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Par

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Understanding Precipitation Extremes over West Africa: Characteristics, Drivers and Projections

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Specialisation: Climate Change and Disaster Risk Management

By

Chukwudi Samuel EKWEZUO

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Publicly defended on 19th March 2025 before the jury composed of:

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Understanding Precipitation Extremes over West Africa: Characteristics, Drivers and Projections

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Dedication

This thesis is dedicated to the memory of my beloved late father, Brother Francis Okereke EKWEZUO. Continue to rest in paradise.

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Glory and praise to God Almighty, whose mercy and love have been my anchor since I came to this world. Indeed, I saw and experienced your mercy during this doctoral journey. I appreciate the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL), funded by the German Ministry of Education and Research (BMBF), for the scholarship that enabled me to undertake this study with ease.

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Abstract

Extreme precipitation during the West African summer monsoon causes significant flooding and drought, impacting food security, infrastructure, and regional socioecological systems. This thesis examines monsoon precipitation's dynamics, variability, and future projections using gridded climate (1950–2022) and survey data. Results show spatially heterogeneous trends, with significant changes detected in monsoon precipitation variability, except in August. Two dominant precipitation modes were identified using season-reliant empirical orthogonal function (SEOF) analysis: the Sahel mode (16.3% variance) linked to equatorial Pacific, Mediterranean, Indian, and North Atlantic sea surface temperature (SST) anomalies and the Guinea coast mode (9.5% variance) influenced by equatorial and South Atlantic SST. Wet years exhibit strong low-level convergence over Africa and upper-level divergence over the Pacific, driven by Walker circulation changes. CMIP6 models perform better over the Sahel than the Guinea coast, projecting future drying trends. Extreme precipitation events impact agriculture, infrastructure, and food security, with adaptation hindered by poor infrastructure, technical capacity gaps, and funding constraints. These findings are crucial for climate adaptation, informing policymakers on resilient infrastructure and adaptive strategies to mitigate adverse impacts of climate extremes in West Africa.

Keywords: *Anomalous precipitation, climate change projections, CMIP6 models, sea surface temperature, West Africa*.

Comprendre les extrêmes de précipitations en Afrique de l'Ouest: Caractéristiques, facteurs et projections

Résumé

Les précipitations extrêmes pendant la mousson d'été en Afrique de l'Ouest provoquent des inondations et des sécheresses importantes, qui ont un impact sur la sécurité alimentaire, les infrastructures et les systèmes socio-écologiques régionaux. Cette thèse examine la dynamique, la variabilité et les projections futures des précipitations de mousson en utilisant des données climatiques maillées (1950-2022) et des données d'enquête. Les résultats montrent des tendances spatialement hétérogènes, avec des changements significatifs détectés dans la variabilité des précipitations de mousson, sauf en août. Deux modes dominants de précipitations ont été identifiés en utilisant l'analyse de la fonction orthogonale empirique (SEOF) basée sur la saison : le mode Sahel (16.3% de variance) lié aux anomalies de température de surface de la mer (SST) du Pacifique équatorial, de la Méditerranée, de l'Inde et de l'Atlantique du Nord et le mode côte guinéenne (9.5% de variance) influencé par les SST de l'Atlantique équatorial et de l'Atlantique Sud. Les années humides présentent une forte convergence des basses couches sur l'Afrique et une divergence des hautes couches sur le Pacifique, sous l'effet des changements de la circulation de Walker. Les modèles CMIP6 sont plus performants sur le Sahel que sur la côte guinéenne, projetant des tendances futures à l'assèchement. Les précipitations extrêmes ont un impact sur l'agriculture, les infrastructures et la sécurité alimentaire, l'adaptation étant entravée par des infrastructures médiocres, des lacunes dans les capacités techniques et des contraintes de financement. Ces conclusions sont cruciales pour l'adaptation au climat, car elles informent les décideurs politiques sur les infrastructures résilientes et les stratégies d'adaptation visant à atténuer les effets négatifs des extrêmes climatiques en Afrique de l'Ouest.

Mots clés: *Précipitations anormales, projections de changement climatique, modèles CMIP6, température de surface de la mer, Afrique de l'Ouest.*

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LIST OF ACRONYMS

ATL3: Atlantic Niño

CIDs: Climate Impact Drivers

CMIP6: Coupled Model Intercomparison Projects phase 6

EMS: Eastern Mediterranean Sea index

GCM: Global climate model

IOB: Indian Ocean Basin index

IPCC: Intergovernmental Panel on Climate Change

MMM: Multi-model mean

Niño3.4: Equatorial Pacific index

RCP: Representative Concentration Pathways

SSP: Shared Socioeconomic Pathways

SST: Sea Surface Temperature

WCE: Weather and Climate Extremes

WCRP: World Climate Research Programme

WMO: World Meteorological Organization

GENERAL INTRODUCTION

Background to the Study

Precipitation is fundamental to the global ecological, agricultural, and economic systems, serving as the primary source of water for rain-fed agriculture, domestic use, industrial activities, and hydropower generation (Gnanaseelan et al., 2020; Ozcan et al., 2013; Rehman et al., 2018; Ruane et al., 2022). In West Africa, precipitation is crucial for food security, livelihoods, and social well-being, its patterns directly impact regional stability and resilience (Anyamba et al., 2014; Ekwezuo et al., 2018, 2024; Ekwezuo & Ezeh, 2020; Ezeh et al., 2021; Knippertz & Fink, 2008; Motha et al., 1980). Therefore, continuous study of climatic variables such as precipitation patterns is essential for informing policy, improving disaster risk management, and promoting sustainable development, especially in regions vulnerable to climate variability (Biastoch et al., 2024; Kienberger & Alexander, 2014; Tadesse, 2018; Welle et al., 2011).

West Africa's climate system is driven by a complex interplay of atmospheric and oceanic processes, most notably the West African Monsoon (WAM) system, which controls seasonal precipitation across the region (Cook & Vizy, 2006; Diatta et al., 2020; Ruti et al., 2011; Talib et al., 2022; Worou et al., 2020). A more significant percentage of the annual precipitation in the region occurs from June to September, which accounts for over 58% of the yearly rainfall on the Guinea Coast and 84% in the Sahel (Worou et al., 2020). Furthermore, most precipitation-induced disasters occur during this period. The seasonal precipitation distribution divides the region into two distinct subregions: unimodal and bimodal (Hall & Peyrillé, 2006; Herrmann & Mohr, 2011).

This seasonality is crucial for the regional economy, as agriculture, water resources, and the livelihoods of the region's people heavily depend on it. Despite the regular cyclic behaviour of the mean state, there is significant interannual variability in rainy season precipitation, leading to years with extreme wet or dry events (Vischel et al., 2019). Precipitation extremes are typically defined as events where rainfall deviates significantly from historical norms, leading to severe environmental, economic, and social impacts (Balch et al., 2020). Such extremes often manifest as prolonged wet or dry conditions and sometimes as sudden heavy downpours, bringing profound impacts on the region's economies, affecting crop yields, food production, settlements, hydroelectric power generation, and water resource management (Ehsan et al., 2021).

Historically, precipitation variability in West Africa has been profound. For example, West Africa experienced devastating droughts from 1970 to the 1990s. This drought is regarded as the most intense and longest drought ever recorded in the world (Armon et al., 2024; Dai et al., 2004; Herrmann & Hutchinson, 2005; Sanogo et al., 2022); also anomalous wet events were reported in Nigeria and other countries in West Africa in 2012, 2019, 2020, 2022 (Amouin et al., 2021; Nka et al., 2015; Oyedele et al., 2022). Between July and September 2024, heavy and intense precipitation events ravaged most parts of Burkina Faso, Guinea, Mali, Nigeria, and Niger, causing over 1,500 deaths, affecting 4 million people, and displacing over 1.2 million people (International Organization for Migration, 2024), even Maiduguri a town in northeastern Nigeria previously thought to be resilient to flood disasters was adversely affected. Monsoon precipitation variation over the years has been ascribed to human-caused and natural climatic oscillations, including atmospheric and oceanic dynamics. Nonetheless, several studies highlight the difficulty of pinpointing the variables influencing precipitation variability in West Africa due to the WAM's incorporation of numerous processes at various spatial and temporal scales (Vischel et al., 2019).

Weather and climate extremes (WCEs) are among the most impactful consequences and evidence of climate variability and changes, as most observed weather and climate hazards are caused by them (Ranasinghe et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) (2012) refers to WCEs as "*the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable*". A climate extreme event is any systematic change in weather extremes that is accompanied by a systematic change in extreme impact events (Intergovernmental Panel on Climate Change (IPCC), 2012). WCEs are therefore selected as one of the World Climate Research Programme (WCRP) Grand Challenges (Sillmann et al., 2017).

Compared to short-duration (weather) events, extreme climate events are potentially more devastating, because they result from either a few extremely intense events or a persistence of anomalies of the same sign over an extended period of time and tend to affect wider areas (Shongwe, 2010). They therefore deserve considerable research attention as they play important role in shaping and sustaining the natural and social environment. Also, due to their ability to disrupt systems and exert large impacts, they are also called climate hazards or climate impact drivers (CIDs) (Ranasinghe et al., 2021).

Understanding these hazards has significant impact in disaster risk management and climate change adaptation (Emanuel, 2016).

The socioeconomic implications of precipitation variability in West Africa are enormous. Periods of insufficient rainfall led to droughts, reduced agricultural yields, and food insecurity, while periods of excessive rainfall contribute to flooding, infrastructure damage, and displacement (Diasso & Abiodun, 2017; Ekwezuo & Ezeh, 2020; Hales et al., 2003; Stephan et al., 2023; Tall et al., 2023; Verhoeven et al., 2022). These consequences disproportionately affect vulnerable populations, exacerbating poverty, health crises, and regional inequalities (Balch et al., 2020; Sylla et al., 2016).

Furthermore, with the adverse implications of climate change, there is an urgent need to understand the characteristics and drivers of precipitation variability. Because of their profound impacts on West Africa, policymakers, planners, decision-makers and other stakeholders are increasingly seeking information on the nature of such anomalous events on time scales from hours to days, to seasons, to decades and centuries for risk planning and sustainable developments.

Disaster risk assessment (DRA) is the foundation for the management of all risks associated with disasters (Uitto & Shaw, 2016). They constitute the knowledge basis for disaster prediction, prevention, compensation, and all other works related to disastrous weather conditions (Gong & Forrest, 2014). Climate risk assessment, a subfield of DRA characterises the patterns and magnitudes of CID(s) and proposes scientific means and systematic methods to be used for risk reduction. Extreme precipitation events occur due to forcings and feedback in the earth’s climate system (Nie et al., 2020). Understanding the forcings (e.g. ocean and atmospheric dynamics) associated with the development of a range of extreme precipitation events, provides the scientific knowledge required for the development of statistical and dynamical seasonal climate forecast models and related risk products (McGregor, 2015).

The need to understand this forcings coupled with the limitation of purely statistical-based models have motivated the development and use of physics-based numerical climate models, primarily in the form of global circulation(climate) models (GCMs). GCMs use theoretical and empirical understanding of the spatiotemporal physics and chemistry of the oceans, atmosphere, and land surfaces, as well as the increasing computational resources, to simulate historical and future climate system scenarios. Chief among the concerns of all the state-of-the-art approaches to understand the earth’s climate system is the model ability to reliably simulate the characteristics of extreme events. This is because often times climate models simulate divergent climate outcomes across the globe (Cai et al., 2018; Endris et al., 2021; Flato et al., 2013; Konda & Vissa, 2023; Nworgu et al., 2024; Sardana et al., 2023; Tebaldi & Neill, 2020; Zheng, 2019). This study seeks to advance the understanding of the dynamics, projections and impacts of West African summer monsoon precipitation variability that causes large-scale extreme wet and dry conditions. This understanding is essential for enhancing climate risk awareness and preparedness in the region.

Statement of the Research Problem

Precipitation extremes have profound impacts on West African's economy, affecting crop yields, food production, settlements, hydroelectric power generation, and water resource management (Ehsan et al., 2021; Ekwezuo et al., 2018). These extremes lead to substantial agricultural losses, which have triggered notable humanitarian crises across the region (Antwi-agyei et al., 2018; Kotir, 2011; Sultan et al., 2005; Williams et al., 2018). While anomalously wet events often overwhelm inadequate infrastructure, causing floods that disrupt transport networks and economic activities (Amouin et al., 2021; Kim & Dominguez, 2023; Nka et al., 2015; Oyedele et al., 2022; Tabari, 2020), prolonged dry conditions diminish agricultural productivity, deplete water resources, and exacerbate health risks, including mental health impacts (Diasso & Abiodun, 2017; Ekwezuo & Ezeh, 2020; Stephan et al., 2023; Tall et al., 2023; Verhoeven et al., 2022).

Mitigating the adverse impacts of these extreme precipitation events is critical for West Africa, given the region's limited financial, technical, and institutional capacities, which hinder effective response and adaptation (Climate and Development Knowledge Network, 2012). Although previous studies have identified coupled ocean-atmosphere interactions as drivers of West African summer monsoon (WASM) variability (Badou et al., 2019; Druyan & Fulakeza, 2015; Gaetani et al., 2017; Gómara et al., 2018; Joly & Voldoire, 2010; Jules et al., 2021; Okoro et al., 2017; Tamoffo et al., 2024), there remains limited understanding of large-scale anomalous precipitation conditions, the joint influence of oceanic modes on extreme wet and dry conditions, and how the dominant mode will evolve in a changing climate in the future.

This study aims to address these knowledge gaps by examining the dynamics, projections, and impacts of extreme monsoon precipitation conditions in West Africa. An improved understanding of these phenomena is crucial for enhancing climate risk awareness, preparedness, and resilience in the region, thus supporting the broader goal of sustainable development.

Research Questions

The general question this thesis seeks to answer is "What is driving large-scale extreme wet and dry events over West Africa, and what are the perceived impacts of these extreme events in the region?". The specific questions include:

What are the trends and dominant patterns of large-scale wet and dry event occurrences in West Africa during the monsoon period?

What are the physical mechanisms associated with the two dominant modes of precipitation variability over West Africa?

How do different joint phases of the dominant climate modes cause large-scale extreme wet and dry conditions over West Africa?

How will the dominant mode of precipitation variability in the region evolve in the future?

What are the perceived impacts and barriers to effective climate risk reductions in West Africa?

Aim and Objectives of the study

The study seeks to understand the dynamics, projections and risk reduction strategies to rainy season precipitation variability over West Africa. In order to achieve this aim, the following specific objectives were pursued, to:

Assess the characteristics of anomalous precipitation variability over West Africa (1950-2022)

Analyse the mechanisms associated with extreme wet and dry conditions during the West African monsoon season

Examine the impact of dominant oceanic modes on extreme wet and dry conditions over West Africa

Examine future projections of precipitation variability over West Africa under different CMIP6 scenarios

Assess perceived impacts and constraints to effective risk reduction and adaptation strategies to extreme precipitation conditions in West Africa

Research hypotheses

The following scientific hypotheses is proposed to guide this study.

H_1: Anomalous precipitation variability over West Africa from 1950 to 2022 exhibits significant spatial and temporal heterogeneity, with distinct interannual wet and dry phases.

H_2: Extreme wet and dry conditions during the West African monsoon season are primarily driven by dynamic interactions between atmospheric circulation, feedbacks, and regional moisture transport mechanisms.

H_3: Dominant oceanic modes, such as ENSO, Atlantic Niño, and MedSSTA, significantly modulate extreme wet and dry conditions over West Africa by altering large-scale atmospheric circulation and moisture availability.

H_4: Future precipitation variability over West Africa will exhibit increased intensity and frequency of extreme wet and dry conditions under different CMIP6 scenarios, with spatially heterogeneous impacts across the region.

H_5: The perception of the impacts of extreme precipitation events varies significantly across countries and climatic domains of West Africa.

Scope of the thesis

This thesis focuses on the evolution and dynamics of anomalous precipitation during the West African rainy season, specifically analysing large-scale extreme wet and dry conditions using monthly gridded climate data products. The study concentrates on physical climate-impact drivers, examining how interannual variations in precipitation influence regional climate dynamics. Although the analysis includes objective climate data, the study also incorporates the perceptions of residents gathered through a cross-sectional survey conducted in selected West African countries.

The scope is limited to physical climate variables and does not account for socio-economic drivers or other environmental factors that may influence the region's vulnerability to precipitation extremes. Additionally, the reliance on monthly data constrains the analysis to broader intraseasonal trends, potentially overlooking finer temporal variability. The survey component offers valuable insights into community perceptions.

Definition of key terms

Climate: The composite pattern of weather conditions that can be expected in a given region base on the interactions of different components of the climate system. It also refers to the general weather over a long period. This can include rainfall, temperature or any other weather condition usually over a period of 30-35 years.

Climate Change: A trend in the climate that is discernible (for instance, via statistical analyses) by the alteration of its average conditions and/or variability and that lasts for a significant length of time, generally about decades or more.

Climate Mode: The climate system's natural variability, specifically on seasonal and longer scales, mostly takes place with preferred geographical patterns and time measures through the characteristics of atmospheric circulation and connections with land and ocean surfaces.

Climate Model: A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties.

Climate Prediction: The result of an attempt to produce an estimate of the actual evolution of the climate in the future.

Climate Projection: A simulation of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models.

Climate Scenario: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models.

Climate Shift: An abrupt shift or jump in mean values signalling a change in regime.

Climate Variability: Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events.

