation (Figure4.30) clearly shows the monthly evolution of data in West Africa and its subregions for near and far future representation for the three scenarios and historical data. In the far future the amount of precipitation is expected to increase for ssp2-4.5 and ssp5-8.5 over West Africa and the three subregions. In contrast to these two scenarios, the ssp1-2.6 shows the opposite of this temporary evolution in West Africa and its three subregions in an unexpected way. This denotes the complexity of scenario models in their design allowing scientists to find adaptation mechanisms to extreme cases of flood or drought risks

4.6.2: Near future simulation with all the scenarios and historical data

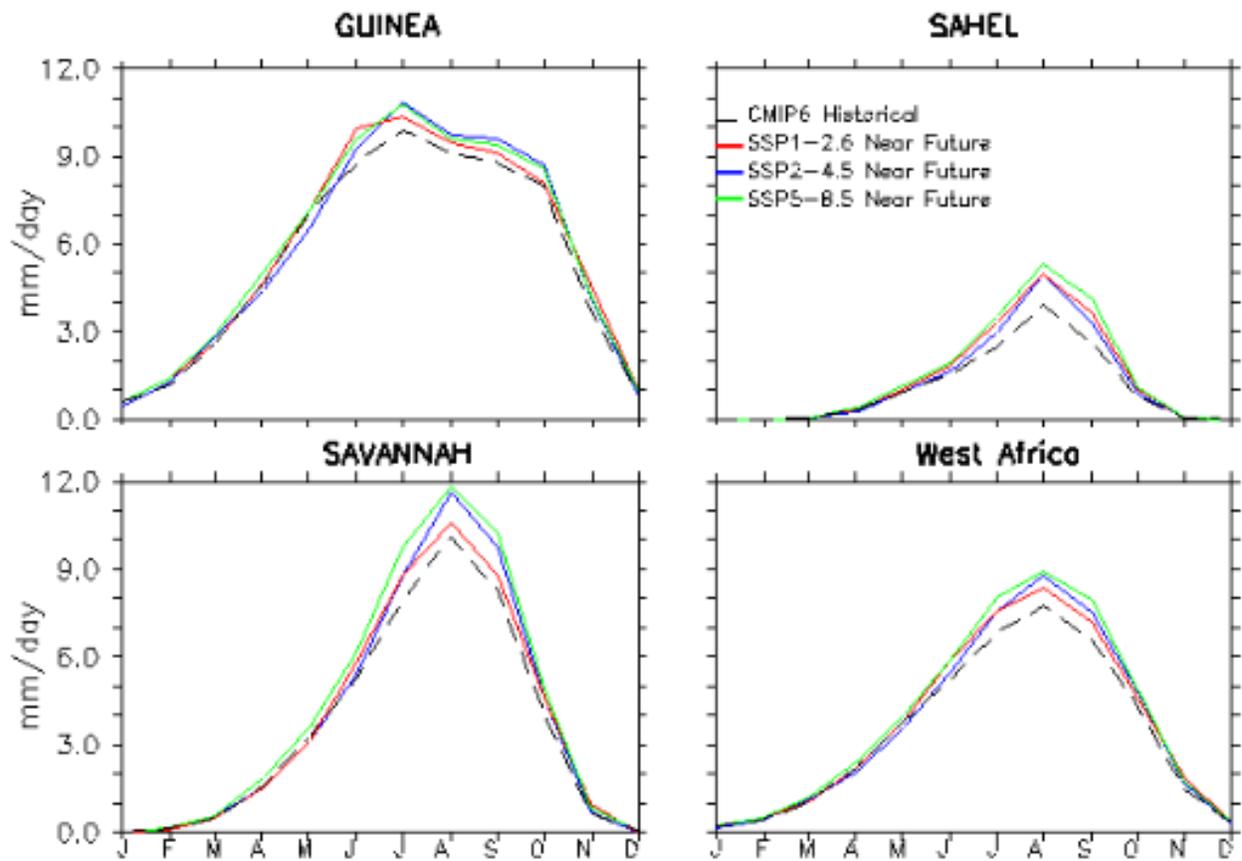


Figure 4.31: Annual cycle of monthly average with cmip6 historical (1985-2014) in (dash) and near future (2021-2050) using three scenarios: ssp1-2.6 in (red), ssp2-4.5 in (blue) and ssp5-8.5 in (green) color over West Africa and his three zones (Guinea, Savannah and Sahel)

This picture (Figure 4.31) allowed us to see how each scenario in the near future behaves in each zone, it can also help to highlight their particularity and their ability to represent the annual cycle of precipitation, we obviously noticed the two peaks in the Guinean zone for ssp1-2.6 in June and September while the peak in June peak moves to July for ssp2-4.5 and ssp5-8.5. The observed pattern in the annual cycle of rainfall monthly average over the three zones of West Africa can be attributed to the region's unique climate and weather patterns. The West African region experiences a distinct wet and dry season, with the wet season usually lasting from May to October. The Guinea zone, located closer to the equator, experiences a bimodal rainfall pattern with two peaks in June and September. This can be attributed to the region's proximity to the Inter-Tropical Convergence Zone (ITCZ), a low-pressure belt that circles the Earth near the equator. The ITCZ moves northwards during the summer months, bringing rain to the Guinea zone. The Sahel and Savannah zones, located further north, have a simpler unimodal rainfall pattern, with a single peak in August. This can be attributed to the region's distance from the ITCZ and the influence of the West African Monsoon. The length of the rainy season is longer in the Guinea zone than in the Savannah and Sahel, with the rainy season starting earlier and ending later. This can be attributed to the region's proximity to the equator and the ITCZ, which brings rain to the region for a longer period. Climate change is believed to be altering the timing and intensity of rainfall patterns in the region, which could have significant impacts on agriculture, water availability, and human livelihoods in the region. It is important to understand the underlying factors driving these patterns and how they might change in the future due to climate change.