Detection and Attribution (D&A): Detection of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Greenhouse Effect: The trapping of heat in the atmosphere. Incoming short-wavelength solar radiation penetrates the atmosphere, but the longer-wavelength outgoing radiation is absorbed by water vapour, carbon dioxide, ozone, and several other gases in the atmosphere and is re-radiated to earth, causing an increase in atmospheric temperature.

Green House Gases: The gases present in the earth's atmosphere that cause the greenhouse effect.

Hazard: The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.

Monsoon: A tropical and subtropical seasonal reversal in both the surface winds and associated precipitation, caused by differential heating between a continental-scale land mass and the adjacent ocean.

Predictability: The extent to which future states of a system may be predicted based on knowledge of current and past states of the system.

Projection: A potential future evolution of a quantity or set of quantities, often computed with the aid of a model.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognising the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure and hazard.

Synoptic Scale (large scale): Size scale generally referring to weather systems with horizontal dimensions of several hundred miles or more.

Teleconnection: A connection between climate variations over widely separated parts of the world. In physical terms, teleconnections are often a consequence of large-scale wave motions, whereby energy is transferred from source regions along preferred paths in the atmosphere.

Trend: A change, generally monotonic in time, in the value of a variable.

Plan of the thesis

The thesis is organised in the following order:.

General introduction. This comprises the background of the study and the statement of the research problem. The next are aim and objectives of the study, the research questions, the research hypotheses, scope of the study, the definition of key terms used in the study, and finally the plan of the thesis, which describes the order of organisation of the thesis.

Chapter 1 is the literature review and theoretical framework. This comprises a review of relevant literature and theoretical frameworks.

Chapter 2 describes the materials and methods adopted for the study. Its content includes a description of the geography of the study area, types and sources of data, and the analytical techniques employed in the study.

Chapters 3 to 7 focus on the presentation and discussion of the obtained results. The results are presented based on the stated objectives of the study.

General conclusion and perspectives.

CHAPTER 1: LITERATURE REVIEW AND THEORETICAL FRAMEWORK

This chapter reviews the relevant literature on the study. It focuses on key themes within the field, identifies gaps in existing research, and outlines the theoretical framework relevant to this study. The aim is to deepen understanding of the dynamics of large-scale extreme precipitation conditions in West Africa and the response strategies.

Literature Review

Overview of the Climate of West Africa and the Significance of the Monsoon Season

Precipitation is a key component of the Earth's climate system, impacting environmental processes, ecosystems, and human activities throughout the globe. Its variability, whether in the form of excessive rainfall, drought, or a complete absence thereof, has a substantial influence on agriculture, water management, infrastructure, and public health. These impacts are particularly evident in West Africa, where precipitation patterns dictate food security, economic stability, and disaster resilience (Anyamba et al., 2014; Satgé et al., 2020). Understanding these patterns, particularly in the face of climate change, is increasingly urgent for sustainable development and effective disaster preparedness. Thus, studies analysing precipitation variability and its consequences have become vital for informing policy and planning decisions.

Researchers rely on various datasets to analyse precipitation variability, including station-based measurements, satellite observations, reanalysis data, and climate model outputs. Satgé et al., (2020) extensively evaluated 23 gridded precipitation datasets, revealing significant discrepancies in their reliability across different regions of West Africa, particularly when compared to rain gauge measurements. This variance is particularly pronounced at daily and monthly timescales, which is critical for the agricultural sector that depend on precise short-term rainfall forecasts. Similarly, Quagraine et al. (2020) assessed five global reanalysis datasets to represent summer monsoon rainfall characteristics, finding that while these datasets effectively captured average rainfall patterns and seasonal cycles, notable regional biases were present. These biases have important implications for understanding local climate dynamics and can hinder effective disaster risk reduction efforts.

The West African Sahel, a region prone to drought and heavy rainfall, has experienced significant changes in precipitation patterns over the past 30 years. Bichet and Diedhiou (2018) noted increased rainfall, particularly shorter and more frequent dry spells, which have altered agricultural productivity and reduced some drought risks. However, this increased rainfall has also led to heightened flood risks, highlighting the complex nature of precipitation variability. Nouaceur and Murarescu (2020) supported this finding, emphasising the dual threats and opportunities of shifting rainfall patterns in the Sahel. More intense rainfall events, largely attributed to stronger storm systems, are driving the annual maxima of daily rainfall, as demonstrated by Chagnaud et al., (2022), who noted that 80% of the increase is due to storm intensity, while only 20% is related to storm frequency.

Further research by Diba et al., (2019), using the Regional Climate Model version 4.5 (RegCM4.5), explored how warming influences West African monsoon dynamics. Their study revealed that rainfall amounts tend to decrease in the Sahel and Guinea regions during the hottest years, underscoring the sensitivity of precipitation patterns to temperature fluctuations. These findings highlight the region's precarious balance between drought and flood risks, further exacerbated by warming temperatures. Elagib et al., (2021) expanded on this by examining the increasing frequency, spread, and severity of floods in the Sahel, linking these events to changes in rainfall intensity, human environmental impacts, and inadequate urban planning. These factors contribute to heightened vulnerabilities, particularly in urban areas where flood management infrastructure is often lacking. Interestingly, despite their destructive potential, extreme rainfall events present opportunities for addressing water scarcity in the region. Harvesting and managing excess rainwater can significantly mitigate regional water shortages (Elagib et al. 2021). Thus, they reinforce the necessity of integrating sustainable water management practices into climate adaptation strategies.

Additionally, understanding precipitation's spatial and temporal dynamics, referred to as "modes," is crucial for predicting rainfall variability. Anyadike, (1987) employed hierarchical clustering and factor analysis to categorise West African climates, emphasising that the most significant variations occur along coastal and highland areas. This work, supported by Janicot, (1992), demonstrated that distinguishing between regions north and south of 10°N can enhance comprehension of inter-annual rainfall variability, further refined by (Moron, 1994; Paeth & Stuck, 2004). Nnamchi et al., (2021), continuing in the two leading precipitation modes paradigm examined the influence of trend and no trend in the Sahel and Guinea Coast modes of variability. They observed that the trend account for approximately 33% of the variance in rainfall from July to September. This understanding of precipitation modes provides valuable insight into West Africa's rainfall patterns, offering a foundation for improved climate forecasting and adaptation efforts. Various studies have contributed to this growing body of literature on West African precipitation variability, including (Akinsanola & Zhou, 2019; Braimah et al., 2022; Le Barbé et al., 2002; Nicholson & Webster, 2007) each adding to the collective understanding of this complex and critical climate system.

Characteristics of Anomalous Precipitation Variability Over West Africa

The West African monsoon exhibits significant variability across various timescales, from intraseasonal to decadal, resulting in anomalous precipitation patterns that can trigger floods and droughts. This variability influences the region's hydrological events and, consequently, the socioeconomic conditions of the population. Le Barbé et al., (2002) emphasised the importance of analysing rainfall regimes by assessing both the frequency and intensity of rain events, which leads to a better understanding of West Africa's weather dynamics. This idea is further corroborated by Sun et al., (2012), they argue that identifying and interpreting patterns in precipitation and their associated principal components (PCs) helps to understand and predict floods and droughts. Which becomes crucial when studying large datasets, as it allows for identifying years with hydrological extremes.

Similarly, Ankrah et al., (2023), applied the Standardised Precipitation Evapotranspiration Index (SPEI) to examine drought and wetness events between 1981 and 2021 in the coastal Savannah agroecological zone. They discovered that the Central and Volta regions experienced more frequent droughts and wetness than Greater Accra. However, the intensity and duration of these events were more robust in the Greater Accra and Central regions. Araujo Bonjean et al., (2023), using an extreme value mixture model, identified high drought hazard index hotspots in the northern part of Nigeria, southern Chad, and central Cameroon, thus further underscoring the spatial disparities in drought risk across West Africa.

Variability in the West African summer monsoon precipitation directly affects floods and droughts, impacting agriculture, water resources, and human livelihoods. Reduced precipitation, for instance, can result in agricultural decline, exacerbating food insecurity, conflict, and migration, whereas excessive precipitation often leads to devastating floods

(Dibi-Anoh et al., 2023). These hydrometeorological extremes (drought and floods) carry significant socioeconomic consequences for the region, which heavily relies on rainfed agriculture. Dibi-Anoh et al. (2023) further emphasise that the vulnerability of West Africa to these extremes stems from its reliance on rain-dependent farming, making the region highly sensitive to precipitation anomalies. Eltahir and Gong (1996) proposed a framework linking the interannual variability of West African precipitation to the meridional gradient of the boundary layer entropy and monsoon circulation. They argue that cold sea surface temperature anomalies (SSTAs) in the equatorial Atlantic strengthen monsoon circulation, leading to wet conditions in the Sahel. In contrast, warm SSTAs weaken the circulation, resulting in dry conditions. This relationship between SSTAs and precipitation anomalies provides a theoretical basis for understanding the occurrence of hydrometeorological extremes in the region.

Efforts to predict anomalous rainfall conditions have been a focus of research aimed at mitigating the impacts of these extremes. Hounkpè et al., (2022) employed simple and multiple linear regressions to predict flood events in West Africa, finding that the western dipole mode index was the most accurate individual predictor of above-normal floods. Moreover, combining climate indexes improved the accuracy of above- and below-normal flood predictions. Similarly, Omotosho et al., (2000) proposed that monitoring variations in equivalent potential temperature could help predict rainfall onset, while Rodrigues et al. (2014) demonstrated that a simple statistical model outperformed more complex dynamical forecast systems in predicting the PCs associated with the Guinean and Sahelian rainfall regimes. This underscores the importance of empirical models in operational forecasting contexts. Further research by Scaife et al., (2019) quantified the seasonal prediction skill of rainfall variability in various tropical ocean basins, with the tropical East Pacific showing the highest predictive skill, while the tropical Atlantic and Indian Oceans had lower but statistically significant prediction scores. These predictive studies are critical for managing the region's vulnerability to floods and droughts.

Droughts, in particular, pose a unique challenge due to their slow onset, making them difficult to detect until they are well underway. Drought indices, such as the Standardised Precipitation Index (SPI) and SPEI, have been widely used to monitor and forecast drought conditions. Ekwezuo and Ezeh, (2020) employed the SPI to show divergent trends in short-term and medium-term moisture conditions across West Africa, with the northern Sahel being the most vulnerable to droughts. In contrast, highly humid regions demonstrated a significant decrease in rainfall, highlighting the region's climatic variability. Tsutsui et al., (2021) used ecohydrological variables to quantify severe droughts in the Sahel-inland region, finding a strong correlation between drought severity and millet yields. Meanwhile, Diasso and Abiodun, (2017) used SPEI to reveal that the spatio-temporal variability of drought in West Africa can be categorised into four distinct modes, which affect different parts of the region. This further emphasises the complex and region-specific nature of drought dynamics in West Africa.

Globally, research has expanded on using drought indices to characterise and track drought events. Ojha et al., (2021) compared SPI and SPEI to assess drought conditions in India's Punpun River basin, observing increased drought intensity and duration since 2004, a trend that mirrors patterns seen in parts of West Africa. (Verhoeven et al., 2022) introduced a novel method for spatial drought tracking, S-TRACK, which revealed shifting drought and wet event hotspots in Australia in response to changes in precipitation patterns since the 1970s. Their findings align with those of Artikanur et al. (2022), who used the Normalised Difference Drought Index to classify drought severity in East Java, Indonesia, showing that high-severity droughts affected only small portions of the region. Ullah et al., (2022) employed SPEI to analyse drought conditions in Pakistan's Rabi and Kharif cropping seasons, finding increased drought severity over arid and semi-arid regions. However, Araujo Bonjean et al., (2023) caution against relying solely on SPI for assessing region-specific hazards, advocating for using extreme value theory to study drought in West Africa.

Understanding The Drivers of Extreme Climate Events in West Africa

Research into extreme climate events frequently highlights the critical roles played by major modes of atmospheric variability and sea surface temperature anomalies. In West Africa, the West African Summer Monsoon (WASM) drives summer precipitation, distributing rainfall in a belt-like pattern across the region. The variations in this monsoon significantly impact the frequency of disastrous weather events, such as droughts and floods, leading to substantial economic repercussions (Li & Zeng, 2000). Extensive studies have demonstrated the impact of the WASM on precipitation variability in West Africa. The monsoon's weakening correlates with decreased summer rainfall in the Guinea Coast, while its strengthening results in increased precipitation in the Sahel (Armon et al., 2024). However, the WASM dynamics are complex and influenced by many atmospheric and oceanic processes. As such, considerable research has focused on unravelling these interactions to better understand their implications for West African climate. Armon et al., (2024) showed a limited mechanistic understanding of precipitation patterns, particularly in arid regions like the Sahara, which complicates formulating effective climate change adaptation strategies. The highest density of heavy precipitation events is recorded in the southern Sahara-Sahel region, predominantly during summer. It is associated mainly with convective activity related to the African monsoon and the Saharan heat low. These heavy precipitation events are often linked to surface cyclones that anomalously affect much of the Sahara.

In their analysis of the West African monsoon, Martin and Thorncroft (2014) explored the differences between the warm and cold phases of the Atlantic Multidecadal Oscillation (AMO). Their findings show that Sahel precipitation increases during warm AMO phases, driven by a stronger shallow Saharan meridional circulation (SMC). The intensified circulation enhances moisture flux from the south into the Sahel during spring, while increased westerly winds from the Atlantic further augment moisture transport during spring and summer. Moreover, strengthening the heat low during warm AMO phases coincides with elevated Mediterranean Sea surface temperatures, resulting in heightened moisture flux convergence in the northeastern Sahel. Contrarily, Shekhar and Boos (2017) challenged the prevailing notion that enhanced Sahel rainfall results from a stronger SMC. They proposed that a robust SMC might inhibit Sahel rainfall by advecting warmer and drier mid-tropospheric air into the precipitation zones. This perspective aligns with findings from Mutton et al., (2024), they observed that reductions in Sahel rainfall were linked to changes in large-scale temperature gradients and localised warming related to soil moisture feedback mechanisms. Nnamchi et al., (2021) emphasised the significance of interactions between meridional displacements of the Intertropical Convergence Zone (ITCZ) and zonal variations in the Walker Circulation for understanding the precipitation dynamics in both the Sahel and the Guinea Coast. Lélé et al. (2015) noted that during the peak monsoon season (July to September), southerly moisture transport weakens, while westerly transport increases and extends inland, driven by the strengthening of the West African jet off the coast. Their analysis of seasonal moisture flux components revealed that while zonal transport is the primary contributor to moisture influx into the Sahel, meridional transport plays a more significant role in the Guinea Coast region. The interplay of these factors results in notable spatial and temporal variations in rainfall patterns. During wet years in the Sahel rainy season, active anomalies tend to shift farther north than the long-term average, impacting the latitude of the ITCZ, moisture flux extent, and convergence zones. Conversely, dry years exhibit opposing patterns.

Nicholson and Grist (2003) examined the annual rainfall cycle and general circulation features over West and Central Africa from 1958 to 1997, finding that mid-tropospheric jets significantly influence the development of the rainy season. They further noted that rainfall patterns affect surface temperature gradients, impacting these jets. Gong and Eltahir (1996) contributed to understanding West African rainfall by demonstrating that evaporation from the tropical Atlantic Ocean, along with regions in West and Central Africa, plays a crucial role in the moisture supply to the monsoon system. Nicholson (1989) highlighted the challenges in predicting Sahelian droughts due to the interplay of competing climatic drivers, including circulation patterns, land surface feedback, and aerosol effects. This complexity, as emphasised by Armon et al., (2024), poses significant hurdles for effective climate change adaptation strategies in the region. Thus, while the mechanisms governing WASM and its impact on precipitation variability are continually studied, further research is needed to refine our understanding of these dynamics and their implications for climate resilience in West Africa.

Impact of Greenhouse Gas Emissions on Climate Variability

The study of extreme events has grown in importance due to the likelihood of an increase in their frequency and magnitude under anthropogenic-enhanced climate change. Research has indicated a link between aerosols and different particulates and modifications to climate, as they can either strengthen or hinder cloud formation. Ajoku et al. (2020) find that, on average, during enhanced aerosol transport, there are about 10–15Wm^{-2} reductions in surface shortwave radiation across the Gulf of Guinea, with aerosols contributing roughly 33–50% of that reduction. A reduction in shortwave radiation is linked to a decrease in convective available potential energy (CAPE). The impact illustrates that a heightened transport of aerosols disrupts surface radiation, alters convection in the lower atmosphere, and ultimately changes cloud coverage, with the possible impact of declining monsoon rainfall. Marvel et al., (2020) breaks down the model-predicted impacts of greenhouse gases and anthropogenic aerosols on Sahel rainfall during the 20th and 21st centuries. Models indicate that a discernible signal from aerosol forcing will likely arise in the middle of the 20th century and a discernible signal from greenhouse gas forcing at the start of the 21st century. The study from Solmon et al., (2021), employing regional climate modelling experiments, demonstrates that Central and Southern African biomass-burning (SABB) aerosols can notably affect West African monsoon dynamics, by using two separate and competitive regional-scale and inter-hemispheric dynamical feedbacks originating from heightened diabatic heating noticed in the Southeastern Atlantic low-cloud deck region, as well as aerosol and cloud-induced. These processes cause a decline in June to September WAM (West African Monsoon) precipitation, while they could enhance late-season rainfall in coastal areas of the region. Moreover, according to Dong and Sutton (2015), the dominant cause of the recent rainfall recovery in the Sahel was the increased concentration of greenhouse gases in the atmosphere, as variations in sea surface temperatures (SSTs), while significant, did not considerably affect the recovery. A study by Hirasawa et al., (2022) indicate that the equilibrium between reactions to SST anomalies in the Atlantic, Pacific, and Indian Oceans determines the ocean-borne influence on the Sahel precipitation response to aerosol.