4.6.3 Far future simulation with all the scenarios and historical data

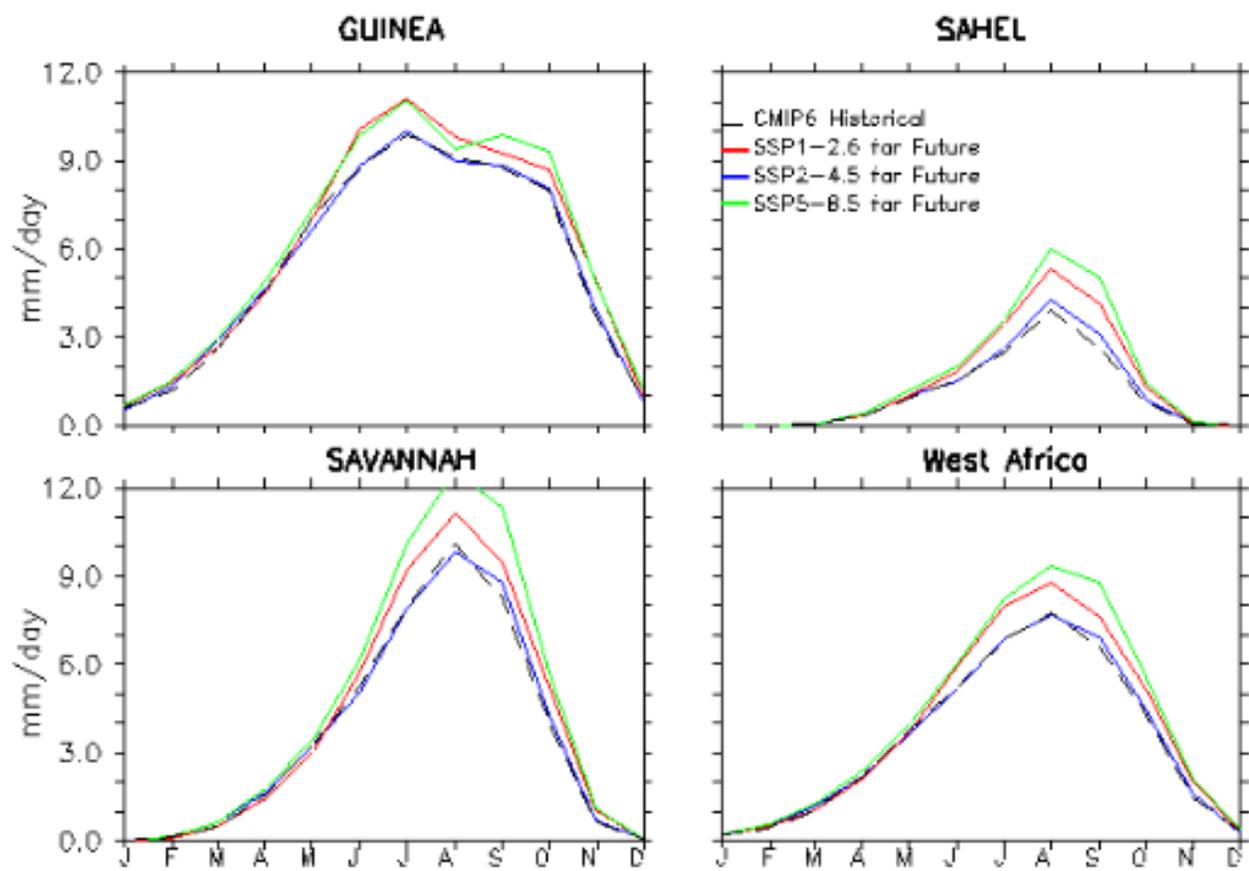


Figure 4.32: Annual cycle of monthly average with cmip6 historical (1985-2014) in dash and far future trends (2071-2100) using three scenarios: ssp1-2.6 in red, ssp2-4.5 in blue and ssp5-8.5 in green color over West Africa and his three subregions (Guinea, Savannah and Sahel)

However, for the far future (Figure 4.32), we noted a shift of the first peak in the Guinean zone for all scenarios to the month of July while in the savannah we see an increase in monthly rainfall amounts in August. This implies a possible flooding in the savannah and a concentration of high rainfall amounts from June to September in the Guinean zone that could cause flooding. The Guinea zone, which includes Sierra Leone, Liberia, Cote d'Ivoire, and parts of Guinea, experiences a bimodal rainfall pattern with two peaks, one in June and the other in September Nicholson et al., (2013). In contrast, the rainy season in the Sahel and Savannah zones is shorter, lasting for about four months, from June to September Sylla *et al.*, (2016).

In all the graphs in (Figure 4.32), we see a clear pattern of the ssp1-2.6 scenario being higher than the ssp2-4.5 scenario in West Africa and its subregions. This demonstrates once again its conceptual complexity. Indeed, ssp2-4.5 better illustrates historical data for the far future time series representation, while for the near future, the ssp1-2.6 fit better with Ensemble CMIP6 historical data.

4.6.4 Time Latitude analysis over West Africa

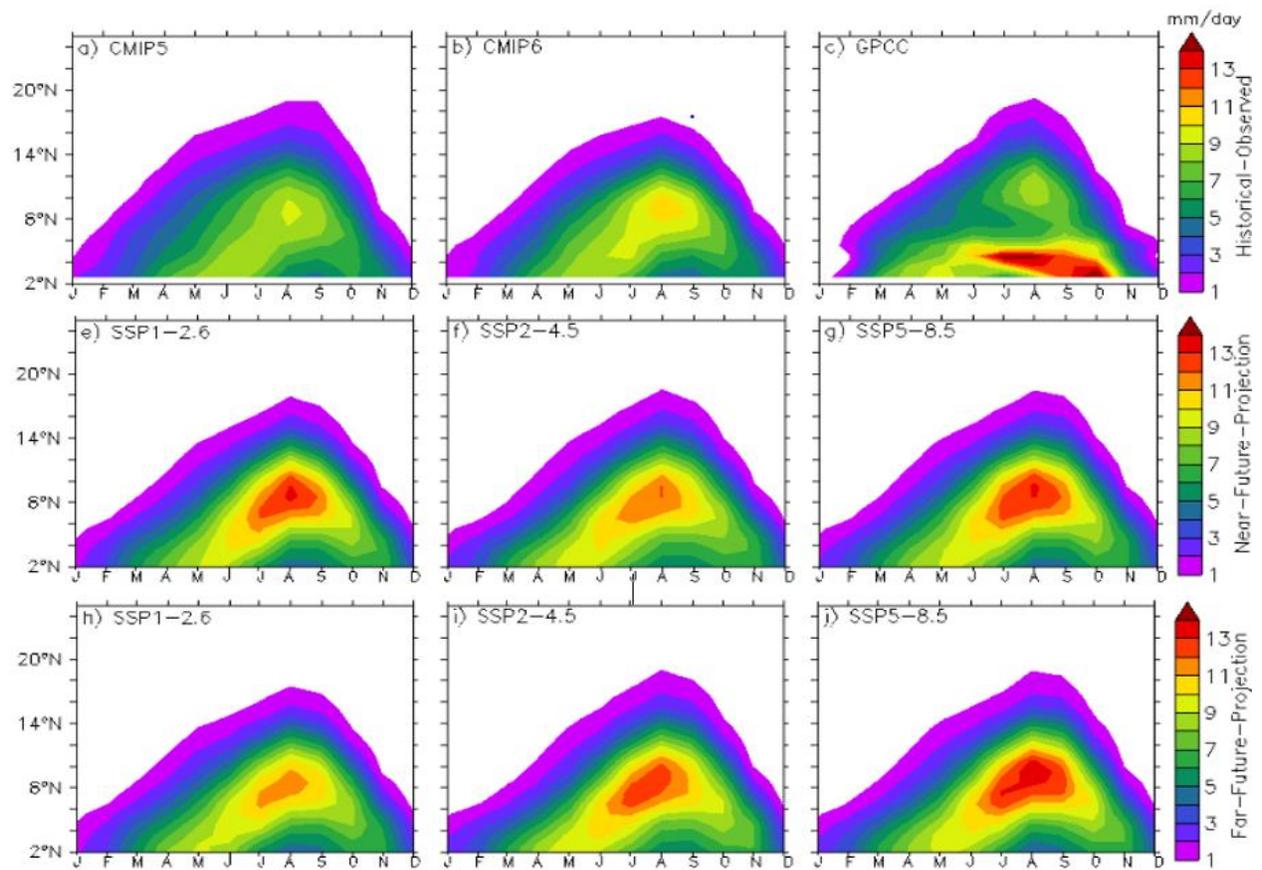


Figure 4.33: Time latitude plot over West Africa with Historical CMIP5 and CMIP6 during the period (1983 – 2012) on top (a, b and c); near future (2021 – 2050) medium (e, f and g) and far