According to Schurer et al., (2020), a combination of satellite and in situ data from 1988–2019 indicates that the sharpening of the contrast between dry and wet regions characterises the CMIP6 model-simulated trend. They determine that most of the identified change is derived from the growing concentration of greenhouse gases in the atmosphere. A study by Gaetani et al., (2017), examined the mechanisms connecting the WAM dynamics to the CO2 forcing. It revealed that the warming of sea surface temperatures (SST) alters Sahelian precipitation through changes in the global tropical atmospheric dynamics, reducing regional driving forces' influence.

The Influence of Sea Surface Temperatures on Precipitation Variability in West Africa

The intricate relationship between sea surface temperatures (SSTs) at both basin and global scales has been increasingly recognised as a significant driver of precipitation variability across various regions (Asefi-Najafabady & Saatchi, 2013; Behera, 2019; Rifai et al., 2019; Suárez-Moreno et al., 2018; Supari et al., 2018; Ullah et al., 2021; Vizy & Cook, 2001; Ying et al., 2015; Zhuo & Rose, 2024). Notably, the phenomena of La Niña have been shown to contribute to prolonged dry spells in South America, particularly in Brazil, Argentina, Paraguay, and Uruguay during the 2019/2020 period. Gomes et al., (2021) documented that positive SST anomalies across various oceans, particularly in the North Atlantic, facilitated subsidence over South America via meridional circulation. Furthermore, Famien et al., (2024) highlighted the effects of the Atlantic Multidecadal Oscillation (AMO) on regional climates, noting that a positive AMO phase correlates with rising temperatures in the Sahara and a deepening of the Saharan Heat Low and Arabian Heat Low. This leads to enhanced rainfall over the Sahel, with the Arabian Heat Low as a critical indicator of decadal rainfall variability in the region, independent of other variability drivers.

Zhuo and Rose (2024) quantified the contributions of remote SST changes and anthropogenic greenhouse gas emissions to the recent warming observed in the Sahara. Their findings reveal that remote SST forcing largely governs Saharan temperature increases. As ocean temperatures rise, they transport additional energy to the Sahara, intensifying surface warming. Notably, the warming contrast between the Sahara and the average tropical land is primarily influenced by lapse-rate feedback (LR), favouring Saharan warming while suppressing temperature increases in the broader tropics. Wane et al., (2023) examined the impact of northeastern Tropical Atlantic SSTs on the Intertropical Convergence Zone (ITCZ) during precipitation phases in the Sahel. Their results indicated that cold anomalies in the North Atlantic lead to significant reductions in precipitation in the western Sahel. In contrast, warm anomalies in the Gulf of Guinea correspond to increased rainfall in the eastern Sahel. These changes are linked to positive anomalies in upper-tropospheric moisture transport divergence, influenced by the acceleration of the African easterly jet.

On interannual timescales, key oceanic drivers of West African precipitation variability include the El Niño-Southern Oscillation (ENSO), the Equatorial Atlantic Mode (Atlantic Niño), and Mediterranean SST anomalies (Giannini et al., 2003; Park et al., 2016; Suárez-Moreno et al., 2018; Diatta and Fink, 2014; Gómara et al., 2018; Janicot et al., 2001; Joly and Voldoire, 2009, 2010; Okonkwo et al., 2015; Pomposi et al., 2016, 2020). ENSO, a quasi-periodic oscillation resulting from air-sea interactions in the tropical Pacific, alternates between El Niño and La Niña phases, affecting global weather patterns. Research indicates that El Niño conditions correlate with reduced precipitation in the Sahel, while La Niña promotes wetter conditions (Diatta & Fink, 2014; Giannini et al., 2003; Janicot et al., 2001).

In the aftermath of the notable 2015 El Niño, Pomposi et al., (2020), posited that the response of Sahelian precipitation to ENSO events may not follow conventional expectations, suggesting a more nuanced interaction. Didi et al., (2023), further asserted that the influence of Equatorial Pacific SSTs on daily rainfall intensity in West Africa is notably stronger than their effect on rainfall frequency. Bombardi et al., (2014) explored the role of the South Atlantic Dipole (SAD) during neutral ENSO events, revealing its significance in cyclogenesis and the dynamics of the South Atlantic Convergence Zone.

Positive SST anomalies in the South Atlantic correlate with increased cyclogenesis near southeast Brazil and the northward migration of extratropical cyclones, enhancing convection and precipitation in eastern South America. The Equatorial Atlantic also plays a pivotal role in shaping climate variability. The Atlantic Zonal Mode (AZM) or Atlantic Niño mirrors the impacts of ENSO, exerting significant influences on regional and global climate patterns (Zhang & Han, 2021). Adeniyi and Dilau (2018) noted a dipole structure in drought patterns relative to the Atlantic Niño index, although they found this structure less pronounced in mean precipitation relationships. Brandt et al., (2011) hypothesised that zonal wind anomalies in the western equatorial Atlantic during late winter to early summer set the stage for boreal summer cold and warm events in the eastern equatorial Atlantic, significantly influencing the West African monsoon. Caniaux et al. (2011) explain the coupling mechanisms between the Atlantic cold tongue and the West African monsoon, particularly in boreal spring and summer. Diatta and Fink (2014) identified key SST predictors for West African rainfall across different regions from 1921 to 2009, emphasising the importance of the Indian Ocean, Eastern Mediterranean Sea, and Atlantic region (ATL3) in influencing rainfall patterns.

Research by Zhang and Han, (2021) demonstrated that enhanced rainfall in the western tropical Indian Ocean during positive Indian Ocean Dipole (IOD) phases disrupts easterly trade winds over the tropical Atlantic, causing warm anomalies and triggering the Atlantic Niño. Pottapinjara et al. (2014), analysed the impact of the AZM on monsoon depressions in the Bay of Bengal, finding that more monsoon depressions form during cold phases compared to warm phases. Zhang et al., (2023) highlighted that the central Atlantic Niño has a more substantial influence on tropical climate than its eastern counterpart, which has weakened significantly in recent decades. This shift shows the necessity of distinguishing between the two types of Atlantic Niño and exploring their distinct climatic impacts in future studies.

Also, Mo and Thiaw (2002) and Ward, (1998) suggested that the North Tropical Atlantic SST has minimal impact on West African rainfall. However, Thiam et al., (2024) and Camberlin and Diop, (1999) found that climatic anomalies in the northern Tropical Atlantic influence precipitation in Senegal than those in the equatorial Atlantic. Park et al., (2016) identified Mediterranean SSTs as crucial to recent Sahel rainfall recovery, linking anthropogenic warming in this area to shifts in tropical Atlantic and Indo-Pacific influences that have historically driven Sahelian drought. Gaetani et al., (2010) attributed the Mediterranean's influence on the West African monsoon to SST-induced modifications in lower tropospheric moisture content, whereby warmer eastern Mediterranean conditions in late summer enhance moisture transport toward the Sahel. Ficchì et al., (2021) compared the roles of ENSO and climate variability from the Indian and Atlantic Oceans in driving flood hazards across Sub-Saharan Africa. Their findings suggest that the impacts of these oceanic climate models are comparable to those of ENSO, advocating for their consideration in seasonal forecasting and climate change adaptation strategies throughout the continent.

Teleconnections and their Influence on precipitation extremes in West Africa

Teleconnections are climate anomalies that manifest over regions at a distance but are interconnected by atmospheric circulation patterns (Feldstein & Franzke, 2017). These worldwide climate interactions significantly influence regional climate variability, especially in places such as West Africa, where frequent extreme precipitation events pose a serious challenge. This investigation assesses the effect of teleconnections such as the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Indian Ocean Dipole (IOD) on precipitation extremes in West Africa. Realising these teleconnections is significant in our effort to foresee and handle extreme weather events, especially in areas especially susceptible to climate variability, such as West Africa. Based on the teleconnections theory, this framework outlines how global climate systems manipulate regional precipitation extremes and acts as a starting point for our study of West Africa's rainfall patterns.

El Niño-Southern Oscillation (ENSO)

ENSO (El Niño-Southern Oscillation) is a prominent global teleconnection pattern, and its two phases (El Niño and La Niña) significantly impact global and regional climate systems, according to Trenberth (2020), El Nino-Southern Oscillation modulates the movement of the atmosphere by changing the sea surface temperatures (SSTs) in the Pacific Ocean, thereby causing shifts in weather patterns worldwide (Dong et al., 2006). ENSO has a vital impact on precipitation extremes in West Africa, especially during the West African Monsoon season. Atmospheric circulation patterns tend to weaken the West African Monsoon during an El Niño event. This outcome leads to drier-than-typical conditions across the Sahel region, contributing to droughts and diminished crop yields. Alternatively, La Niña occurrences are generally related to boosted rain in West Africa, which escalates the likelihood of flooding and severe weather events (Nobre et al., 2019). The link between ENSO and rainfall in West Africa is challenging, as it interacts with both local and regional climate variables, including the Atlantic Sea surface temperatures and the intensity of the Sahara Heat Low (SHL) (Biasutti, 2019). As a result, the effects of ENSO on severe precipitation differ throughout West Africa.

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) also plays a significant role in how West African climate variability is influenced. The NAO represents changes in pressure between the Azores High and the Icelandic Low, impacting wind patterns and moisture transport across the Atlantic (Hurrell et al., 2003). The West African Monsoon's strength can be influenced by the North Atlantic Oscillation, impacting the flow of moisture from the Atlantic into the region (Braconnot et al., 2019). A positive phase of NAO can be defined by a stronger Azores High and Icelandic Low, which enhances westerly winds, bringing more moisture into West Africa and potentially increasing rainfall. On the other hand, a negative NAO phase diminishes these winds, resulting in drier conditions in the Sahel and an increased likelihood of drought. The North Atlantic Oscillation has been thoroughly investigated in relation to winter conditions in Europe, whereas its impact on West African rainfall during the monsoon season is still relatively unknown (López-Moreno et al., 2011).

The Indian Ocean basin (IOB) and Indian Ocean Dipole (IOD)

The Indian Ocean basin (IOB) mode dominates the interannual sea surface temperature (SST) variability in the Indian Ocean, followed by the Indian Ocean dipole (IOD) (Hamal et al., 2020; Huang et al., 2021; Li et al., 2023; Wang et al., 2024).

The Indian Ocean Dipole (IOD) refers to a teleconnection pattern driven by differences in sea surface temperatures between the western and eastern tropical Indian Ocean (Jiang et al., 2022). During a positive IOD phase, the contrast between warmer western Indian Ocean waters and cooler eastern waters sets up a temperature gradient that disrupts the atmospheric circulation pattern within the Indian Ocean area (Schott et al., 2009). This leads to increased rainfall in East Africa, which has consequences for West African climate patterns that are triggered by alterations in atmospheric pressure and wind circulation (Saji et al., 1999). Although ENSO and NAO significantly influence West Africa, the IOD can still influence its climate by modifying atmospheric circulation. For example, powerful positive IOD events can change the Walker circulation, a large-scale atmospheric circulation system, thus influencing the rainfall pattern in the Indian Ocean and the areas around it, encompassing sections of West Africa (Jiang et al., 2021).

Stationarity in Teleconnection Patterns

The stationarity in teleconnection patterns has also attracted much interest. For example, Losada et al., (2012), relying on AGCMs which do not replicate the observed precipitation variability pattern over the Sahel region, found that at interannual timescales, there has been a non-stationary relationship between the anomalies of West African rainfall and tropical SSTs. Wang et al., (2008) observed that since the late 1970s, the overall coupling between the Asian–Australian monsoon (A–AM) system and ENSO; ENSO and the western North Pacific, East Asian, and Indonesian monsoons have all become enhanced during ENSO's developing, mature, and decaying phases, overriding the weakening of the Indian monsoon–ENSO anticorrelation during the developing phase. Before the late 1970s (1956–79), the first mode showed a strong biennial tendency, and the second did not lead to ENSO. After 1980, the first mode shows a weakening biennial tendency, and the second mode provides a strong precursory signal for ENSO. These interdecadal changes are attributed to the increased magnitude and periodicity of ENSO and the strengthened monsoon–ocean interaction. Rodríguez-Fonseca et al., (2009) examine the connections and stationarity between Pacific and Atlantic Ninos from 1950–2002 period. They observed evidence of a change in the Atlantic-Pacific Ninos connection since the late 60's. The mechanism (for the positive Atlantic phase) involves strengthening the Walker circulation with an ascending branch over the Atlantic and a descending branch over the central Pacific. The enhanced surface divergence in the latter region shallows the equatorial thermocline, triggering coupled processes and favouring the development of a Pacific La Nina. Wang, (2006) explain that rainfall responds to the inter-Pacific-Atlantic SST gradient by showing an anti-symmetric configuration between the two equatorial oceans, suggesting that rainfall is sensitive to the equatorial inter-basin SST gradient, regardless of which ocean is anomalously warm or cold. Rodríguez-Fonseca et al., (2015) report that at interannual time scales, a warming of the equatorial Atlantic and Pacific/Indian Oceans results in rainfall reduction over the Sahel, and positive SST anomalies over the Mediterranean Sea tend to be associated with increased rainfall. At decadal time scales, warming over the tropics leads to drought over the Sahel, whereas warming over the North Atlantic promotes increased rainfall.

According to Torralba et al., (2015), the Atlantic Niño influenced rainfall variation over the northeastern South American region at the start of the twentieth century and after 1970, while the impact of the Pacific Niño was significant regarding variability from 1970 onwards. After the 1970s, the aggregated impact of both basins increased the unexpected rainfall response. Svendsen et al., (2023) propose that depending on specific conditions in the global ocean, we should use the information on the Atlantic Niño to improve our forecasts of El Niño and La Niña events. The changes in the canonical Atlantic Niño after the 1970s are the reason behind the non-stationarity of the Atlantic Niño/Niña (ANN)-ENSO teleconnection. Again, the "non-canonical" Atlantic Niño was the leading influence before the 1970s. The shift in Atlantic Niño configuration that occurred in the 1970s triggered a westward change in the equatorial Atlantic convection area, along with an increased equatorial Pacific response to Atlantic Niños (Losada & Rodríguez-Fonseca, 2016; Svendsen et al., 2023). Arages et al., (2013) provided observational evidence of how changes in West African and Euro-Mediterranean atmospheric teleconnections relate to remote regions since the late 70s. This insight is significant for the seasonal forecasts in the region.

Land-Atmosphere Interactions

The interactions between land and atmosphere, particularly through natural vegetation and land cover changes, play a crucial role in shaping regional climates like the West African Monsoon (WAM). One key aspect is the soil moisture-atmosphere feedback, which influences intraseasonal variations in monsoon circulation. Talib et al., (2022) found that dry spells in the Sahel cause significant surface drying, leading to a southward shift of the monsoon circulation by about 1.5° latitude. This highlights the sensitivity of the WAM system to surface conditions, adding complexity to predicting future rainfall patterns. Human-induced land use changes are also central to modifying land-atmosphere feedback mechanisms. For instance, while early studies like Zheng & Eltahir, (1997) showed that land cover changes in the northern Sahel have minimal impact on rainfall, deforestation along West Africa's southern coast can significantly reduce precipitation and disrupt the monsoon circulation. This shows how human activities, particularly deforestation, can destabilise regional weather systems.

The global effects of land surface changes on weather and climate are well documented, as these modifications alter land-atmosphere fluxes. Spracklen et al. (2018) explored this in detail, showing how changes in land cover influence atmospheric processes. In Burkina

Faso, Sougué et al., (2023) linked the increase in flood disasters more to land use, population growth, and urbanisation than to rainfall extremes, reflecting how human-driven land changes exacerbate vulnerability to natural hazards. Reforestation efforts also have notable climate implications. Camara et al., (2022) examined the effects of reforesting the Sahel-Sahara interface, finding that reforestation can decrease extreme heat and drought events while increasing wet extremes due to enhanced atmospheric moisture. This suggests that restoration efforts may improve environmental health and moderate local climate extremes. Nogherotto et al., (2013) observed that deforestation in the Congo basin could locally reduce precipitation while strengthening the West African monsoon, leading to more rainfall over the Sahel but less over the Guinea Coast. The potential of large-scale projects like the Sahel Greenbelt to mitigate climate extremes is also promising. Saley et al., (2019) demonstrated that the Greenbelt would increase the frequency of rainy days and reduce extreme dry spells, fundamentally shifting the modes of precipitation variability across the Sahel. Such initiatives could become a critical tool in climate adaptation strategies for the region. Zaveri et al., (2020) assessed the agricultural impacts of rainfall variability, finding that repeated dry anomalies lead to cropland expansion in developing countries as a coping mechanism for reduced yields, whereas wet events had no significant effect. This shows how land use practices are reactive to climate anomalies, creating feedback loops that further alter land cover and, by extension, local climate patterns.

Role of Atmospheric Dynamics in Modulating Precipitation Extremes

Understanding the response of extreme precipitation to global warming is of great importance to society and ecosystems, as extreme precipitation sensitivity is expected to increase due to an increase in temperature following the Clausius-Clapeyron [CC] scaling. However, significant variations on the regional scale are observed, mainly due to changes in the vertical motion associated with extreme precipitation (Nie et al., 2020).