CMIP6 is more concentrated to the south than to the north compared to CMIP5 and better reproduces the GPCC observation data (Figure 4.33). The far projection scenarios ssp2-4.5 and ssp5-8.5 are more accentuated than their near projection. However, for the scenario ssp1-2.6, the close projection (2021 - 2050) is more significant than the far projection (2071 - 2100). This confirms the representation of the annual cycle of ssp1-2.6 (Figure 4.30). The observed pattern in the time-latitude of rainfall monthly average over West Africa is indicative of future climate change scenarios. The far future projection with the ssp1-2.6 scenario shows a more significant pattern than the near future projection, indicating that the effects of climate change will be more pronounced over time. The ssp1-2.6 scenario assumes a more sustainable and eco-friendly future, with lower greenhouse gas emissions, leading to a more moderate change in climate. The ssp2-4.5 and ssp5-8.5 scenarios assume a more fossil fuel-driven and unsustainable future, with higher greenhouse gas emissions, leading to a more extreme change in climate. The contrast in patterns between the scenarios indicates the importance of reducing greenhouse gas emissions and transitioning to a more sustainable future. The changes in rainfall patterns in the region can have significant impacts on agriculture, water resources, and biodiversity. It is important to continue studying these phenomena and developing effective strategies for adaptation and mitigation to minimize the potential impacts of climate change on the region. The data also highlights the need for international cooperation and collective action to address climate change and work towards a sustainable future. These differences in rainfall patterns and length of the rainy season have significant implications for agriculture, water availability, and human livelihoods in the region. It is important to understand the underlying factors driving these patterns and how they might change in the future due to climate change.

Table 4.1: Statistical result between calculated models CMIP5 and CMIP6 and GPCC for consecutive dry days (CDD). All correlation higher than 0.95 are underline

CDD		CMIP5						CMIP6					
		CanESM2	CNRM-CM5	CMCC-CESM	FGOALS-s2	ISPL	MIROC5	CanESM5	CNRM-CM6	CMCC-CM6	FGOALS-g3	ISPL	MIROC6
Guinea region	STdev	0.162	0.149	0.201	0.382	0.184	0.15	0.177	0.134	0.108	0.13	0.199	0.14
	RMSE	0.097	0.086	0.077	0.159	0.091	0.148	0.061	0.069	0.064	0.067	0.106	0.06
	Cor.Coef	0.892	0.93	0.93	0.858	<u>0.963</u>	0.826	0.939	0.915	0.898	0.924	0.867	0.934
	MBE(%)	-0.07	-0.09	0.169	0.138	-0.29	1.39	0.023	0.043	-0.15	-0.12	0.29	-0.15
Savannah region	STdev	0.216	0.217	0.223	0.32	0.221	0.183	0.225	0.22	0.191	0.212	0.224	0.217
	RMSE	0.031	0.027	0.063	0.189	0.126	0.140	0.041	0.17	0.151	0.027	0.074	0.033
	Cor.Coef	<u>0.989</u>	<u>0.992</u>	<u>0.961</u>	<u>0.980</u>	0.838	0.839	<u>0.982</u>	0.777	0.754	<u>0.993</u>	<u>0.996</u>	<u>0.989</u>
	MBE(%)	-0.026	-0.01	-0.11	1.28	0.203	-0.39	-0.003	0.71	-0.26	0.009	0.29	0.03
Sahel region	STdev	0.192	0.210	0.218	0.189	0.16	0.217	0.174	0.168	0.178	0.129	0.177	0.197
	RMSE	0.103	0.116	0.141	0.211	0.083	0.167	0.07	0.143	0.068	0.1	0.105	0.098
	Cor.Coef	0.877	0.878	0.786	0.854	0.924	0.787	0.932	0.7	0.932	0.884	0.849	0.898
	MBE(%)	-0.20	-0.31	-0.04	1.30	0.50	-0.57	0.074	0.42	0.16	0.36	0.40	-0.19

Table 1.2: Statistical result between calculated models CMIP5 and CMIP6 and GPCC for consecutive wet days (CWD). All correlation higher than 0.95 are underline

CWD		CMIP5						CMIP6					
		CanESM2	CNRM-CM5	CMCC-CESM	FGOALS-s2	ISPL	MIROC5	CanESM5	CNRM-CM6	CMCC-CM6	FGOALS-g3	ISPL	MIROC6
Guinea region	STdev	0.148	0.12	0.197	0.15	0.182	0.104	<i>0.177</i>	<i>0.134</i>	<i>0.109</i>	<i>0.132</i>	<i>0.258</i>	<i>0.137</i>
	RMSE	0.029	0.054	0.078	0.15	0.08	0.084	<i>0.055</i>	<i>0.066</i>	<i>0.084</i>	<i>0.055</i>	<i>0.257</i>	<i>0.039</i>
	Cor.Coeff	<u>0.991</u>	<u>0.989</u>	0.93	0.856	0.903	<u>0.979</u>	<i>0.949</i>	<i>0.923</i>	<i>0.9</i>	<u><i>0.96</i></u>	<i>0.206</i>	<u><i>0.99</i></u>
	MBE(%)	0.089	0.165	-0.19	1.03	-0.16	0.424	<i>-0.03</i>	<i>-0.05</i>	<i>0.15</i>	<i>0.12</i>	<i>-0.29</i>	<i>0.15</i>
Savannah region	STdev	0.225	0.217	2.710	0.444	0.223	0.191	<i>0.225</i>	<i>0.213</i>	<i>0.2</i>	<i>0.272</i>	<i>0.331</i>	<i>0.194</i>
	RMSE	0.041	0.027	3.694	0.614	0.051	0.097	<i>0.041</i>	<i>0.137</i>	<i>0.044</i>	<i>0.259</i>	<i>0.178</i>	<i>0.117</i>
	Cor.Coeff	<u>0.982</u>	<u>0.992</u>	0.899	0.691	<u>0.979</u>	0.914	<u><i>0.982</i></u>	<i>0.857</i>	<u><i>0.984</i></u>	<i>0.502</i>	<i>0.919</i>	<i>0.878</i>
	MBE(%)	-0.04	0.009	2.33	1.71	-0.2	0.28	<i>0.002</i>	<i>-0.60</i>	<i>-0.08</i>	<i>-0.008</i>	<i>0.74</i>	<i>-0.42</i>
Sahel region	STdev	0.179	0.211	0.205	0.242	0.161	0.217	<i>0.174</i>	<i>0.168</i>	<i>1.303</i>	<i>0.129</i>	<i>0.177</i>	<i>0.198</i>
	RMSE	0.159	0.087	0.078	0.208	0.127	0.148	<i>0.061</i>	<i>0.135</i>	<i>1.4</i>	<i>0.121</i>	<i>0.094</i>	<i>0.068</i>
	Cor.Coeff	0.675	0.931	0.931	0.812	0.875	0.828	<u><i>0.979</i></u>	<i>0.803</i>	<i>0.947</i>	<i>0.886</i>	<i>0.926</i>	<u><i>0.952</i></u>
	MBE(%)	0.18	0.31	0.04	1.20	-0.49	0.65	<i>-0.074</i>	<i>-0.42</i>	<i>0.78</i>	<i>-0.37</i>	<i>-0.41</i>	<i>0.193</i>

We observe that most of the higher correlation between model and GPCC are over Savannah in both (Table4.1 and Table4.2). With the CDD indices in CMIP6 and CMIP5 models all the highest correlation greater than 0.95 are displaying over Savannah except the IPSL output from CMIP6 which is displayed over Guinea zone.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Climate simulations predict that the West African region will likely undergo increased rainfall in the coming decades as a result of global warming, leading to both more frequent extreme weather events like floods and droughts. The CMIP data have been analysis over West Africa and the three subregions, the results showed that:

The rainfall intensity has decreased during the last decade over Sahel, however the CMIP6 scenarios (SSP2-4.5 and SSP5-8.5) showed an increasing in near and far future period over Savannah and Guinea coast.

5.2 CONTRIBUTION OF THE RESEARCH TO KNOWLEDGE

The results obtained from the research have been able to:

- iv. enhance the understanding about the present climate in terms of precipitation variability, extreme cases and spatiotemporal variation over West Africa;
- v. provide insight on the projected future climate under some shared socioeconomic pathways which are likely occur in the future climate of West Africa this will help the government and policy makers to have idea of possible future trends, and
- vi. formulate appropriate policies for both adaptation and possible mitigation protocols for West Africa.

5.3 RECOMMENDATIONS

In response, it is essential that future quantifications of the SSPs should incorporate the likelihood of growth disruptions, informed by scenarios of the relevant political contexts that historically have been relevant in curbing growth.

The Climate Model Intercomparison Project Phase 6 (CMIP6) provides a framework for climate models to be compared and evaluated. The models can then be used to make projections about future climate change. Here are some of the main findings and recommendations from the CMIP6 model for present, near, and far future:

Global temperatures have already increased by about 1°C above pre-industrial levels. Continued emissions of greenhouse gases are expected to cause further warming and more extreme weather events, such as heatwaves, droughts, and floods. Immediate action is needed to reduce greenhouse gas emissions and limit global warming to below 1.5°C. Global temperatures are projected to continue to rise, reaching about 1.5°C above pre-industrial levels by the 2030s under a high-emissions scenario. Extreme weather events, such as heatwaves, droughts, and floods, are expected to become more frequent and severe. The impacts of climate change, such as sea level rise and ocean acidification, will become more pronounced.

Overall, the CMIP6 model recommends immediate and sustained action to reduce greenhouse gas emissions and limit global warming to below 1.5°C. This will require a transition to a low-carbon economy and widespread adoption of renewable energy sources.

References

- Abiodun B. J., Lawal K. A., Salami A. T., and Abatan A. A. (2013). Potential influences of global warming on future climate and extreme events in Nigeria. *Regional Environmental Change*, **13**, 477–491.
- Adejuwon J., Ilesanmi O., Obafemi B., Ogunleye O., Olanrewaju A., Olugbade O. and Aluko, O. (2021). Climate change and the challenges of flood risk management in West Africa. *Journal of Environmental Management*, **295**, 113031.
- Adedoyin, A., Abiodun, B. J., Adeyeri, O. E., Sanni, T., Oguntunde, P. G., Adeyemi, A. O. and Azeez, L. O. (2020). Spatial distribution of rainfall in West Africa during boreal summer. *Journal of Earth System Science*, **129** (2):1-15.
- Adefisan, E. A. and Abatan A. A. (2015). Agroclimatic Zonning of Nigeria Based on Rain-fall Characteristics and Index of Drought Proneness. *Journal of Environment and Earth Science* **5**, 115 – 125.
- Adegoke, O. O., Olabiyi, A. I., and Adebisi, A. (2017). Impacts of climate change on rainfall characteristics over West Africa. *International Journal of Climatology*, **37**(9):3717-3731.
- Akinsanola, A. A., Ogunjobi, K. O., Ajayi, V. O., Adefisan, E. A., Omotosho, J. A., and Sanogo, S. (2016). Comparison of five gridded precipitation products at climatological scales over West Africa. *Journal of Geophysical Research: Atmospheres*, **121**(15), 8747-8765.
- Akintomide, A. A., Victor, O., and Gabriel, J. K. (2021). Evaluation of CMIP6 models in simulating the statistics of extreme precipitation over Eastern Africa. *Journal of Climate*. Advance online publication. <https://doi.org/10.1016/j.atmospheres.2021.105509>.

- Alfieri, S., Bates, P., Freer, J., Dadson, S., Neal, J and Wood, M. (2019). Disentangling the impacts of human and environmental change on catchment response during Hurricane Harvey. *Environmental Research Letters*, **14**, 124023. <https://doi.org/10.1088/1748-9326/ab5234>
- Allada, D. A. C. Y., Baloitcha, E., Alamou, E. A., Awo, F. M., Bonou, F., Pomalegni, Y., Biao, E. I., Obada, E., Zandagba, J. E., Tilmes, S., and Irvine, P. J. (2020). Changes in West African Summer Monsoon Precipitation under Stratospheric Aerosol Geoengineering. **8**(7). <https://doi.org/10.1029/2020EF001595>
- Allen, M and Ingram, W. (2002). Constraints on future changes in climate and the hydrologic cycle. *Nature*, **419**(6903), 224-232 <https://doi.org/10.1038/nature01092>
- Almazroui, M., Islam, M. N., Saeed, S., Alkhalaf, A. K and Dambul, R. (2017). Assessment of uncertainties in projected temperature and precipitation over the Arabian Peninsula using three categories of CMIP5 multimodel ensembles. *Earth System Science and Environmental Engineering*, **1**, 1-20. [[Google Scholar](#)] [[CrossRef](#)][[Green Version](#)]
- Almazroui, M., Islam, M. N., Saeed, F., Alkhalaf, A. K., Dambul, R., Kucharski, F and Saeed, S. (2021). Projected Changes in Temperature and Precipitation Over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth System Science & Environmental Engineering*, **5**, 1-24. <https://doi.org/10.1007/s41748-021-00199-5>.
- Amouin, J., Kouadio, K. Y., Kacou, M., Djakouré, S and Ta, S. (2021). Diagnosis of the Causes of the Rain Flooding in June in the West Africa Coastal Area. **11**, No. 1.
- Avila-Diaz, A., Rodríguez, D. A., Carvalho, L. M., Marengo, J. A., Montoya, N., Andrade, M. F and Kayano, M. T. (2020). Assessing current and future trends of climate extremes across

- Brazil based on reanalysis and earth system model projections. *Climate Dynamics*, **55**(4), 1403-1426. <https://doi.org/10.1007/s00382-020-05333-z>.
- Ayoade, J.O., Adeleke, S.O., Oke, O.T., and Adesina, A.A. (2001). Variability of seasonal precipitation over West Africa. *International Journal of Climatology*, **21**(3), 319-333.
- Ayugi, B., Zhihong, J., Zhu, H., Ngoma, H., Babaousmail, H., Rizwan, K and Dike, V. (2021). Comparison of CMIP6 and CMIP5 models in simulating mean and extreme precipitation over East Africa. *International Journal of Climatology*, **41**(15), 6474-6496.
- Barkhordarian, A., von Storch, H., Behrangi, A., Loikith, P. C., Mechoso, C. R., and Detzer, J. (2018). Simultaneous regional detection of land-use changes and elevated GHG levels: The case of spring precipitation in tropical South America. *Geophysical Research Letters*, **45**, 6262–6271. [[Google Scholar](#)]
- Bhatt, A. S. (2020). Trend in Extreme Precipitation Indices Based on Long Term In Situ Precipitation Records over Pakistan. *Water*, **12**(3), 797. <https://doi.org/10.3390/w12030797>.
- Bercos-Hickey, E., Nathan, T. R and Chen, S.-H. (2020). The relationship between the African Easterly Jet, Saharan mineral dust aerosols, and West African precipitation. *Journal of Climate*, **33**(9), 3533–3546. <https://doi.org/10.1175/JCLI-D-18-0661.1>
- Bercos-Hickey, E and Patricola, C. M. (2021). Anthropogenic Influences on the African Easterly Jet-African Easterly Wave System. *Climate Dynamics*. Advance online publication. doi:10.1007/s00382-021-05838-1
- Berthou, S., Kendon, E. J., Rowell, D. P., Roberts, M. J., Tucker, S and Stratton, R. A. (2019). Larger Future Intensification of Rainfall in the West African Sahel in a Convection-Permitting