Schupelius, (1976) demonstrates that the upper-air atmospheric conditions are more linked to the variability of rainfall in the region, suggesting a discrepancy with the common view that the South Atlantic pressure system is decisive in causing high or low rainfall seasonality in tropical West Africa. According to Bunting et al., (1975), West African rainfall possesses at least some seasonal persistence from July onwards, permitting a forecast of the seasonal rainfall with variations of geopotential height as predictors.

How various atmospheric drivers have affected the area has been investigated. Bliefernicht et al., (2022), using a two-step classification system examined the seasonal and day-to-day changes in rainfall across the Sudan-Sahel zone in West Africa. They found that surface pressure and meridional moisture fluxes are the most dependable variables for describing seasonal rainfall changes. Batebana et al., (2016) state that atmospheric anomalies contribute to rainfall variability across the West African Guinea coast nations. Their findings reveal that positive low-level geopotential height anomalies are linked to dry years, whereas negative geopotential height anomalies are associated with wet years.

Akinsanola and Zhou, (2019), employed a moisture budget analysis to assess the controlling mechanisms and quantify different factors' contribution to this increasing trend in summer monsoon rainfall during 1980–2012. Their result reveal that most of the increasing rainfall over the central-eastern Sahel (CES) is balanced by increased vertical moisture advection, of which the dynamic component exhibits the largest contribution to the trend, followed by the thermodynamic component. Also, Akinsanola and Zhou (2020), based on the composite of dry and wet years, assert that a weaker (stronger) African Easterly Jet (Tropical Easterly Jet) is observed during the wet years. Also, a well-developed and deep low-level westerly flow at about 850 hPa is evident in wet years, while an obvious reversal is observed in dry years. Considering this, they proposed using two easterly jet streams and low-level westerly wind to objectively define an effective WASM index (WASMI).

Liu et al., (2020) determined the low-level moisture transport related to the West African Westerly Jet (WAWJ) on a seasonal scale and investigate the relationship between the jet and West African precipitation using a moisture budget analysis. They discovered that the Western African wind speed and rainfall patterns over most part of the western Sahel (0°-10°W, 8°-18°N) are positively and significantly correlated. Higher (lower) rainfall amounts occur in months with a robust (weak) West African Wind Jet, combined with low-level moisture flux anomalies associated with the jet, rather than the southerly West African monsoon.

Nicholson and Grist, (2003) examined the potential influence of the jets on West and Central African rainfall and the possible feedback effects of rainfall on them. They found that the mid-tropospheric jets influences the onset of the rainy season which inturn affects the surface temperature gradient and ultimately the jets.

During the monsoon season in the Wet (1998-2002) and dry (1981-85) selected years, Rufus et al., (2013) investigated characteristics of the tropospheric circulation over the West African region. Between the (dry) years 1981-85, the upper and lower troposphere feature weaker air flows with a stronger Africa easterly jet (AEJ) and a shift southward in the main weather patterns and multiple dynamical parameters. In contrast, during the (wet) years 1998-2002, the pattern of the troposphere's upper and lower levels is influenced by strong flows that align with a weak AEJ and a strong northward movement of the zonal and meridional cell circulations. The convective activity in West Africa's tropical region is dynamically affected by intense upper-level divergence in the TEJ region linked to ascending flows in the lower atmosphere, where the disturbances are formed. These fluctuations might be linked to contrasts in the monsoon layer between wet and dry years.

Shekhar and Boos, (2017) disproved the idea that the recent increase in Sahel rainfall is due to a stronger shallow meridional circulation (SMC) over the Sahara, instead they posit that a stronger SMC inhibits Sahel rainfall, perhaps by advecting midtropospheric warm and dry air into the precipitation maximum. Atiah et al., (2023) reported that the most impactful flood events recorded in South-Western Africa are mainly due to mesoscale convective activity.

Future projections of precipitation variability

This section examines the performance of climate models and reanalysis products in simulating precipitation patterns over the tropics, with a particular focus on West Africa. Accurately projecting the West African Monsoon (WAM) remains challenging due to significant discrepancies across models in simulating the mechanisms driving WAM precipitation changes (Mutton et al., 2024). Global Climate Models (GCMs) are central to understanding climate dynamics. However, they often exhibit systematic bias when compared with ground observations, particularly due to their limited spatial resolution—typically at scales of hundreds of kilometres, which hampers their practical applications (Flato et al., 2013). These limitations are particularly evident in the context of the complex monsoon system. For example, Cai et al., (2018) analysed 30 CMIP5 models' ability to reproduce the Arctic Oscillation (AO) and Arctic Dipole (AD), finding that while most models captured the AO reasonably well in summer, their correlation with the reference dataset (ERA-Interim) was weaker compared to winter simulations. Similarly, models could represent the AD's dipole pattern, but only 20 models accurately reproduced it in the second EOF mode. These discrepancies highlight the difficulty in simulating large-scale climate patterns, which extends to tropical systems like the WAM.

Specific studies on the Atlantic Equatorial Mode (AEM) and its relationship with extreme rainfall events over the Guinea coast reveal additional challenges. Worou et al., (2023) noted that models tend to overestimate rainfall frequency and wet spell duration while predicting an intensification of daily rainfall and a decrease in the duration of wet periods under future scenarios. This shows the need for more precise models for the complex interactions driving precipitation patterns. Akinsanola et al., (2020) found that WAM rainfall variability is expected to increase by 10-28% under global warming, mainly driven by increased atmospheric moisture, consistent with the Clausius-Clapeyron relationship.

Higher-resolution Regional Climate Models (RCMs), such as those from the CORDEX-Africa ensemble, have shown promise in improving simulations of extreme precipitation across West Africa. Olusegun et al., (2022) reported that these models better captured the annual cycle of precipitation indices along the Guinea and Sahel regions, offering more reliable insights for future projections. Similarly, Mutton et al., (2024) identified that decreases in WAM precipitation under uniform ocean warming are linked to dynamic changes in monsoon circulation, emphasising the need for models to capture subtle shifts in moisture gradients and atmospheric circulation.

However, improving model accuracy is not solely about refining rainfall patterns. Scaife et al., (2019) suggest that advancing our understanding of inter-basin rainfall connections is crucial for enhancing predictive skills. However, efforts to reduce rainfall biases may only significantly improve seasonal forecasts with realistic simulation of these teleconnections. For instance, Konda and Vissa, (2023) proposed that refining GCMs' representation of Indian Summer Monsoon (ISM) variability could be achieved by improving ocean-atmosphere feedback mechanisms and accounting for orographic influences. Similarly, Darshana et al., (2022) evaluated 40 CMIP6 models, and found that only 12 accurately simulated ISM rainfall patterns linked to the Indo-western Pacific Ocean capacitor (IPOC) mode, indicating the difficulty in capturing these teleconnections. Focusing on West Africa, Annor et al., (2023) analysed the West African Monsoon System (WAMS) using eight CMIP6 models, showing that while the general dynamics of the West African Heat Low (WAHL), West African Heat Band (WAHB), and West African Rain Band (WARB) were represented, there were significant biases. The WAHL was too weak in most models, while the WAHB and WARB were positioned too far south, leading to inaccuracies in precipitation simulations. This highlights a key area for improvement in climate modelling for West Africa.

Moreover, Monerie et al., (2023) demonstrate that much of the uncertainty in Sahel precipitation projections up to 60% is driven by future temperature changes in the North Atlantic and Euro-Mediterranean regions. Addressing this uncertainty is essential for refining Sahel precipitation forecasts. At the same time, the representation of Atlantic zonal modes and their interaction with WAM precipitation has yet to be fully explored in CMIP6 models, which is crucial for understanding variability in WAM rainfall. Long-term projections suggest significant changes in West African precipitation patterns. Gaetani et al., (2020) project the emergence of a new climate state in the Western Sahel, with reduced wet day occurrences between 2015 and 2036, while increased occurrences of very wet days are likely in the Eastern Sahel by 2050. Biasutti and Sobel, (2009) further predicted that Sahel rainfall patterns would shift, with the rainy season becoming shorter and starting later due to rising greenhouse gas concentrations.

Perception of climate variability and changes

Perception, as shaped by various psychological, social, and environmental factors, is a key determinant of adaptation (Ezeh et al., 2022; Yaro, 2013). The intricate nature of how different communities and individuals perceive climate variability and change is a crucial aspect of this thesis. This understanding is not only fascinating but also essential for developing effective adaptation strategies.

Despite a growing awareness of the need for adaptation to extreme precipitation, several constraints hinder the implementation of effective risk-reduction strategies in West Africa (Ikeme, 2003; Mubiru et al., 2018). At different spatial units, perceptions of climate risks are often shaped by immediate, short-term survival concerns, leading to coping mechanisms focusing on reactive rather than proactive adaptation (Akponikpè et al., 2010; Aldunce et al., 2024; Amadou et al., 2022; Attoumane et al., 2022; Bojang et al., 2020).

At the policy level, there is a significant gap between national adaptation plans and their implementation at the local level. While governments in West Africa have adopted frameworks aimed at reducing disaster risks, such as the African Union's Programme of Action for the Implementation of the Sendai Framework, the effective deployment of these strategies is often constrained by limited coordination between stakeholders, lack of funding, and poor infrastructural development (Nemakonde & Van Niekerk, 2023). The disconnect between national climate strategies and local realities is a significant constraint, as local perceptions of risk often need to be incorporated into policy planning, reducing the efficacy of adaptation measures. To overcome these constraints, it is crucial for researchers and policymakers to advocate for more inclusive adaptation approaches that integrate local knowledge, improve access to climate information, and enhance institutional capacity to implement risk reduction strategies. Their role in this advocacy is key to the successful integration of local knowledge in adaptation strategies.

Risk reduction strategies to extreme wet and dry conditions in West Africa

West Africa faces extreme wet and dry conditions caused by climate variation and human-induced climate change that result in hazards to agriculture, water, and socioeconomic conditions. The situation exposes the region to climatic extremes, mainly because it greatly relies on rain-fed agriculture (Sultan et al., 2017). Seasonal precipitation variability can adversely affect agricultural output and food security, which is essential for this region's demographic and economic stability (Quenum et al., 2021). Consequently, managing these risks necessitates using adaptation and risk reduction measures such as structural and non structural strategies.

According to Quenum et al., (2021), the seasonal fluctuation of the WAM has put West Africa in a precarious position of either experiencing very little rainfall or excessive flooding. West Africa being an agrarian region, their proposed solutions include: crop management to combat such climatic conditions through crop rotation and selecting heavier seeds that are drought-resistant or planting crops during a different season as well as changing planting dates to further correspond to these extremes. Closely linked to the agricultural adaptation strategies, Sy (2023) suggests that in countries like Senegal, community based adaptation strategies should be prioritised. Various indigenous practices like rainwater management and soil management practices like agroforestry have been used effectively in the management of both drought and flood conditions. Community involvement is another way of ensuring that the measures implemented to adapt to the changing climate are resourceful and relevant. Sy's research also highlights the success of community-driven early warning systems and disaster preparedness initiatives, which are more effective than externally imposed solutions. This community-based approach promotes ownership and ensures that adaptation measures are culturally relevant and environmentally sound (Sy, 2023).

Another aspect of adaptation strategy and resilience to climate change in West Africa is water management, especially where there are droughts and floods, which are recurrent in most parts of the region. Savino et al., (2023) opine that water resource management requires incorporating information from climate data into hydrological models. These models can be used to decide where to build a new reservoir or which irrigation systems to employ, as well as the plans for water distribution. Thereby, different communities can mitigate the water deficit during seasons of drought and water surplus during floods. (Savino et al., 2023) stressed that these innovations are critical for maintaining production efficiency and meeting food demand in a changing climate. The possibility of increasing drought resistance has also been associated with using the agroforestry system. A study by Ayanlade et al., (2023) buttress the importance of reforestation (using trees in agricultural operations) to prevent soil moisture loss and further reduce soil erosion. In arid zones such as the Sahel, shelterbelts and other forms of agroforestry minimise soil evaporation and enhance the rainfall retention necessary for long-term agricultural productivity. The authors also note that agroforestry improves yields and moderates drought risks, making the system more sustainable and resilient to climatic changes (Ayanlade et al., 2023). It is also important to include climate-smart agriculture (CSA) to avoid the effects of extreme weather. Antwi-agyei et al., (2023) proposition is worthwhile. These scholars underscore that CSA practices, which integrate local ecological knowledge and technological advancement, have been effective, particularly in rural communities in Ghana. Meagre control and water management techniques like drip irrigation and the use of crops that are resistant to flooding are some of the frameworks of CSA that enable farmers to adapt to harsh weather conditions. The authors also opine that incorporating CSA practices within the national agriculture policies will expand the impact of enhancing resilience to climate variability across the West African region (Antwi-agyei et al., 2023).

Based on the reviewed literature, several gaps exist in understanding the dynamics of West African Summer Monsoon (WASM) precipitation variability and adaptation strategies:

The influence of regional-scale dynamics on extreme precipitation events is still an ongoing research area and needs to be better understood. While general patterns are identified, the specific contributions of different atmospheric processes, such as vertical motion and moisture transport, need further exploration (Nie et al., 2020). There is a limited understanding of the non-stationary nature of teleconnections between West African precipitation and global SSTs. More research is needed to quantify how these relationships change over time and impact WASM precipitation (Losada et al., 2012; B. Wang et al., 2008; Worou et al., 2021). The impact of land use and land cover changes, including reforestation and deforestation, on WASM dynamics and precipitation patterns requires further investigation. Furthermore, the complex feedback between land surface conditions and atmospheric processes has not been fully understood and simulated in climate models (Camara et al., 2022; Nogherotto et al., 2013).

The role of aerosols and particulate matter in modifying precipitation patterns is an open question, especially the mechanisms through which aerosols influence cloud formation, radiation balance, and convective processes (Ajoku et al., 2020; Marvel et al., 2020).

Current climate models and reanalysis datasets exhibit significant biases and uncertainties in simulating WASM precipitation. Improved simulations of inter-basin teleconnections and atmospheric processes in climate modes are needed for enhanced understanding and prediction of WASM variability (Quagraine et al., 2020; Mutton et al., 2024). The drivers of extreme precipitation events and their variability on intra-seasonal and interannual timescales must be better understood. More research is needed to link these events to specific atmospheric and oceanic conditions (Bliefernicht et al., 2022; Rufus et al., 2013).

SST impacts on West African precipitation variability are much more complex and non-linear than initially thought; different factors operate on different timescales and interact. To better understand the links between West African precipitation and the broader tropical climate, the thesis argues that a renewed focus on the Walker Circulation is important given the key role played by zonal SST gradients, zonal winds, and vertical velocity in West African climate.

The interaction between climate modes, such as ENSO, IOB, and the Atlantic Niño, and their combined effect on WASM variability is not fully explored. Understanding these interactions could improve seasonal forecasting (Rodríguez-Fonseca et al., 2015; Roy et al., 2024). The feedback mechanisms between atmospheric circulation patterns, such as the African Easterly Jet and the Tropical Easterly Jet, and precipitation are not fully elucidated. More research is needed to understand how these jets interact with surface processes and influence rainfall (Akinsanola & Zhou, 2020; Nicholson & Grist, 2003).

There is need for high-quality meteorological and hydrological data in West Africa as its lack hinders comprehensive analysis. Improved data collection and sharing are essential for advancing research in this region (Sougué et al., 2023). Addressing these gaps will require improved observational data, enhanced modelling capabilities, and focused studies on specific regional and inter-regional processes influencing WASM precipitation variability. Thus, this study seeks to advance the literature on West African extreme precipitation dynamics by showing the joint sea surface temperature indices that drives large scale wet and dry conditions in the region and projected trend in monsoon seasons precipitation evolution in CMIP6 model under different scenarios.

Theoretical Framework

The theoretical frameworks relevant to understanding precipitation extremes over West Africa encompass multiple disciplines, ranging from atmospheric science to climate change and environmental systems theory. These frameworks are essential for guiding the study's approach to analysing extreme precipitation events' evolution, drivers, and projections. Key frameworks and theories include the Climate-Impact Drivers, and Climate risk management.

Climate-Impact Drivers (CIDs) Framework

The Climate-Impact Drivers (CIDs) framework encompasses the physical climate conditions that directly influence socio-ecological systems, serving as critical pathways through which climate variability and change manifest their effects. These drivers include a variety of phenomena, such as temperature extremes, precipitation variability, droughts, floods, and sea-level rise (Ruane et al., 2022; Scafetta, 2024). Each of these elements plays a significant role in shaping the interactions between natural ecosystems and human systems, ultimately influencing the risk of adverse outcomes, including crop failures, water scarcity, public health crises, and economic losses (Ranasinghe et al., 2021; Ruane et al., 2022). CIDs can be categorised into distinct types based on their specific characteristics. Temperature-related drivers encompass heatwaves and cold spells, while water-related drivers include heavy precipitation events and drought conditions. Wind-related drivers, such as storms and cyclones, and ocean-related drivers, including sea-level rise and ocean acidification, are also critical components of this framework (Ranasinghe et al., 2021; Ruane et al., 2022). The impacts of these drivers are not uniform; they are modulated by the exposure and vulnerability of the systems affected, as well as their capacity to adapt to changing conditions. Therefore, understanding the nuances of these drivers is essential for predicting how climate impacts will evolve in different contexts.

In West Africa, specific CIDs play pivotal roles in determining the region's climate resilience and vulnerability. Key drivers include variations in precipitation linked to the West African Monsoon (WAM), extreme temperature events, and persistent droughts. These factors have profound implications for agriculture, water resources, public health, and the livelihoods of millions (Dibi-Anoh et al., 2023; Ekwezuo & Ezeh, 2020; Nnamchi & Li, 2016; Sultan et al., 2017). The region's high reliance on rain-fed agriculture renders it particularly susceptible to shifts in precipitation patterns. Even minor changes in the timing or intensity of rainfall can precipitate severe food and water insecurity, exacerbating existing socioeconomic challenges.