Model. *Geophysical Research Letters*, **46**(22), 13299-13307.
<https://doi.org/10.1029/2019GL083544>

Biasutti, M. (2019). Rainfall trends in the African Sahel: Characteristics, processes, and causes. *Wiley Interdisciplinary Reviews: Climate Change*, **10**(4), e591.
<https://doi.org/10.1002/wcc.591>

Britannica, the Editors of Encyclopaedia. "Guinea Highlands". Encyclopedia Britannica, Invalid Date, <https://www.britannica.com/place/Guinea-Highlands>. Accessed 20 March 2023.

Brown, A., Abell, R., Thieme, M. L., Revenga, C., Spalding, M. D and Taylor, M. (2010). Inner Niger Delta. Freshwater Ecoregions of the World. The Nature Conservancy and World Wildlife Fund, Inc. Retrieved from http://www.feow.org/ecoregion_details.php?eco=508

Bucchignani, E., Mercogliano, P., Panitz, H. J and Montesarchio, M. (2018). Climate change projections for the Middle East-North Africa domain with COSMO-CLM at different spatial resolutions. *Advances in Climate Change Research*, **9**, 66–80. [[Google Scholar](#)] [[CrossRef](#)]

Chagnaud, G., Biasutti, M., Taylor, C. M and Harrison, G. P. (2022). A synthetic view of rainfall intensification in the West African Sahel. *Environmental Research Letters*, **17**, 044005.

Collins, W. J. (2020). Long-term climate change: projections, commitments and irreversibility. In IPCC Working Group I Contribution to AR6. 1, pp. 105-224).

Dan Shepard. Global warming: severe consequences for Africa (2019),
<https://www.un.org/africarenewal>

- Dawit, M., Dinka, M. O., Leta, O. T and Muluneh, F. B. (2020). Impact of climate change on land suitability for the optimization of the irrigation system in the Anger River Basin, Ethiopia. *Climate*, **8**, 97. <https://doi.org/10.3390/cli8090097>
- Debortoli, N. S., Camarinha, P. I. M., Marengo, J. A., Chou, S. C., Cuartas, L. A., Soares, W. R and Viana, D. B. (2017). An index of Brazil's vulnerability to expected increases in natural flash flooding and landslide disasters in the context of climate change. *Natural Hazards*, **86**, 557-582. <https://doi.org/10.1007/s11069-016-2705-2>
- Derya. Camur, Ozbayram, E.G., Koker, L., Oguz Cam, A., Akcaalan, R and Albay, M. (2022). The effects of climate change on aquatic ecosystems in relation to human health. *Aquatic Sciences and Engineering*, **37**(3), 123-128. DOI: <https://doi.org/10.26650/ASE2022105716>
- Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H and Willett, K. M. (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *Journal of Geophysical Research: Atmospheres*, **118**(5), 2098-2118. <https://doi.org/10.1002/jgrd.50150>
- Dosio, A., Jury, M., Remedio, A. R. C., Coelho, C. A. S., Prudhomme, C., Bhaskaran, B and Gbobaniyi, E. (2021). Projected future daily characteristics of African precipitation based on global (CMIP5, CMIP6) and regional (CORDEX, CORDEX-CORE) climate models. *Climate Dynamics*, **57**. <https://doi.org/10.1007/s00382-021-05859-w>
- Duan. T, Chapman. S.C, Guo. Y and Zheng. B. (2017). Dynamic monitoring of NDVI in wheat agronomy and breeding trials using an unmanned aerial vehicle, **210**, 71 – 80. <http://dx.doi.org/10.1016/j.fcr.2017.05.025>

- Gbobaniyi, E., Sylla, M. B., Diallo, I., Sarr, A., Kamga, A., Kamsu-Tamo, P. H and Nikiema, M. (2014). Climatology, annual cycle and interannual variability of precipitation and temperature in CORDEX simulations over West Africa. *International Journal of Climatology*, **34**(7), 2241-2257. <https://doi.org/10.1002/joc.3834>
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J and Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, **9**(5), 1937-1958.
- Falayi, E. O., Adepitan, J. O., Adewole, A. T and Roy-Layinde, T. O. (2021). Analysis of rainfall data of some West African countries using wavelet transform and nonlinear time series techniques. *Environmental Science and Pollution Research International*, **28**(6), 7432-7450. <https://doi.org/10.1080/14498596.2021.2008539>.
- Faye, A and Akinsanola, A.A. (2021). Evaluation of extremes precipitation indices over West Africa in CMIP6 models. *Climate Dynamics*, 1-13. <https://doi.org/10.1007/s00382-021-05942-2>.
- Fawzy, S., Osman, A. I., Doran, J., Elhag, M., Elnahas, S. O., Mawad, M and Farahat, E. (2020). Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters*, **18**(6), 2069-2094. <https://doi.org/10.1007/s10311-020-01059-w>.
- Felix, O. A; Botao, Z; Gnim, T. G and Anselem, O. (2020). Evaluation of the Performance of CMIP6 HighResMIP on West African Precipitation. *J. Clim.* **11**(10), 1053. <https://doi.org/10.3390/atmos11101053>.
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W and Zhou, T. (2013). Evaluation of climate models.

In, T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, and P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 741-866). Cambridge University Press.

Fontaine, B., Guillaume, A., Bader, J. C., Becker, M., Brouwer, J., Coll, J and Rodríguez-Fonseca, B. (2011). A review of climatic controls on West African riverine and estuarine hydrology. *Journal of Hydrology*, **404**(1-2), 216-233.

Francesco Bosello and Enrica De Cian. (2014). Climate change, sea level rise, and coastal disasters. A review of modeling practices, 46(C). P: 593-605.
<http://www.sciencedirect.com/science/article/pii/S0140988313001977>

Nkrumah, F., Vischel, T., Panthou, G., Klutse, N.A.B., David C and Diedhiou A.A. (2019). Recent Trends in the Daily Rainfall Regime in Southern West Africa, **10**(12), 741;
<https://doi.org/10.3390/atmos10120741>

Frederick, K.D and Major, D.C, (2021). Climate Change and Water Resources. *Climatic Change* **37**, 7–23. <https://doi.org/10.1023/A:1005336924908>

Zhang, G., Cook, K. H., and Vizzy, E. K. (2016). The Diurnal Cycle of Warm Season Rainfall over West Africa. Part I: Observational Analysis. *Journal of Climate*, **29**(23), 8423-8437.
<https://doi.org/10.1175/JCLI-D-15-0874.1>

Gentilli, J., Krishnamurti, T. N and Smith, P. J. (n.d.). (2023). West African monsoon. In *Encyclopedia Britannica*. <https://www.britannica.com/science/West-African-monsoon>