The WAM is particularly influential as it governs the region's seasonal rainfall patterns. Disruptions to the WAM can lead to significant fluctuations in precipitation, resulting in either excess rainfall, which can cause flooding, or insufficient rainfall, leading to drought. Such variations can have cascading effects on food production systems, potentially triggering widespread crop failures and threatening food security across West African countries. The interannual variability of the WAM complicates these challenges further, as farmers must adapt their planting schedules and crop choices to the uncertainties inherent in climate patterns (Sultan et al., 2017). Effective management of CIDs in West Africa necessitates a comprehensive understanding of the underlying drivers. This understanding is crucial for improving predictions and projections of climate impacts, which can inform appropriate adaptation and mitigation strategies. For example, enhancing the accuracy of climate models that incorporate the dynamics of the WAM can provide valuable insights into potential future scenarios. Researchers and policymakers can better assess the region's climate risks and develop targeted interventions to strengthen resilience in the region. Also, considering the adaptive capacity of various socio-ecological systems is vital. Adaptive capacity refers to the ability of communities and ecosystems to adjust to changing climate conditions, including implementing innovative agricultural practices, developing water management systems, and enhancing public health initiatives. Building adaptive capacity requires integrating local knowledge with scientific research, ensuring communities are empowered to respond effectively to climate challenges.

Climate risk management framework

The Climate Risk Management (CRM) framework provides an integrated and holistic strategy to assess, manage, and mitigate the risks of climate variability and change to socio-ecological systems (Brown, 2018). Climate risks arise from the interaction of climate hazards with the vulnerability and exposure of natural ecosystems and human communities (Dolan & Walker, 2004). A systematic CRM framework allows for an in-depth analysis of these risks and guides how to adapt to evolving climate conditions. The framework is critical for reducing potential negative impacts and for leveraging opportunities that arise from climate change. In this regard, a comprehensive CRM strategy necessitates focusing on climate data, risk assessment, adaptation strategies, capacity building, and governance.

Information and knowledge, including climate events, trends, forecasts, projections, and local experience, feed into the decision-making process. Two key assumptions - capacity (resources and skills to act) and incentive (motivation or benefits to act) influence this process. Climate-resilient decisions aim to reduce losses from climate impacts and capitalise on opportunities created by climate change.

Synthesis of these two frameworks and their relevance to this study

The CRM framework begins with identifying and understanding Climate-Impact Drivers (CIDs), which are physical climate conditions directly influencing socio-ecological systems (Tebaldi et al., 2023). CIDs, such as rainfall variability and extreme conditions such as floods and droughts serve as pathways for climate induced disasters that threaten ecological and human systems (Bell et al., 2018). These drivers interact with natural processes and human activities, leading to adverse impacts such as crop failures, public health crises, water shortages, and economic losses (Barendrecht et al., 2024; Mashi et al., 2019; Ward et al., 2020). The impacts of CIDs are highly variable and depend on the vulnerability and exposure of systems and populations. Vulnerability refers to the susceptibility of a system to climate hazards, determined by factors such as socioeconomic conditions, governance structures, and ecosystem resilience (Birkmann, 2007). On the other hand, exposure relates to the degree to which systems and populations are situated in hazard prone area. Vulnerable communities in developing countries, particularly those dependent on natural resources and rain-fed agriculture, are disproportionately affected by climate risks (Sathyan et al., 2018). In the context of West Africa, for example, vulnerability is amplified by socioeconomic challenges, such as poverty, reliance on agriculture, and inadequate infrastructure. Climate risks in this region are driven largely by variations in precipitation due to the West African Monsoon (WAM), extreme temperature events, and frequent droughts (Sultan et al., 2017). The interannual variability of the WAM creates uncertainties for farmers, as changes in the timing and intensity of rainfall can have dire consequences for food production, water security, and livelihoods (Nnamchi & Li, 2016).

Effective climate risk management requires robust risk assessment techniques incorporating climate models and projections. Climate models are critical tools for predicting future climate scenarios, enabling stakeholders to assess the likelihood and magnitude of potential climate impacts. In West Africa, improving the accuracy of climate models that simulate the dynamics of the WAM can lead to better-informed decisions. Enhanced models allow for more reliable predictions of rainfall patterns, drought events, and extreme temperatures, all of which are vital for managing agricultural and water resources (Mishra & Singh, 2011).

Adaptation is central to reducing the impacts of climate risks. Successful adaptation strategies focus on enhancing the adaptive capacity of socio-ecological systems, ensuring that they are better equipped to cope with changing climate conditions. This can involve implementing innovative agricultural practices, improving water management systems, and strengthening public health infrastructure (Iglesias & Garrote, 2015; Mollinga et al., 2007) among others. In West Africa, adaptive capacity is particularly critical due to the region's high vulnerability to shifts in precipitation. Farmers, for instance, need to adopt climate-resilient crop varieties, adjust planting schedules, and utilise irrigation systems that conserve water. Local governments can also implement early warning systems for droughts and floods, reducing the risks associated with extreme events (Pulwarty & Sivakumar, 2014). Adaptation measures that integrate local knowledge with scientific research are more likely to be successful as they build on communities' existing strengths.

Furthermore, effective climate risk management depends on capacity building at all levels, from individual households to governments and international organisations. Capacity building involves developing technical skills, institutional frameworks, and financial resources for implementing climate adaptation and mitigation strategies (Khan et al., 2018). Local communities must be empowered to take action by providing the necessary tools and information to manage climate risks. Governance is another crucial aspect of CRM, involving coordinating policies, regulations, and institutions that facilitate climate-resilient decision-making. Policymakers must ensure that climate risk management is integrated into broader development strategies, particularly in vulnerable regions. For instance, in West Africa, governments must collaborate with international organisations, the private sector, and local communities to create policies that enhance climate resilience while addressing socioeconomic challenges (Palazzo et al., 2017).

CHAPTER 2: MATERIALS AND METHODS

2.1 The Study Area

2.1.1. Location

West Africa is defined as extending from Latitudes 2 to 25 degrees north and Longitudes 20°W to 15°E of the Greenwich meridian (Fig. 1).

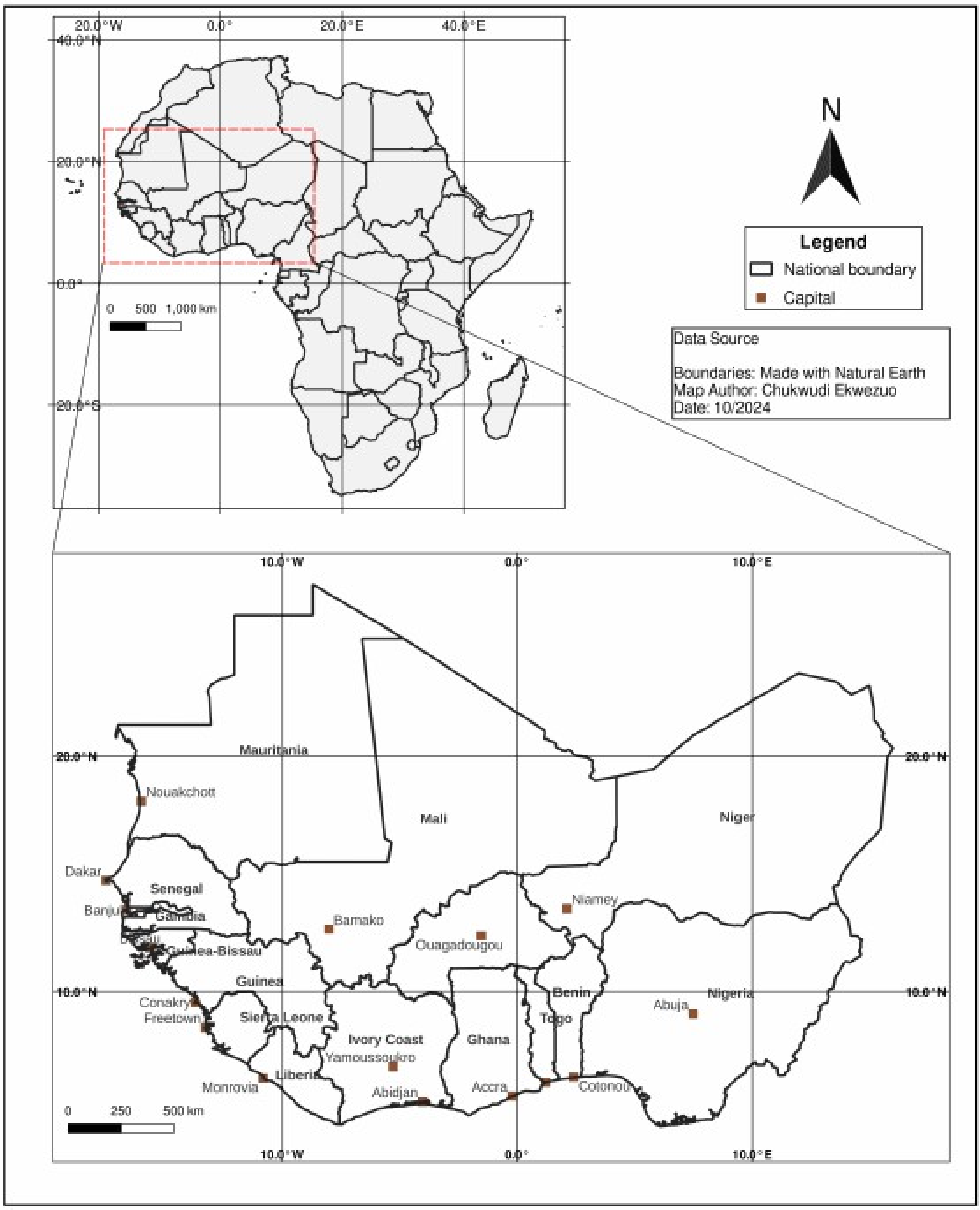

Figure 1: *Africa showing the West African region enclosed in a rectangle*

Some sections of Chad, Cameroon, and the Central African Republic are all included in the delineation. The Study area is bounded to the North by Morocco, Algeria and Libya, in the East by the republics of Chad and Cameroon and in the West and South by the Atlantic Ocean. The entire land area is 7,492,597 Km^2 (2,892,908 sq. miles).

2.1.2 Relief and Drainage

The exposure and vulnerability of people, infrastructure and regions to extreme climate events (meteorological hazards) is related to the relief and drainage of the area. West Africa's relief features diverse landscapes, ranging from coastal plains to rugged highlands and plateaus. It's relief mainly consists of an undulating low plateau below 500 metres above sea level, fringed on the west and south by a coastal plain; this plain is widest in Senegal, the southern Cote d'Ivoire, the Niger delta and the lower valleys of the Volta and Niger rivers (Fig. 2).

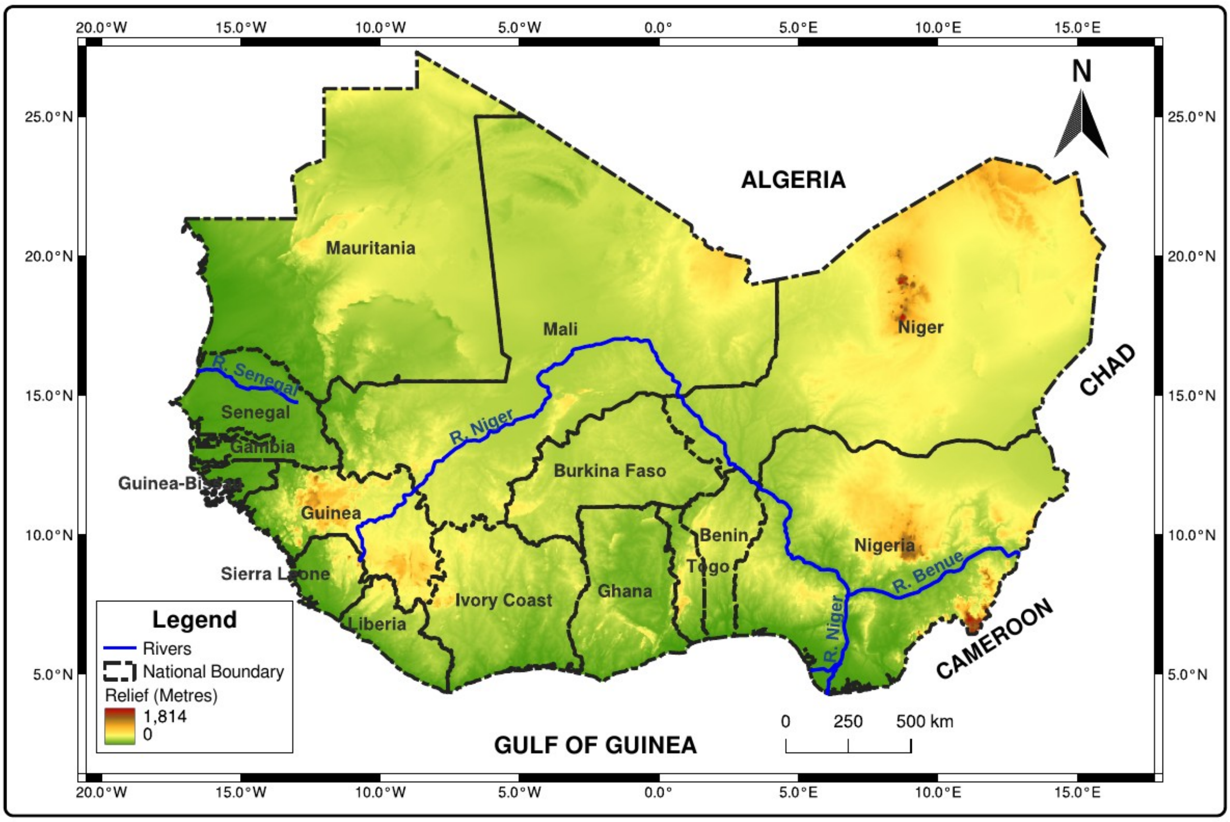

***Figure 2**: Relief and major drainage of West Africa*

There are some isolated highland areas above 500 metres and some peaks exceed 1000 metres. The most dominant are Nimba Mountain (1380 m), Fouta Djallon (1537 m), Guinea Highland (1656 m), Sierra Leone Mountain (1945 m), Jos Plateau (1800 m), Mandara Mountain (2046 m), the Saharan uplands of Air (1850 m) and the Plateau of

Djado (1120 m) in northern Niger. The region is drained by three major river systems. The Long Rivers (the Niger, Volta, Gambia, and Senegal) pass through several countries before draining into the Atlantic. The Short Rivers: these rivers are short, slow-flowing, and empty their waters into the Atlantic too. Examples include the Densu River, Imo River, Benin River, Ogun River, Bandama River, and Cestos River, amongst several others. And finally, the inland drainage rivers that empty into Lake Chad without appearing to flow into the ocean. The Hadeija, Yobe, Logon, and Shari rivers flow into Lake Chad and are classified as inland drainage.

2.1.3. Climate

From a moisture perspective, West Africa is divided into two broad ecological zones - the dry zone and the humid zone. These two broad zones can further be divided into five sub-regions based on the combined spatial distribution of precipitation and vegetation (Comité Permanent Inter-états de Lutte contre la Sécheresse dans le Sahel (CILSS), 2016). The dry zone includes part of the Sahara (which covers about 22% of the area of the sub-region), along with the Sahelian and Sudanian phytogeographic areas. The ecosystem is dominated by steppe vegetation, thorny bush cover, and open savanna woodlands. The humid zone presents varied ecosystems consisting of savanna, semi-deciduous tropical forest, and tropical rain forest.

The rainfall patterns in this region are determined by the monsoon system and topography. The region encompasses three major climatic areas and several climate transition zones that cross the region from east to west, forming virtually parallel strips from the Tropic of Cancer to the Equator. In the north of the study area, above latitude 18◦N, the climate is either semi-desert, northern Sahelian type, or desert. The rainy season is concentrated over one or two months, and the average annual rainfall varies from 300 mm to less than 100 mm. Further south, the tropical climate is characterized by very distinct dry and wet seasons. The length of the wet season and the amount of annual rainfall allows for distinguishing three types of tropical climates. The Sahelian, or semi-arid tropical climate, this lies between latitudes 12° and 18°N; here the dry season lasts seven to ten months, and the average annual rainfall varies between 300 and 700 mm. The Sudanian, or pure tropical, climate corresponds to a dry season of five to six months, with the average annual rainfall between 700 and 1000 mm (1200 mm on the Senegalese coast). The Guinean, or transitional tropical, climate corresponds to a shorter dry season, from four to five months, and an average annual rainfall above 1000 mm. The transitional equatorial and equatorial climates lie below 10◦N over the countries of the Gulf of Guinea.

The annual precipitation are abundant, generally above 1000 mm with a bimodal distribution (two dry seasons). However, the rainfall distribution is quite heterogeneous in this area. The climate is very humid, with an annual rainfall above 2500 mm in the coastal regions of Guinea, Nigeria and Cameroon. By contrast, the Dahomey Gap, which includes parts of Ghana, Togo, and Benin and has an annual rainfall total of 1000 to 1200 mm, and is abnormally dry for the region (Araujo Bonjean et al., 2023; Ekwezuo et al., 2020), thus have distinct characteristics.

2.1.4 Landcover and Landuse

West Africa exhibits diverse vegetation and land cover types, influenced by its varied climate (moisture availability), topography, and human activities, which collectively play crucial roles in modulating precipitation variability across the region. The vast expanse of tropical rainforests along the Guinea coast and into the interior supports high biodiversity and contributes to regional moisture recycling through transpiration and evapotranspiration processes. The transition from semi-arid Sahelian savanna to more humid Sudanian savanna and wooded savanna further south influences the distribution and intensity of rainfall, as vegetation cover affects surface albedo, heat fluxes, and atmospheric stability. Additionally, coastal mangrove forests and wetlands play vital roles in regulating local microclimates, enhancing atmospheric moisture, and mitigating coastal erosion, thereby influencing precipitation patterns in adjacent coastal regions. Human-induced land cover changes, such as deforestation, urbanization, and agricultural expansion, further alter surface characteristics, impacting local and regional climates, including precipitation regimes.

2.1.5. Historic floods and drought events

According to EM-DAT (2023), the West African region do experience flood and drought events. Reported cases of flood and drought disasters in different West African countries from 1950 to 2022 is shown in Figure 3.

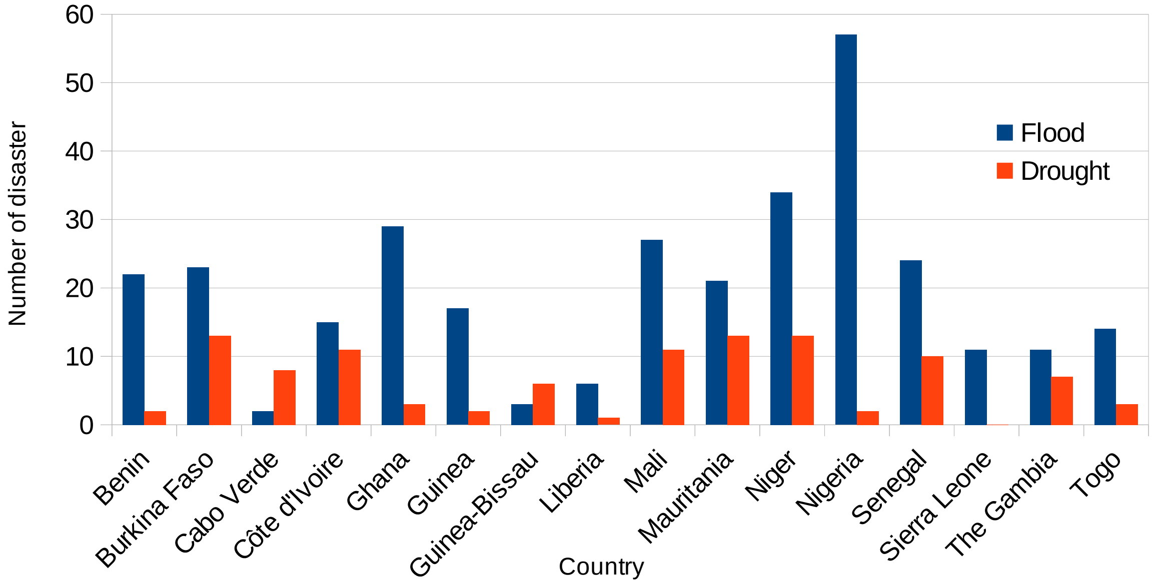

Figure 3: *Frequencies of flood and drought disasters in different West African countries from 1950 to 2022*

Source: EM-DAT (2023)

A total of 316 (105) flood (drought) disasters had been reported over the region, with Nigeria, Niger, Ghana, Mali, Senegal, Burkina Faso, Benin and Mauritania accounting for 75% of flood disasters in the region. Likewise, Niger, Burkina Faso, Mauritania, Mali, Côte d'Ivoire, Senegal and Cabo Verde accounted for 75.24% of the drought disasters in the region. Niger, Mali, Burkina Faso, and Senegal are the most exposed countries to flood and drought disaster in West Africa. While Nigeria and Niger are the most exposed and vulnerable to flood disaster.

2.1.6 Population

West Africa is home to a diverse and rapidly growing population, characterized by significant variations in population density, sex ratio, livelihood options, and other important demographic characteristics. The population density ranges from almost no residents per km^2 in desert areas to as high as 6,871 per km^2 in Lagos, with a regional average density of 66 persons per km^2. In 2023, the overall population was around 492,536,717 with Nigeria accounting for the vast majority (223,804,632) (https://www.worldometers.info/). The region accounts for 6.22% of the total world population and is demographically one of the fastest-growing on the African continent. The livelihood options in West Africa are diverse, reflecting the region's rich natural resources, agricultural potential, and growing urban economies. While agriculture remains a primary source of livelihood for many, especially in rural areas, urbanisation and industrialisation are driving shifts towards non-agricultural sectors such as manufacturing, services, and informal trade. However, challenges such as unemployment, underemployment, and poverty persist, particularly among youth and marginalized populations, necessitating targeted interventions to promote inclusive growth and sustainable development. Also, the region's youthful demographic profile, with a large proportion of the population under the age of 25, presents both opportunities and challenges for the social and economic development of the region.

2.2. Data

2.2.1. Data sources

The data sources are grouped into two: primary and secondary sources. The primary data was obtained from questionnaires survey and Key Informant Interviews. These primary data include answers to the various questions on dominant extreme precipitation events, causes, impacts, vulnerability and coping strategies among others. While secondary sources include climate data from respected repositories and archives.

2.2.1.1. Primary data

The survey were conducted using a semi structured questionnaire instrument. The survey aimed to assess the respondents' perception and understanding of the dominant pattern of rainy season precipitation variability in the last five years, and adaptation responses/constraints to adaptation in their area of residence. The choice of the last five years for assessing rainy season precipitation variability is justified based on its relevance to respondents' memory recall, the immediacy of recent climate variability impacts, and the policy relevance of short-term climate trends. Research has shown that individuals recall and report recent weather and climate events more accurately than those from the distant past, reducing recall bias (Demski et al., 2017; Howe et al., 2019). and making the findings more applicable for current and future policy interventions.

Additionally, open-ended interviews with selected informed stakeholders were conducted to further explore the perceived challenges of extreme wet and dry conditions in West Africa. The questionnaire was administered mainly through smartphones via the Kobo Collect application, which is a module of Kobo Toolbox (https://www.kobotoolbox.org).

The application is used for questionnaire set-up, data collection, management, analysis and visualization. Through this toolbox, the data collected in the field were directly submitted to the server (with or without internet connection) at the time of collection. Online surveys has been employed in several studies (Abeling, 2015; Fekete & Sandholz, 2021; Fonseca et al., 2023; Freihardt & Buchs, 2023) and confirmed to be very robust and reliable. The survey took place over 10 days, from September 20 to September 30, 2024 simultaneously across nine (9) purposively selected countries in West Africa. The countries are listed in section 2.3.2. Objective 5.

Ethical Considerations

Surveys are increasingly raising ethical concerns, including people's right to privacy, the need for informed permission, and the obligations that come with releasing personal information during a survey. As a result, these concepts have to be considered from the beginning while designing the survey questions. Respondents were informed of the nature of the research before agreeing to participate in the survey, and their agreement was obtained by doing so. Furthermore, anonymity was maintained throughout the study because the survey instrument contained no names or identifying information about the respondents.

2.2.1.2. Secondary data

2.2.1.2.1. Observed data

Gridded observational monthly precipitation product from the Climate Research Unit (CRU) TS v. 4.07 (Harris et al., 2020), that covers only lands at a resolution of 0.5° and which spans from 1901 to present was also used. The CRU observational data sets have been extensively used in climate research in West Africa (e.g. Diasso & Abiodun, 2017; Nnamchi & Li, 2011; Srivastava et al., 2019; Worou et al., 2020)) and in evaluation of previous Coupled Model Intercomparison Project phases (CMIPs) (Wang & Clow, 2020). Furthermore, the Hadley Centre global Sea-Ice and Sea Surface Temperature (HadISST1) dataset (Rayner et al., 2003), which is a blend of historical SST and modern SST observations from ships, buoys, drifters and sea ice observations, partly from historical ship-and air-borne and partly from satellite data with a 1.0° x 1.0° spatial resolution on a cartesian grid was also analysed.

2.2.1.2.2. Reanalysis data

Monthly vertically integrated moisture divergence and horizontal winds at pressure levels from the fifth generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA5) (Hersbach et al., 2020) were also used. The data has a spatial resolution of 0.25° x 0.25° and spans from January 1940 to the present (Hersbach et al., 2020). Furthermore, velocity potential and divergent winds were estimated from the ERA5 horizontal wind components using the centred finite differences method. The 200 hPa level captures upper-level divergence and convergence associated with tropical convection and the Hadley circulation, while the 850 hPa level effectively represents low-level divergence and convergence, crucial for understanding moisture transport and the development of tropical weather systems (Choi et al., 2016; Hermawan et al., 2022).

2.2.1.2.3. CMIP6 model data

We use precipitation outputs of the first members (r1i1p1f1) from 24 models that participated in phase six of the coupled model intercomparison project (CMIP6) for historical (1850-2014) and future (2015-2100) time frames (see Table 1). This datasets was obtained from https://esgf-data.dkrz.de/projects/cmip6-dkrz/. We focus on four shared socioeconomic pathway (SSP), with SSP5-8.5 representing high mitigation challenge and low adaptation challenge, resulting in high emissions (O'Neill et al 2017). The SSP scenarios provide information on possible development trajectories based on emissions of greenhouse gases, aerosols and changes in land use that led to climate change (van Vuuren et al., 2011). The other three SSPs assume some level of mitigation of greenhouse gas emissions, and are useful for estimating how various mitigation strategies might ameliorate climate change (Tebaldi & Neill, 2020). The multi-model ensemble mean (MME) of the good CMIP6 models were computed and used in the study. The motivation for using MME was based on the argument that MME is superior to individual models (Ajibola et al., 2020; Nnamchi & Diallo, 2024; Nooni et al., 2023).

Table 1: CMIP6 models used in this study

S/N	Model name	Modelling institution	Resolution(Lon. X Lat.)
1	ACCESS-CM2	CSIRO, Australia	192 X 144
2	ACCESS-ESM1-5		192 X 145
3	BCC-CSM2-MR	BCC, China	384 X 192
4	CAMS-CSM1-0	CAMS, China	320 X 160
5	CanESM5	CCCma, Canada	128 X 64
6	CESM2	NCAR, USA	144 x 96
7	CESM2-WACCM	NCAR, USA	144 x 96
8	CMCC-CM2-SR5	CMCC, Italy	288 X 192
9	CMCC-ESM2		
10	EC-Earth3-Veg	EC-Earth Consortium, Europe	512 X 256
11	FGOALS-f3-L	CAS, China	180 X 80
12	FGOALS-g3	CAS, China	180 X 80
13	FIO-ESM-2-0	China	320 × 384
14	GFDL-ESM4	NOAA-GFDL, USA	288 X 180
15	IITM-ESM	CCCR-IITM, India	192 X 94
16	INM-CM5-0	INM, Russia	180 X 120
17	KACE-1-0-G	NIMS-KMA, Republic of Korea	192 X 143
18	MIROC6	MIROC, Japan	144 X 143
19	MPI-ESM1-2-HR	MPI, Germany	384 X 192
20	MPI-ESM1-2-LR		192 X 96
21	MRI-ESM2-0	MRI, Japan	320 X 160
22	NESM3	NUIST, China	192 X 96
23	NorESM2-LM	NCC, Norway	144 X 96
24	NorESM2-MM	NCC, Norway	288 X 192

The gridded datasets were remapped to a common spatial resolution using bilinear interpolation (BIL) method and implemented using Climate Data Operator software. BIL is a simple and efficient method for interpolating data values in two dimensions. This method is easy to use when the source and destination grids are rectilinear.

Nevertheless, this method is not suitable for curvilinear and unstructured grids. It is commonly used in remapping climate models.

2.3. Methods

The analysis method for each of the stated objectives of the study is presented. This is to guide our understanding of how to address each objective. The study adopts a hybrid diagnostic approach to climate risk assessment (Jones & Preston, 2011), where both top-down and bottom-top approaches were adopted. These approach enable us to maximise their advantages, while minimising their individual weaknesses by using the outputs from the top-down approach to feed into the bottom-up approach.

2.3.1. Period of study

This study specifically focused on the summer monsoon months of June-July-August-September (JJAS). Cumulatively, this period accounts for more than 58% of the annual precipitation in the Guinea coast and 84% in the Sahel domains of West Africa respectively (Worou et al., 2020). Also, in some specific analysis, the months are increased or joined to form a single season. Furthermore, various time periods were used in this analysis and they are summarised in Table 2 and grouped into two main categories: the historical and future periods.

Table 2: *Periods analysed in the study*

	Description	**Period**	**Years**
Observed/Historical	Observed	1950-2022	73
	Dry period	1963-1992	30
	Wet period	1993 - 2022	30
	Historical	1950 - 2014	64
Future	Near future	2020-2059	40
	Far future	2060 -2099	40

2.3.2. Statistical analysis

In this section the statistical techniques employed in answering the research question posed earlier in the introduction chapter are presented for each of the specific objectives.

Objective 1

The mean statistic is used in the study to determine the mean state of precipitation in the study area between 1950 and 2022. The start year was chosen because there were limited and or low density meteorological observations in the region before 1950, leading to sparse data points in gridded precipitation products (Pomposi et al., 2020), in recent years meteorological observations have increase. However, since 1990, difficulty in obtaining Gauged data from National Meteorological Agencies have increased less attention in Climate research (Nicholson, 2013). The mean annual cycle and monthly mean precipitation for the monsoon months (June-September) over West Africa is computed as:

$$X=\frac{1}{N}\sum_{i-1}^{n} xi \qquad (1)$$

Where; *X* is sample mean, *N* is number of observation, *xi* is individual grid points for *i*=1, 2, 3....n.

Domain-averaged precipitation for a given time period was calculated using the Thiessen polygon method.

$$\overline{A}=\sum_{1}^{n} Xi\frac{Ai}{A} \qquad (2)$$

Where; $\overline{A}$ is domain average, *X* represents the climate variable in a given time period at grid stations *i*, and *Ai/A* is the weightage factor.

The standard deviation was used to show the absolute variability in the given climate variable (precipitation).

$$s=\frac{\sqrt{\sum_{i=1}^{n}(x-\overline{x})^2}}{n-1} \qquad (3)$$

The standard deviations are a measure of the degree of interannual variability of precipitation at each grid point for each month and for each year relative to the mean for the temporal analysis.

The long-term trend in precipitation was computed using the linear least square fit equation. This method involves applying a linear equation to the climate dataset in order to establish a relationship between the dependent variable (precipitation) and the independent variable (year). It is calculated as:

$$Y=a+bX \qquad (4)$$

where Y is the dependent variable, X is the independent variable, b is the slope of the line, and a is the intercept constant. A positive and negative value of b indicates that the data tend to increase or decrease with time, respectively.

The Student's t-test was used to determine areas where the linear trends significantly differ from zero (mean) at the 5% significance level.

Three single changepoint detection methods were employed to identify periods of abrupt shift in phase in the precipitation time series. They are the Pettitt test, the Buishand range test, and the standard normal homogeneity test. A brief description of these methods is presented below:

Pettitt's test (Pettitt, 1979) is commonly used to detect single change points in time series with continuous data. In this test, the null hypothesis (H_0), such that no change exists in the time series, is tested against the alternative hypothesis (H_1) with changes in the mean.

$$X_E = max_{1 \le d \le n} |X_d| \qquad (5)$$

Where X_d is calculated as:

$$X_d = 2\sum_{d}^{i=1} ri - d(n+1), d = 1,2,3,4, \ldots. n \qquad (6)$$

n is the number of years, and ri is the rank of the recorded number $i_{th.}$ The significance level at α = 0.05 (95%) was also used in this test.

The Buishand range test (Buishand, 1982) detects shifts in the mean of any given time series by comparing the cumulative deviations from the mean before and after the times of discontinuities. It is calculated as:

$$R_b = \frac{max\, S_k - min\, S_k}{\sigma}, where\, S_k = \sum_{i=1}^{k} (x_i - \hat{x}) \qquad (7)$$

Here, the *p* value is considered with a Monte Carlo simulation by m replicates.

Standard Normal Homogeneity Test (SNH) (Alexandersson, 1986) compares the mean of the first *n* observations with the mean of the remaining (*n*–k) observations with *n* number of data points.

$$T(K) = K\bar{Z}_1 + (n-k)\bar{Z}_2, K = 1,2,3, \ldots.. n \qquad (8)$$

$$\bar{Z}_1 = \frac{1}{n}\sum_{i=1}^{k} \frac{(Yj - \bar{Y})}{S} \qquad (9)$$

$$\bar{Z}_2 = \frac{1}{n-k} \sum_{i=k+1}^{k} \frac{(Yj - \bar{Y})}{S} \qquad (10)$$

$$S = \frac{1}{n} \sum_{i=1}^{N} (Yj - \bar{Y})^2 \qquad (11)$$

Where Yj is the observed value, $\bar{Y}$ is the mean, and S is the standard deviation of the series.

The value of T(k) approaches the maximum value closer to year k=K if a stop occurs in any year K. The test is explained by:

$$T_o = max_{1 \le k \le n} T(k) \qquad (12)$$

The Pettitt test is a non-parametric test and does not require the assumption of a normally distributed time series; the opposite is true for the Buishand range test and Standard Normal Homogeneity Test (SNH) (Ankrah et al., 2023). These tests recognise shifts in the time series and their corresponding years of change.