- Gentilucci, M., Barbieri, M., D'Aprile, F and Zardi, D. (2020). Analysis of extreme precipitation indices in the Marche region (central Italy), combined with the assessment of energy implications and hydrogeological risk. *Energy Reports*, 6(Supplement 1), 804-810. ISSN 2352-4847. <https://doi.org/10.1016/j.egy.2019.11.006>.
- Giannini, A., Saravanan, R., Chang, P., and Vecchi, G.A. (2003). Global warming and changes in the seasonal cycle of precipitation. *Geophysical Research Letters*, **30**(19), 2067.
- Giannini, A and Kucharski, F. (2020). West African rainfall and its predictability: An overview of CMIP6 results. *Climate Dynamics*, **54**(1-2), 1645-1664.
- Giorgi, F and Coppola, E. (2020). Coupled Model Intercomparison Project 6 (CMIP6): Overview and status of the model simulations. *Earth System Science Data*, **12**(3), 2063-2090.
- Gonzalez, P and Meza, F. (2009). Bias Simulation of West African Rainfall. *International Journal of Climatology*, **29**(14), 2095-2111.
- Gouveia, C. D. (2022). Uncertainties in projections of climate extremes indices in South America via Bayesian inference. *Journal of Climate*, **42**(14), 7362-7382. <https://doi.org/10.1002/joc.7650>
- Grant Foster and Stefan Rahmstorf. (2011). Environ. Res. Lett. 6 044022 DOI 10.1088/1748-9326/6/4/044022
- Halvard, B and Jonas V. (2019). On Growth Projections in the Shared Socioeconomic Pathways. *Global Environmental Politics*; **19** (4): 118–132. doi: https://doi.org/10.1162/glep_a_00525

- Hamilton, H. L., Núñez Ocasio, K. M., Evans, J. L., Young, G. S and Fuentes, J. D. (2020). Topographic Influence on the African Easterly Jet and African Easterly Wave Energetics. *Journal of Geophysical Research*, **125**(8). <https://doi.org/10.1029/2019JD032138>
- Hastenrath, S (1985). *Climate and Circulation of the Tropics*. Kluwer Academic Publishers. p. 464. ISBN 90-277-2026-6.
- Heiko. (2011). Progress in regional downscaling of West African precipitation. *Atmospheric Science Letters*, **12**, 75-82. <https://doi.org/10.1002/asl.306>.
- Hosten, A, (2018). “The African Easterly Jet: Double Core Structure and Effect on Easterly Wave Development”. http://purl.flvc.org/fsu/fd/2018_Su_Hosten_fsu_0071N_14570.
- Hourdin, F., Grandpeix, J.-Y., Rio, C., Bony, S., Jam, A., Cheruy, F and Lafore, J.-P. (2013). The Present and Future of the West African Monsoon: A Process-Oriented Assessment of CMIP5 Simulations along the AMMA Transect. *Journal of Climate*, **26**(17), 6471-6505. <https://doi.org/10.1175/JCLI-D-12-00505.1>
- Ilori, O.W and Ajayi, V.O. (2020). Change Detection and Trend Analysis of Future Temperature and Rainfall over West Africa. *Earth Syst Environ* **4**, 493–512 <https://doi.org/10.1007/s41748-020-00174-6>
- Imoleayo E. Gbode, Joseph D. Intsiful, Akintomide Afolayan Akinsanola, Akintayo T. Abolude, Kehinde O and Ogunjobi, (2022). Chapter 4 - Uncertainties in daily rainfall over West Africa: Assessment of gridded products and station gauges, Editor(s): Victor Ongoma, Hossein Tabari, *Climate Impacts on Extreme Weather*, Elsevier, Pages 65-82, ISBN 9780323884563, <https://doi.org/10.1016/B978-0-323-88456-3.00003-4>.

Imran. Z. (2023). The ‘press and pulse’ of climate change strains farmers in Pakistan, <https://thebulletin.org/2023/02/the-press-and-pulse-of-climate-change-strains-farmers-in-pakistan/>

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In R. K. Pachauri and L. A. Meyer (Eds.), Geneva, Switzerland: IPCC. [[Google Scholar](#)]

Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (Eds.), Cambridge University Press. (In Press).

Jalloh. A., Faye, M.D., Nelson. G.C. (2013). West African Agriculture and Climate Change. **14**, 384_391

Janicot, S., Caniaux, G., Chauvin, F., de Coëtlogon, G., Fontaine, B., Hall, N and Sultan, B. (2011). Intraseasonal variability of the West African monsoon. **12**, 58-66.

Jerry R., Hamza K.B. and Stenchikov G. (2019). West African Monsoon: current state and future projections in a high-resolution AGCM. *Clim Dyn* **52**, 6441–6461. <https://doi.org/10.1007/s00382-018-4522-7>

Jiang, D., Zhu, J., Xu, J., Li, J., Li, W., Zhou, T and Li, H. (2020). The flexible global ocean-atmosphere-land system model, Grid-enabled Integrated Earth system model version 1.0

- (GIGC-IECM1. 0): description and its performance for global climate simulations. *Journal of Advances in Modeling Earth Systems*, **12**(8), e2020MS002115.
- Kaddu, J. B., Gebru, B., Kibaya, P and Munabi, I. G. (2020). Change and Health in Sub-Saharan Africa. Retrieved from https://www.cif.org/sites/cif_enc/files
- Joshua White and Anantha Aiyyer. (2021) African easterly waves in an idealized general circulation model: instability and wave packet diagnostics, 2(2), <https://doi.org/10.5194/wcd-2-311-2021>
- Kang, S., & Zou, X. (2013). Bias Simulation of West African Rainfall Using a Regional Climate Model. *International Journal of Climatology*, **33**(2), 519-532.
- Kerry. (2020). Seasonal asymmetry of equatorial East African rainfall projections: understanding differences between the response of the long rains and the short rains to increased greenhouse gases. 55(6). doi:10.1007/s00382-020-05350-y.
- Keyvan, M., Reed, P., Adam, J. (2020). Water rights shape crop yield and revenue volatility tradeoffs for adaptation in snow dependent systems. *Nature Communications*, **11**, 3473. <https://doi.org/10.1038/s41467-020-17219-z>.
- Klutse, N.A.B., Quagraine, K.A., Nkrumah, F. (2021). The Climatic Analysis of Summer Monsoon Extreme Precipitation Events over West Africa in CMIP6 Simulations. *Earth Syst Environ* **5**, 25–41. <https://doi.org/10.1007/s41748-021-00203-y>
- Koffi W, Fichfet, T and Hugues G. (2022). Future changes in the mean and variability of extreme rainfall indices over the Guinea Coast and role of the Atlantic equatorial mode, <https://doi.org/10.5194/wcd-2022-53>

- Koutsogiannis, D., Kozonis, D and Manetas, A. (1998). "A mathematical framework for studying rainfall intensity-duration-frequency relationships". *Journal of Hydrology*. **206** (1–2): 118–135. Bibcode: 1998JHyd.206.118K. doi:10.1016/S0022-1694(98)00097-3
- Kpanou, M, L, Patrick, B, Camberlin, T.P, Roucou, P. (2021). Spatial patterns and trends of extreme rainfall over the southern coastal belt of West Africa, **143** DO - 10.1007/s00704-020-03441-8
- Krishnamurti, T., Gentili, J and Smith P.J. (2023). West African monsoon. *Encyclopedia Britannica*. <https://www.britannica.com/science/>
- Kumi. N and Abiodun. B.J. (2018). Potential impact of 1.5oc and 2oc global warming on rainfall onset, cessation and length in West Africa. **13** (5), 2_11
- Kwesi, B., (2020). West African Summer Monsoon Precipitation Variability as Represented by Reanalysis Datasets. *Climate*, **8**(10), 111. <https://doi.org/10.3390/cli8100111>.
- Lehtonen, H., Aakkula, J and Fronzek, S. (2021). Shared socioeconomic pathways for climate change research in Finland: co-developing extended SSP narratives for agriculture. *Reg Environ Change* **21**, 7. <https://doi.org/10.1007/s10113-020-01734-2>
- Leonard. I. (2020). Climate change is among the greatest challenges of our time. <https://www.brookings.edu/project/brookings-initiative-on-climate-research-and-action/>
- Lisa V.A. (2019). *Environ. Res. Lett.* 14 125008 DOI 10.1088/1748-9326/ab51b6
- Sow, M., and Sylla, M. (2020). Uncertainties in the Annual Cycle of Rainfall Characteristics over West Africa in CMIP5 Models. *Atmosphere*, **11**(2), 216. <https://doi.org/10.3390/atmos11020216>.