The spatial trend for the historical period was analysed for three different periods: the whole period (1950 to 2022), the drier period (1963 to 1992) (Le Barbé et al., 2002), and the more recent period (1993 to 2022) (Ekwezuo et al., 2024; Tefera et al., 2025). These periods ensure the various changing representation of hotspots (i.e., where significant increases or decreases in precipitation have occurred), thereby providing insights into the regional dynamics of precipitation variability in the region during the four monsoon months.

To understand the evolution of the major modes of precipitation variability over the region, three key analytical methods were employed, and they are season reliant empirical orthogonal function analysis, regression analysis, and composite analysis. Prior to employing these methods, the precipitation dataset was detrended to mitigate the potential signal of anthropogenic climate change, and standardised anomalies (except where stated otherwise) were calculated with respect to the considered period in order to eliminate the problem of scale effect.

The season-reliant empirical orthogonal function (S-EOF) method (Wang & An, 2005) was used to detect month- and region-dependent anomalies and their interannual variability. S-EOF is a more effective method for capturing seasonal variations and evolving patterns than classical EOF analysis (Nnamchi et al., 2017; Wu et al., 2009; Xie & Zhou, 2017). It can detect temporal variations and trends that traditional EOF may overlook, making it useful for researching phenomena with strong seasonal cycles. The obtained modes were evaluated for statistically significant separation based on the North rule (North et al., 1982) at a 95% confidence level; Also, the leading principal components (PCs) derived from the S-EOF was normalised and compared with the domain averages they represent.

The detected leading S-EOF modes principal coefficient time series were regressed onto the standardised precipitation over West Africa in order to detect the associated patterns of precipitation variability during each of the leading modes. Areas of significant wet and dry conditions were identified using a two-tailed t-test.

Definition of extreme conditions

The composite analysis was used to classify and identify periods and patterns associated with extreme precipitation conditions during the study period. This event-focused approach provides insights into the conditions that are most relevant to extreme events rather than averaging across a broader range of conditions as in regression and has been employed in several research studies (Akinsanola & Zhou, 2020; Alexander & Nyasulu, 2021; Batebana et al., 2016; Boschat et al., 2016; Dieppois et al., 2013, 2015; Fontaine et al., 2010; Fontaine & Bigot, 1993; Gaetani et al., 2010; Grist & Nicholson, 2001; Joly & Voldoire, 2009; Martin & Thorncroft, 2014; Mohino, Rodríguez-Fonseca, et al., 2011; Nicholson, 1980; Roy et al., 2024; Shelton & Dixon, 2023; Sun et al., 2022; Suppiah, 1994; Thiam et al., 2023). Extreme wet and dry event years were defined as years in which the relevant time series of the leading principal coefficients derived from the S-EOF analysis is ±1 standard deviation. Furthermore, the composites were computed as the differences between the mean anomalies for wet and dry years, defined as years in which the relevant PC is +1σ and less than -1σ, respectively, divided by 2 (Prado et al., 2021; Zhang & Mann, 2005). The statistical significance of the mean composite difference of event years was tested using a two-tailed t-test.

Objectives 2 and 3

In this objective, the derived leading precipitation variability modes over West Africa were used to identify oceanic basins and atmospheric circulation patterns associated with the occurrence of extreme precipitation (i.e., wet and dry) event years over West Africa using composite analysis technique. Thereafter, correlation analysis was employed to establish the relationship between different monsoon months precipitation time series and the identified significant oceanic basin sea surface temperature. Usually, significant correlation coefficients between the predictand and influencing factors imply the potential to include these factors as predictors (Brown & Ward, 2013).

Based on the dominant SST indices, another composite was computed in order to identify different extreme event years based on a threshold of ±0.5 standard deviation to represent warm and cold phases, respectively.

Definition of relevant indices used in this objective

The relevant precipitation and sea surface temperature-based indices used in this thesis are defined and presented in Table 3.

***Table 3**: Indices used in the study*

Index	Longitude	Latitudes	Reference(s)
Sahel (SH)	10°W - 15°E	10° - 16° N	Biasutti et al., 2008
Guinea coast (GC)	10°W - 15°E	4° - 10° N	Fontaine et al., 1998
Eastern Mediterranean SST (EMS)	5°W – 25° E	30° - 42° N	Diatta & Fink, 2014; Rowell, 2003
Atlantic Meriodional Mode (AMM)	50-10° W 30W - 0°	5 – 15 ° N 5- 15 ° S	Diatta & Fink, 2014; Servain, 1991
Atlantic Nino (ATL3)	20°W - 0°	3S - 3°N	Zebiak, 1993
Niño3.4	90–150°W	5°S - 5°N	Trenberth, 1997
South Atlantic Ocean Dipole (SAOD)	20° W – 10° E 40° W – 10° E	15° S – 0° 25° - 40° S	Nnamchi & Li, 2011; Venegas et al., 1996
Indian Ocean Basin (IOB)	40° – 100° E	20° S –20° N	Ashok & Saji, 2007; Chu et al., 2014

Objective 4

The following statistical-based skill metrics were used in assessing the spatiotemporal simulations of rainy season precipitation climatology over the study area during the historical period by the analysed CMIP6 models. The models were evaluated against CRU data.

Model bias, which indicates the systematic error in simulation of precipitation amount, was calculated. A value of zero indicates no systematic difference between simulated and observed precipitation amounts, whereas a large bias indicates that the modelled precipitation amount largely deviates from the observed precipitation amount. Negative values indicate underestimation, whereas positive values indicate overestimation.

$$Model\,Bias = Model - Observation \quad (13)$$

Where model is the value(s) for CMIP6 model precipitation, and observation refers to precipitation from CRU.

CMIP6 model evaluation agreement refers to the degree to which multiple climate models agree on a particular aspect, such as the sign or magnitude of a projected change or the spatial pattern of a climate variable. It is typically used to assess the robustness of climate projection by evaluating the consistency among different models.

The agreement on the sign of the bias or change at each gridpoint is computed as:

$$A = \frac{Number\ of\ models\ with\ poisitive(negative)change}{Total\ number\ of\ models} X\ 100 \qquad (14)$$

Where A represents the percentage of models in agreement on the sign of the change.

Root Mean Square Error (RMSE), as defined below

$$RMSE = \sqrt{\frac{1}{2}\sum(Obs - Model)^2} \qquad (15)$$

These quantitative measures allow to measure model systematic errors and performance as they provide information at both regional and grid point levels (Agosta et al., 2015; Olusegun et al., 2022; Tanimoune et al., 2024)

Regression analysis was further used to estimate the projected mean temporal change of precipitation under different scenarios and modes of variability. Positive values of the slope indicate a tendency towards a more wetter region, while negative values mean a decreasing (drier) projection.

Objective 5

This study employs a combination of descriptive and inferential statistical techniques to analyse the survey data collected from respondents across West Africa regarding their perceptions of extreme wet and dry conditions. The sample size was calculated for an unlimited population using the Krejcie and Morgan Formula (Krejcie & Morgan, 1970).
This method is similar to Cochran's sample size formula (Ahmad & Halim, 2017). The computation shows that 384 or more respondents represent a generalisable sample at a 95% confidence level. Descriptive statistics, such as frequencies and percentages, were used to summarise the socio-demographic characteristics of the respondents and their perceptions of climate variability and impacts. These statistics provide an overview of the

dominant patterns of extreme precipitation events, their impacts, and the risk reduction measures. This approach is essential for identifying trends and patterns in the data, such as the most common impacts and risk reduction strategies for extreme weather events. Bar charts were also used to display the results, making it easier to interpret and communicate key findings.

For inferential statistics, the study uses the Chi-square test to assess whether there is a significant relationship between respondents' country of residence and impacts of the extreme precipitation conditions. The Chi-square tests were employed in cross-tabulations between variables and has been used in several related research (Naz et al., 2019; Obi et al., 2021; Sharma et al., 2019). This combination of descriptive and inferential statistics ensures a comprehensive analysis, enabling both summary and hypothesis testing within the context of climate variability/change adaptation in West Africa.

Socio-demographic characteristics of the survey respondents

The list and country-wise frequency of the respondents are presented in Table 4.

Table 4: *Sampled countries in West Africa*

Country	Frequency	Percentage
Benin	9	2.1
Burkina Faso	12	2.8
Cote d'Ivoire	8	1.9
Ghana	45	10.7
Mali	13	3.1
Niger	18	4.3
Nigeria	166	39.3
The Gambia	111	26.3
Togo	40	9.5
Total	422	100

Source: Authors fieldwork (2024)

Nine countries in West Africa were purposefully selected to represent the different climatic regime in the region. With most of the respondents coming from the Anglophone countries of Nigeria (39.3%), The Gambia (26.3%), and Ghana (10.7%), others include Togo (9.5%), Niger (4.3%), and the remaining countries (9.9%). Moreover, since Nigeria experiences both Sahelian and Guinea coast modes of precipitation variability, the spatial distribution of the respondents falls within the three main ecological zones in the region, namely: the Guinean, Sudanian, and Sahel.

Although the response rate was skewed towards Nigeria, The Gambia, Ghana, and Togo, this does not undermine the study's validity. The purposive sampling method was used to select the nine countries in West Africa due to the availability of known research assistants, ensuring efficient data collection and logistics feasibility. This method allowed the study to leverage existing networks, reducing costs and time constraints while maintaining regional representation. Random sampling was employed to select respondents within the chosen countries to ensure an unbiased representation of diverse perspectives. This approach minimised selection bias, increased the generalisability of findings within each country, and enhanced the statistical robustness of the study's conclusions.

Furthermore, the KoboCollect app was chosen to maximize accessibility and reach across multiple locations, with the understanding that response rates might vary depending on factors such as internet connectivity, local awareness, language, and interest levels. Such heterogeneity is common in multi-country surveys (Folayan et al., 2023) and was expected throughout the planning phase. Any bias caused by answer variance was addressed by weighting changes (proportions) used during analysis, ensuring that the results appropriately reflect the larger target population.

The socio-demographic characteristics of the respondents are presented in Tables 5. 68.7% of the respondents are male, with 90.5% of the survey population having graduated from the tertiary institution. 62.1% of them are single, while 37.7% are married. The majority of the respondents (67.3%) reside in urban areas in their respective countries.

Table 5: *Demographic characteristics of the respondents*

Characteristics	Frequency	Percentage	Total
Gender of Respondents			
Male	290	68.7	422
Female	129	30.6	
Prefer not to say	3	0.7	
Education Level			
Secondary	40	9.5	422
Tertiary	230	54.5	
Masters/Doctorate	152	36	
Marital Status			
Single	262	62.1	422
Married	159	37.7	
Divorced	1	0.2	
Type of Settlement			
Urban	284	67.3	422
Peri-urban	65	15.4	
Rural	73	17.3	

Source: Authors fieldwork (2024)

The mean age of the respondents is 31 years, while the maximum and minimum age are 65 and 19, respectively. Thus all respondents are adults and knowledgeable enough to provide perspective to the research questions. Furthermore, of the 37.9% that are married, their spouses educational qualifications show that 27.5% completed secondary, 50% are graduates from tertiary institutions, and 22.5% had postgraduate qualifications. This shows that the demographic profile of the respondents is knowledgeable enough to understand and respond objectively.

CHAPTER 3: CHARACTERISTICS AND SPATIAL EVOLUTION OF MONSOON PRECIPITATION VARIABILITY OVER WEST AFRICA

3.1. Introduction

Precipitation is a crucial link between atmospheric water and energy cycles, affecting regional hydroclimate by affecting soil and air temperatures, moisture, humidity, runoff, evaporation, streamflow, and drought incidence. Understanding rainy season variability is crucial for comprehending the complex spatio-temporal structure of precipitation trends and variability. Seasonal anomalies are of great interest due to their societal impacts and relevance for climate prediction and risk management. Analysing rainy season precipitation characteristics can provide valuable insights into the climate system and enhance hazard management. In this chapter, the mean spatio-temporal patterns of West African precipitation during the monsoon season, as well as the dominant variability modes, are explored.

3.2. Characteristics of precipitation over West Africa

3.2.1. Mean spatial pattern and variability

The spatial patterns of the monthly precipitation over West Africa are shown in Figure 4a-l. January is the driest month in the region, with relatively no precipitation occurrence in the entire West African region except in few isolated areas. In February, slight isolated precipitation occurs over the coastal areas of Liberia to Ghana and Niger Delta region of Nigeria. By March and April, precipitation onset is observed over most parts of the Guinea coast region. Signalling the beginning of the rainy season, with mean precipitation increasing up to 150 mm in some areas.

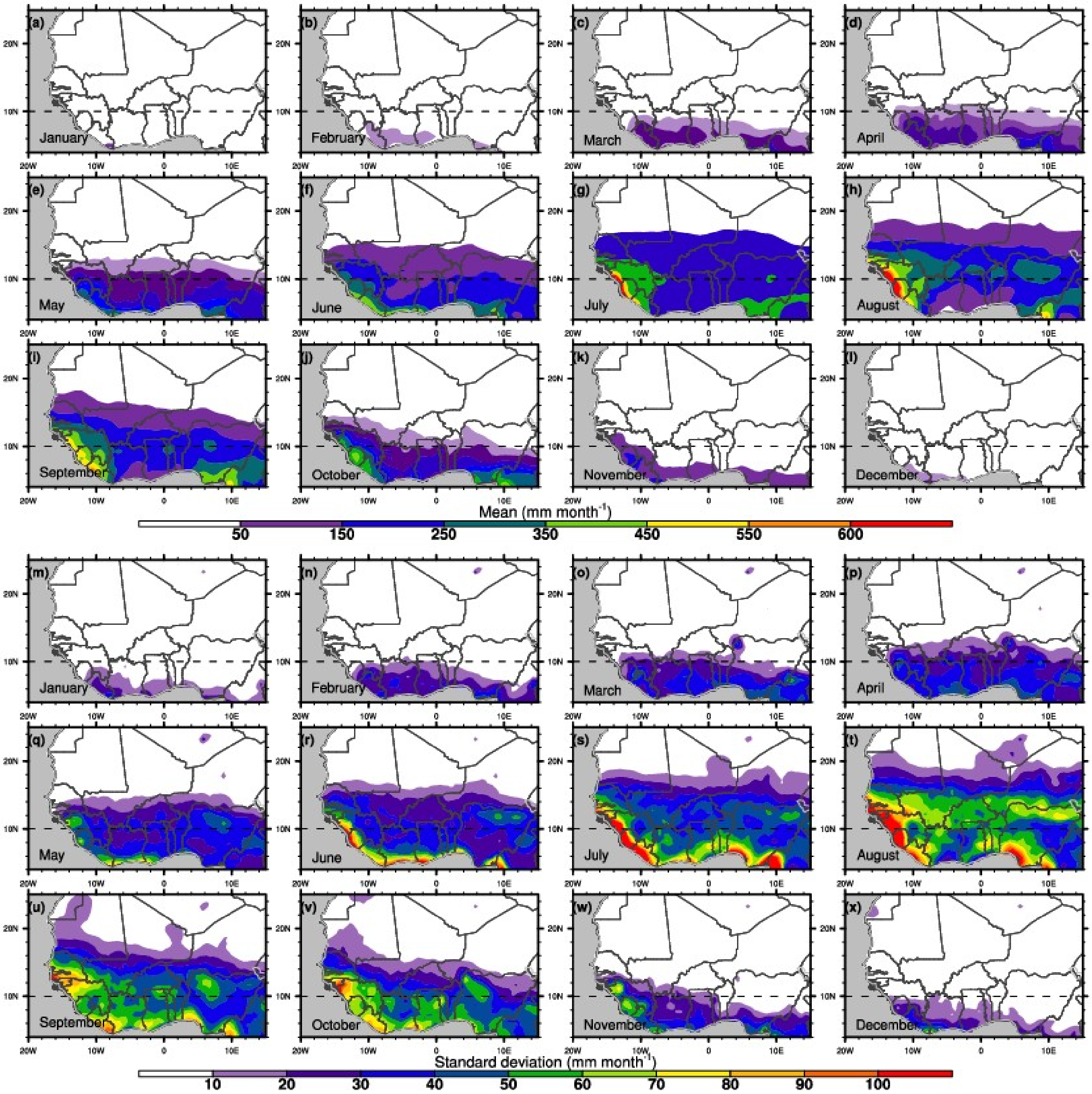

***Figure 4**: Mean state and standard deviations of precipitation over the West African region*

In June (Fig.4f), the mean precipitation is concentrated along the coastal areas, particularly in the western part, with precipitation amounts ranging from 50 to 450 mm per month. Central and eastern parts of the Sahel exhibit minimal precipitation. Progressing to July (Fig. 4g), the precipitation extends further north into the Sahel, with similar intensity and a notable increase in precipitation over most parts of West Africa. August (Fig. 4h) shows the peak of the rainy season, with the highest rainfall (450-950 mm per month) occurring in the coastal areas of West Africa, particularly over Sierra Leone, Liberia, and the Southeastern parts of Nigeria. The rainfall belt extends significantly northward, encompassing much of the Sahel region. By September (Fig. 4i), the precipitation patterns remain robust, with high precipitation amounts persisting along the coastal regions and slightly reduced but still significant rainfall across the Sahel. The heaviest precipitation areas in September are similar to those in August, but the intensity decreases slightly. In October (Fig. 4j), there is a sharp retreat of precipitation from the Sahel region, with increased precipitation amounts over the coastal areas, especially over the Benin-Cote d'Ivoire coasts. Marking the end of the rainy season over most parts of the Sahel. In November, mean precipitation amounts of less than 150 mm occur only along the coastal areas, marking the end of the rainy season over the entire West Africa.