- Malhi Y., Janet, F., Nathalie, S., Martin, S Turner M.G., Field C.B. and Nancy, K. (2020) Climate change and ecosystems: threats, opportunities and solutions *Phil. Trans. R. Soc.* B3752019010420190104. <http://doi.org/10.1098/rstb.2019.0104>
- Marlon M., Fink, A.H, and Knippertz P. (2018). Rainfall types over southern West Africa: Objective identification, *climatology and synoptic environment*, **144**, Issue714, Pages 1628-1648, <https://doi.org/10.1002/qj.3345>
- Michela Biasutti. (2019). Rainfall trends in the African Sahel: Characteristics, processes, and causes **10**(4): e591. doi: [10.1002/wcc.591](https://doi.org/10.1002/wcc.591)
- Monerie, PA., Sanchez-Gomez, E and Gaetani, M. (2020). Future evolution of the Sahel precipitation zonal contrast in CESM1. *Clim Dyn*, **55**, 2801–2821. <https://doi.org/10.1007/s00382-020-05417-w>
- Morice. C. P. (2021), An Updated Assessment of Near-Surface Temperature Change From 1850: *The HadCRUT5 Data Set*, **126**(3). <https://doi.org/10.1029/2019JD032361>
- Myhre, G., Alterskjær, K., Stjern, C.W. (2019). Frequency of extreme precipitation increases extensively with event rareness under global warming. *Sci Rep*, **9**, 16063. <https://doi.org/10.1038/s41598-019-52277-4>
- Mumuni. S and Machol J. A. (2023): Climate variability and change impacts on food security in Africa. **9**(1). <https://doi.org/10.1080/23311932.2023.2171830>
- National Center for Atmospheric Research Staff (Eds). (2013): "The Climate Data Guide: Taylor. <https://edec.ucar.edu/public/ncar-explorer-series/2022-explorer-series>

- Ngcamu B.S and Chari F. (2020): Drought Influences on Food Insecurity in Africa: A Systematic Literature Review. *Int J Environ Res Public Health*. **14**; 17(16):5897.
- Niang, C., Mancho, A.M., García-Garrido, V.J., Díaz, D., Masson, S., & Álvarez, J.A. (2020). Transport pathways across the West African Monsoon as revealed by Lagrangian Coherent Structures. *Scientific Reports*, **10**, 12543. <https://doi.org/10.1038/s41598-020-69159-9>
- Nicholson, S. E. (2013). The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *ISRN meteorology*, 2013.
- Nicholson, S. E. (2017). An overview of African rainfall fluctuations of the last decade. *American Journal of Climate Change*, **6**(3), 257-277.
- Nicholson, S. E. (2018). The ITCZ and the Seasonal Cycle over Equatorial Africa. *Bulletin of the American Meteorological Society*, **99**(2), 337–348. <https://doi.org/10.1175/BAMS-D-16-0287.1>
- Omotosho, J.B. and Abiodun, B.J. (2007) A Numerical Study of Moisture Build-Up and Rainfall over West Africa. *Meteorological Applications*, **14**, 209-225. <https://doi.org/10.1002/met.11>
- O'Neill, Brian C., ElmarKriegler, KeywanRiahi, Kristie L. Ebi, StephaneHallegatte, Timothy R. Carter, RituMathur, and Detlef P. van Vuuren. (2014). A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways. *Climatic Change*, **122**(3): 387–400. <https://doi.org/10.1007/s10584-013-0905-2>.
- Oudar, T., Roujean, J. L., Calvet, J. C., Lafont, S., Jarlan, L., and Le Moigne, P. (2020): Assessment of the Mediterranean hydrological cycle in the CMIP6 models and implications for the future. *Climate Dynamics*, **54**(3-4), 2049-2068.

- Oyebande, O. (2015). The impacts of climate change on rainfall characteristics in West Africa. *International Journal of Environment and Climate Change*, **5**(7), 559-567.
- Nikolaou, P.T., Voudouris, K.S., Economou-Eliopoulos, M and Kallioras, A.G. (2010). Climate Change Implications on Groundwater in Hellenic Region. Retrieved from <https://www.academia.edu/12372692/>
- Monerie, P.-A., Wainwright, C. M., Sidibe, M and Akinsanola, A. A. (2020). West African summer monsoon precipitation variability and teleconnections with global sea surface temperatures. *Climate Dynamics*, **55**(5-6), 1385-1401. <https://doi.org/10.1007/s00382-020-05332-0>
- Patrick Galey. (2022). Africans at risk of famine, drought and displacement, U.N. climate report warns
- Regoto. P, Claudine D., Chou, S.C Anna C.B. (2021). Observed changes in air temperature and precipitation extremes over Brazil, **41**(11). P: 5125-5142. <https://doi.org/10.1002/joc.7119>
- Reij, C., Tappan, G and Smale, M. (2009). Agroenvironmental transformation in the Sahel. Retrieved from <https://ideas.repec.org/p/fpr/ifprid/914.html>
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S and Bauer, N. (2017). The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview. *Global Environmental Change*, **42**, 153-168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>

- Rowell, D. P., Senior, C. A., Vellinga, M., Graham, R. J and Williams, K. D. (2015). Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? *Climatic Change*, **132**(3), 433-446.
- Salack, S., Saley, I. A., Lawson, N. Z., Zabr e, I., and Daku, E. K. (2018). Scales for rating heavy rainfall events in the West African Sahel. *Weather and Climate Extremes*, **21**, 36-42. <https://doi.org/10.1016/j.wace.2018.05.004>
- Salack, S., Saley, I. A and Blieferticht, J. (2018). Observed data of extreme rainfall events over the West African Sahel. *Data in Brief*, **20**, 1274-1278. <https://doi.org/10.1016/j.dib.2018.09.001>
- Sanogo, S.; Fink, A.H.; Omotosho, J.A.; Ba, A.; Redl, R and Ermert, V. (2015). Spatio-temporal characteristics of the recent rainfall recovery in West Africa. *Int. J. Clim.*, **35**, 4589–4605. doi:10.1002/joc.4309.
- Sawadogo, W.; Abiodun, B.J and Okogbue, E.C. (2019). Projected changes in wind energy potential over West Africa under the global warming of 1.5 °C and above. *Theor. Appl. Climatol*, **138**, 321–333. [[Google Scholar](#)] [[CrossRef](#)]
- Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., ... & Ciais, P. (2020). UKESM1: Description and evaluation of the UK Earth System Model. *Journal of Advances in Modeling Earth Systems*, **12**(11), e2019MS001739.
- Serge, B., Jean, C., Paul, D., Marie, E and Pierre, F. (1992). Spatiotemporal Variability of West African Rainfall. Pages 499-511.

- Shabbir, W., Omer, T and Pilz, J. (2023). The impact of environmental change on landslides, fatal landslides, and their triggers in Pakistan (2003–2019). *Environ Sci Pollut Res* **30**, 33819–33832. <https://doi.org/10.1007/s11356-022-24291-z>
- Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W and Bronaugh, D. (2013a). Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. *Journal of Geophysical Research: Atmospheres*, **118**(4), 1716-1733. <https://doi.org/10.1002/jgrd.50203>
- Sillmann, J., V. V. Kharin, X and Zhang, F. W. (2013b). Zwiers. Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical Research Atmospheres*, **118**(6):2473–2493. DOI:[10.1002/jgrd.50188](https://doi.org/10.1002/jgrd.50188)
- Smith, P. J., Krishnamurti, T.N. and Gentilli, J. (2012). West African monsoon. Encyclopedia Britannica. <https://www.britannica.com/science/West-African-monsoon>
- Sylla, I. Diallo and J. S. Pal. (2013). West African Monsoon in State-of-the-Science Regional Climate Models. DOI: 10.5772/55140
- Sylla, I., Giorgi, F., Coppola, E., Mariotti, L., Sannino, G., Ruti, P. M., Dell'Aquila, A., Diro, G. T., Giuliani, G., Calmanti, S., Carillo, A., Gualdi, S., Zampieri, M., Scoccimarro, E., Villarini, G., Vrac, M., Dubois, C., Rixen, M and Rodo, X. (2015). Impact of land cover characterization on regional climate modeling over West Africa. *Climate Dynamics*, **45**(5-6), 1331-1351. DOI: 10.1007/s00382-015-2603-4.
- Sylla, M.B.; Giorgi, F.; Pal, J.S.; Gibba, P.; Kebe, I. and Nikiema, M. (2015). Projected Changes in the Annual Cycle of High-Intensity Precipitation Events over West Africa for the Late Twenty-First Century. *J. Clim.* **28**, 6475–6488. doi:10.1175/JCLI-D-14-00854.1

- Sylla, M. B.; Michel, P. N.; Peter, G.I. Kebe and Nana, A. B. K. (2016). Climate Change over West Africa: Recent Trends and Future Projections. 7 – 9. DOI: 10.1007/978-3-319-31499-0_3.
- Sylla, M. B., Pal, J. S., Wang, G and Rauscher, S. A. (2016). Future changes in climatic extremes over West Africa. *Journal of Climate*, **29**(13), 4547-4569.
- Ta, S., Kouadio, K. Y., Ali, K. E., Toualy, E., Aman, A and Yoroba, F. (2016). West Africa Extreme Rainfall Events and Large-Scale Ocean Surface and Atmospheric Conditions in the Tropical Atlantic. *Advances in Meteorology*, Article ID 1940456, 14 pages. <https://doi.org/10.1155/2016/1940456>.
- Takimoto, A., Nair, P.K.R and Alavalapati, J.R.R. (2008). Socioeconomic potential of carbon sequestration through agroforestry in the West African Sahel. *Mitig Adapt Strateg Glob Change* **13**, 745–761. <https://doi.org/10.1007/s11027-007-9140-3>
- Thibeault. J and Seth. A. (2014). Changing climate extremes in the Northeast United States: observations and projections from CMIP5, **127**(2). P: 273-287. <https://ideas.repec.org/a/spr/climat>
- Todzo. S; Bichet. A and Diedhiou. A (2020). Intensity of the hydrological cycle expected in West Africa over the 21st century **11** (1), 319_328
- Van den Hurk, B. J. J. M., and Van Meijgaard, E. (2010): Diagnosing Land-Atmosphere Interaction from a Regional Climate Model Simulation over West Africa. *Journal of Hydrometeorology*, **11**(2), 467–481. <https://doi.org/10.1175/2009JHM1173.1>
- Van Vuuren, D.P., Edmonds, J and Kainuma, M. (2011): The representative concentration pathways: an overview. *Climatic Change* 109, 5. <https://doi.org/10.1007/s10584-011-0148-z>

- Voldoire, A., Saint-Martin, D., S n si, S., Decharme, B., Alias, A., Chevallier, M and Geoffroy, O. (2019): Evaluation of CMIP6 DECK experiments with CNRM-CM6-1. *Journal of Advances in Modeling Earth Systems*, **11**(7), 2177-2213.
- Wagner, S; Souvignet, M; Walz and Y. (2021): When does risk become residual? A systematic review of research on flood risk management in West Africa **21**(3), 84.
- Wang, F., Yang, X., Zhang, Y., Zhang, L., Zhang, S., and Tang, J. (2019): Performance evaluation of CMIP6 models over East Asia. *Advances in Atmospheric Sciences*, **36**(7), 664-676.
- Wehner, M., Gleckler, P and Lee, J. (2020): Characterization of long period return values of extreme daily temperature and precipitation in the CMIP6 models: Part 1, model evaluation. *Weather and Climate Extremes*, 100283, <https://doi.org/10.1016/j.wace.2020.100283>
- Weiran Liu (2020) Role of the West African westerly jet in the seasonal and diurnal cycles of precipitation over West Africa. *Climate Dynamics* **54**(15) DOI: 10.1007/s00382-019-05035-1
- Wei Z, Hong S., Wei Z., Hu N., Ying G and Wu Y. (2022). Comparison on long-term corrosion performance of WC-CoCr and Al₂O₃-TiO₂ ceramic coatings in sulphide containing 3.5 wt% NaCl solution, *International Journal of Refractory Metals and Hard Materials*, **107**, 105906, ISSN 0263-4368, <https://doi.org/10.1016/j.ijrmhm.2022.105906>.
- Weiskopf, S. R., Fisichelli, N. A., Brookshire, J. L., Carlson, S. M., Currier, C. A., DeWaard, J. R., and Krosby, M. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of the Total Environment*, 733, 137782. <https://doi.org/10.1016/j.scitotenv.2020.137782>

World Population Prospects (2022)". Population.un.org. United Nations Department of Economic and Social Affairs, Population Division. Retrieved 17 July 2022.

Wilson, A.D (2022) Ecological Mechanistic Research and Modelling. *Ecological Psychology*. pp. 1-23. ISSN 1040-7413 DOI: <https://doi.org/10.1080/10407413.2022.2050912>

Xu, C., N.G. McDowell, R.A. Fisher, L. Wei, S. Sevanto, B.O. Christoffersen, E. Weng, and R.S. Middleton. (2019): Increasing impacts of extreme droughts on vegetation productivity under climate change. *Nat. Clim. Change*, 9, no. 12, 948-953, doi:10.1038/s41558-019-0630-6.

Zhang, X., Wang, Y., Jiang, J. H., Su, H., Zhao, C., Xia, X and Qian, Y. (2016). The characteristics of aerosol indirect effect based on dynamic regimes in global climate models. *Atmospheric Chemistry and Physics*, **16**(5), 2765-2783. <https://doi.org/10.5194/acp-16-2765-2016>.

Zhou D., Cao S., Liu J., Li X., Dong Y., Neubauer F., Bai J and Li H. (2022). Carbonation and serpentization of diopside in the Altun Mountains, NW China. *Sci Rep.* **12**(1):21361. doi: 10.1038/s41598-022-25612-5.