Figures 4m-x show the standard deviations of precipitation over West Africa. There is a homogenous and zonal pattern in precipitation variations in each month, with the variability highest in areas and months with higher mean rain. The key area includes the Guinea-Ghana coasts, the Niger Delta, and Western Cameroon. These areas record a variability of more than 200 mm. Whereas relatively less precipitation variability is observed in the areas north of Latitude 16 degrees with an interannual deviation of less than 50 mm yearly.

3.2.2 Mean temporal pattern

The annual cycle of domain-averaged precipitation over West Africa is shown in Figure 5, with the mean and standard deviation representing the interannual variability. In Figure 5a, January is the driest month of the year, while August has the highest precipitation amount. The onset of rain starts in March (May) and ends in November (October) in some parts of the Guinea coast and Sahel region, respectively. This shows that the rainy and dry months are well defined over West Africa.

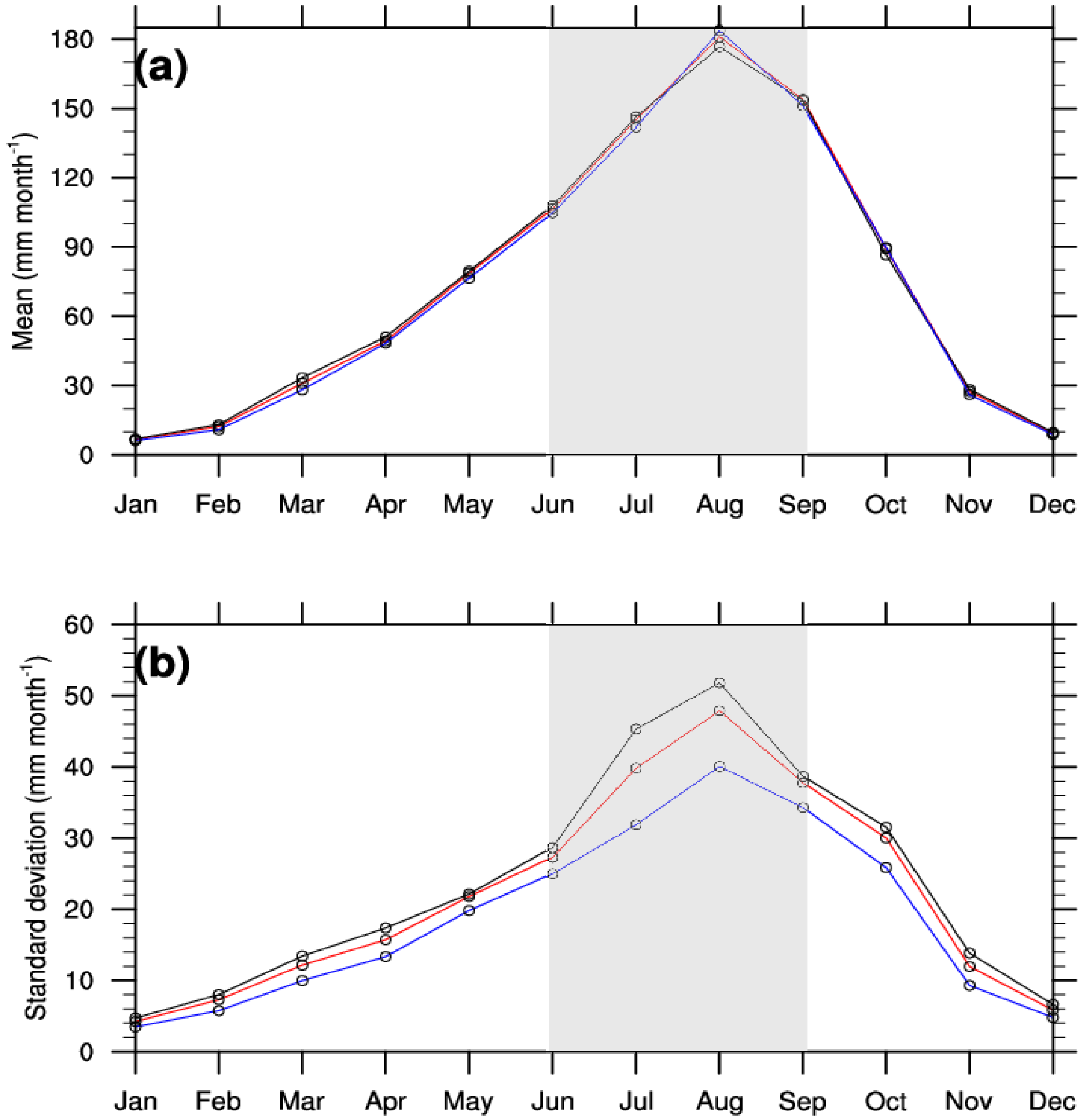

Figure 5: *Annual cycle of the (a) mean and (b) standard deviation of precipitation averaged over West Africa during the three study periods: Red (1950-2022), black (1963-1992) and blue (1993-2022). Shaded months depicts the four monsoon months with the most precipitation occurrence in the region.*

It is well known that the monsoon months of June, July, August, and September contribute the most precipitation extreme events and amount to the annual total precipitation over West Africa. This period is known as the West African summer monsoon season. Based on observed differences in patterns of precipitation variability in the region, three temporal periods were used to examine trends and patterns of precipitation changes over West Africa. The three periods have already been explained in chapter two (Table 2). The results show that the annual cycle of precipitation is very similar during the three different periods with the highest precipitation amount occurring in August and September. However, there are considerable differences in the variability pattern during the monsoon months, as depicted in Figure 5b. The 1963-1992 period witnessed the highest level of variability, while the 1993-2022 period experienced relatively the least variability among the three periods. August is the month with the most rainy and variable precipitation characteristics over the study area, and its precipitation amount has increased considerably in the 1993 to 2022 period relative to the entire period (1950-2022) and the 1963-1992 periods, respectively. This pattern signifies that the rainy months exhibit the most variability, significantly impacting planning as the expected rainfall tends to vary yearly. Subsequent results are presented only for each of the four core rainy months (June-July-August-September) or their combined mean.

Figure 6 depicts the interannual variability of precipitation over West Africa during June, July, August, and September from 1950 to 2022. Each panel (a-d) represents a different month, showing standardised precipitation anomalies with a superimposed linear trend line. The blue bars represent positive anomalies, indicating wetter-than-average conditions, while the red bars denote negative anomalies, corresponding to drier-than-average conditions. The trend for each month is also indicated in the upper right corner of each plot.

In June (Fig. 6a), the trend is significantly negative at -0.17 mm/yr, indicating a gradual decline in precipitation. The precipitation variability shows a significant shift around the 1970s, with more frequent negative anomalies from the late 1960s to the 1980s, corresponding to a period of drought. However, from the 1990s onward, there was an increase in positive anomalies, suggesting some recovery, though the overall trend remained negative. For July (Fig. 6b), the trend is more pronounced at -0.28 mm/yr, highlighting a more substantial decline in precipitation over the years. The 1950s and 1960s show frequent positive anomalies, while the 1970s to the late 1980s are marked by persistent negative anomalies, reflecting significant drought events. Although there is a slight increase in positive anomalies after the 1990s, the significant negative trend indicates an overall decrease in precipitation in July. Furthermore, Figure 6c shows that the trend is almost neutral at -0.01 mm/yr in August, suggesting that there is little to no long-term change in rainfall during this month over the observed period. The anomalies are more evenly distributed between positive and negative values, indicating considerable interannual variability without a strong trend. This could imply that while there have been periods of both dry and wet conditions, the overall precipitation in

August has remained relatively stable over the decades. September (Fig. 6d) shows a negative trend of -0.21 mm/yr, indicating a reduction in precipitation over time, though not as strong as in July. The anomalies reflect a pattern similar to July's, with more positive anomalies in the 1950s and 1960s, followed by more frequent and intense negative anomalies during the 1970s and 1980s. From the 1990s onwards, there was an increase in positive anomalies, yet the overall downward trend suggests a general decrease in September precipitation.

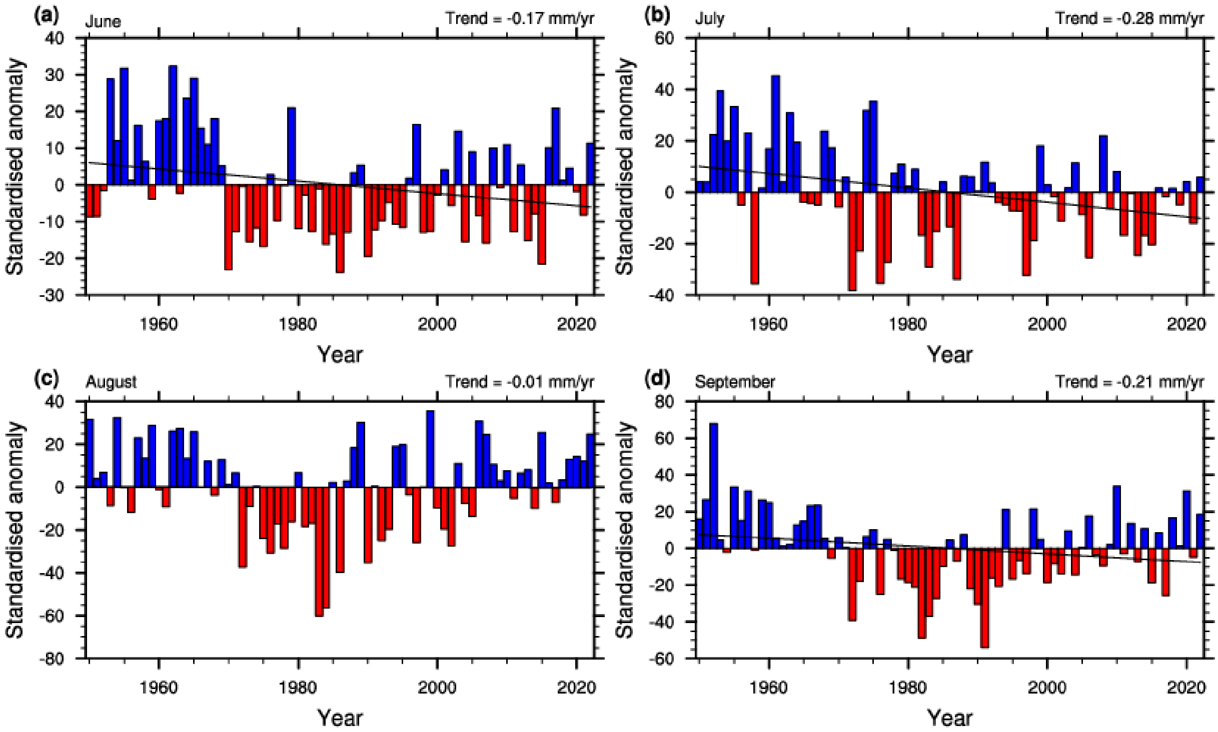

Figure 6: *Interannual variability of rainy months rainfall over West Africa*

These plots collectively illustrate the changing nature of the West African monsoon period. There has been a noticeable decline in precipitation during the core rainy months, particularly in July and September, likely influenced by broader climate variability and trends.

Furthermore, during the study period, there have been some changepoints in the interannual variations of precipitation in West Africa. Table 6 shows the results of the single changepoint analysis for precipitation during the monsoon months. Here, the Pettitt's test (PT), Standard Normal Homogeneity Test (SNH), and Buishand range homogeneity tests (BRT) were used. In June, the three-changepoint test detected the same year of significant change in 1969. In contrast, in July all three show that there is a significant change; the Bushand range test and Pettitt's test show the change year to be 1974, while the Standard Normal Homogeneity test year of change is 1969. In August, all three methods detected the same 1971 as the probably year of change; BRT classified the change to be significant, while SNH and PT show otherwise.

Moreover, in September, significant change was detected in all the changepoint point methods; however, they show different years of change: BRT (1971), SNH (1967), and PT (1970). This divergent change in years indicates differing algorithms in the changepoint method and dynamics of precipitation variability in the region.

Table 6: *Single change point analysis for West African domain-averaged precipitation (1950-2022), significance at 95% confidence level*

Month	**Buishand range test**		**Standard normal homogeneity test**		**Pettitt's test**	
	Year of change	Significance	Year of change	Significance	Year of change	Significance
June	1969	Significant	1969	Significant	1969	Significant
July	1974	Significant	1969	Significant	1974	Significant
August	1971	Significant	1971	Not significant	1971	Not significant
September	1971	Significant	1967	Significant	1970	Significant

Figure 7 presents the spatial patterns of June precipitation trends over West Africa for three periods: (a) 1950-2022, (b) 1963-1992, and (c) 1993-2022. The precipitation trends are measured in mm/year and are colour-coded, with blue shades indicating increasing trends and red shades indicating decreasing trends. Areas with statistically significant trends are marked with black dots. During 1950-2022 (Fig. 7a), notable increases in precipitation are observed in central and eastern Nigeria, northern Ghana, and parts of the western Sahel (southern Mauritania, north of Senegal). At the same time, significant decreases are seen along the Guinea coast, particularly in southern Guinea, Sierra Leone, and Liberia.

In Figure 7b, a few areas show increasing trends. Some increases are observed in northeastern Nigeria and parts of southern Mali, with extensive decreasing trends evident across the Guinea coast, including Guinea, Sierra Leone, and Liberia, extending into southern Cote d'Ivoire and Ghana during 1963-1992. However, in Figure 7c, precipitation increases over central Nigeria and parts of the western Sahel (southern Mauritania, northern Senegal) from 1993 to 2022. Significant decreases are observed along the Guinea coast and southwestern Nigeria, extending into parts of the southern Cote d'Ivoire and Ghana.

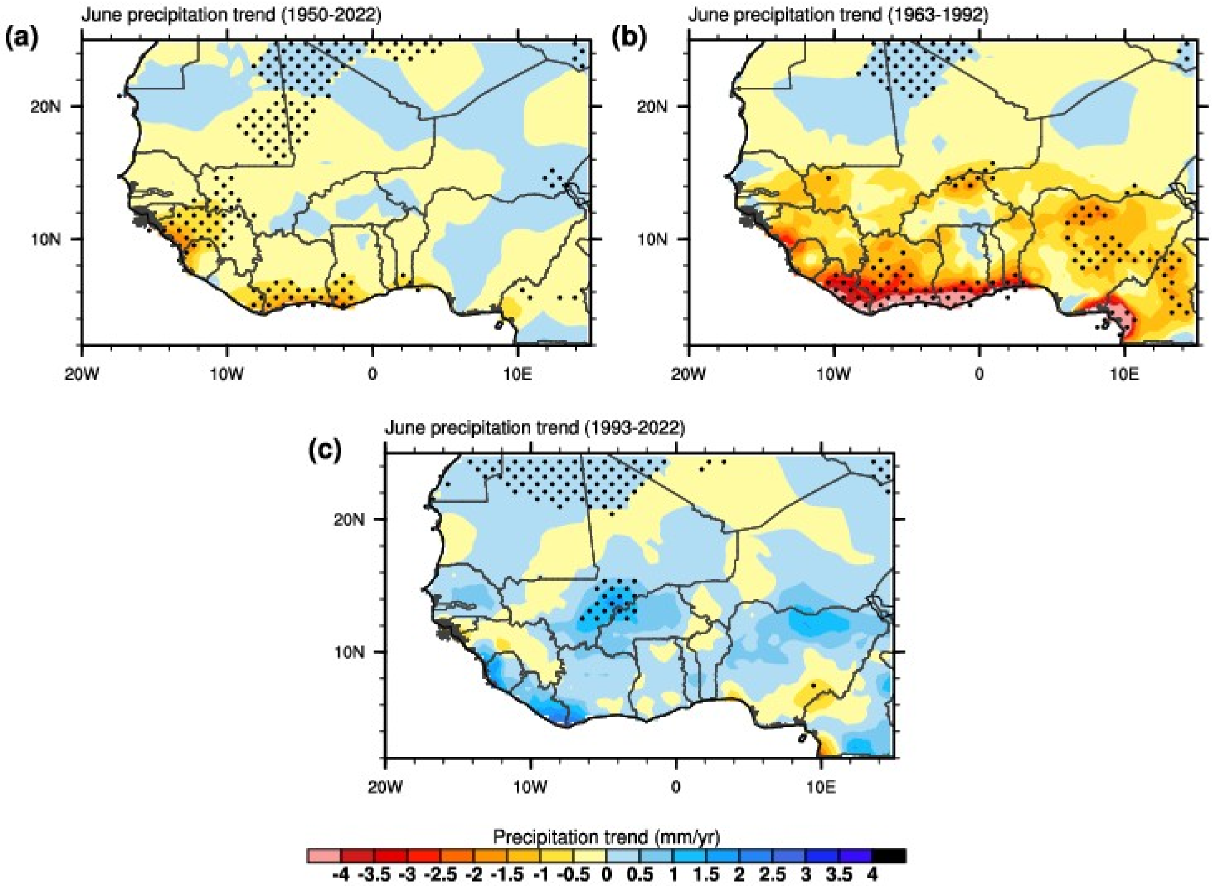

Figure 7: *Patterns of June precipitation trend over West Africa for a) 1950-2022, b)1963-1992, and c) 1993-2022*

Figure 8 illustrates the spatial patterns of July precipitation trends over West Africa. During the entire study period (Fig. 8a), the northern parts of West Africa, particularly central Mali and western Sahel, show increasing trends, while significant decreases are observed in southern Nigeria, southwestern Ghana, and the coast of Liberia.

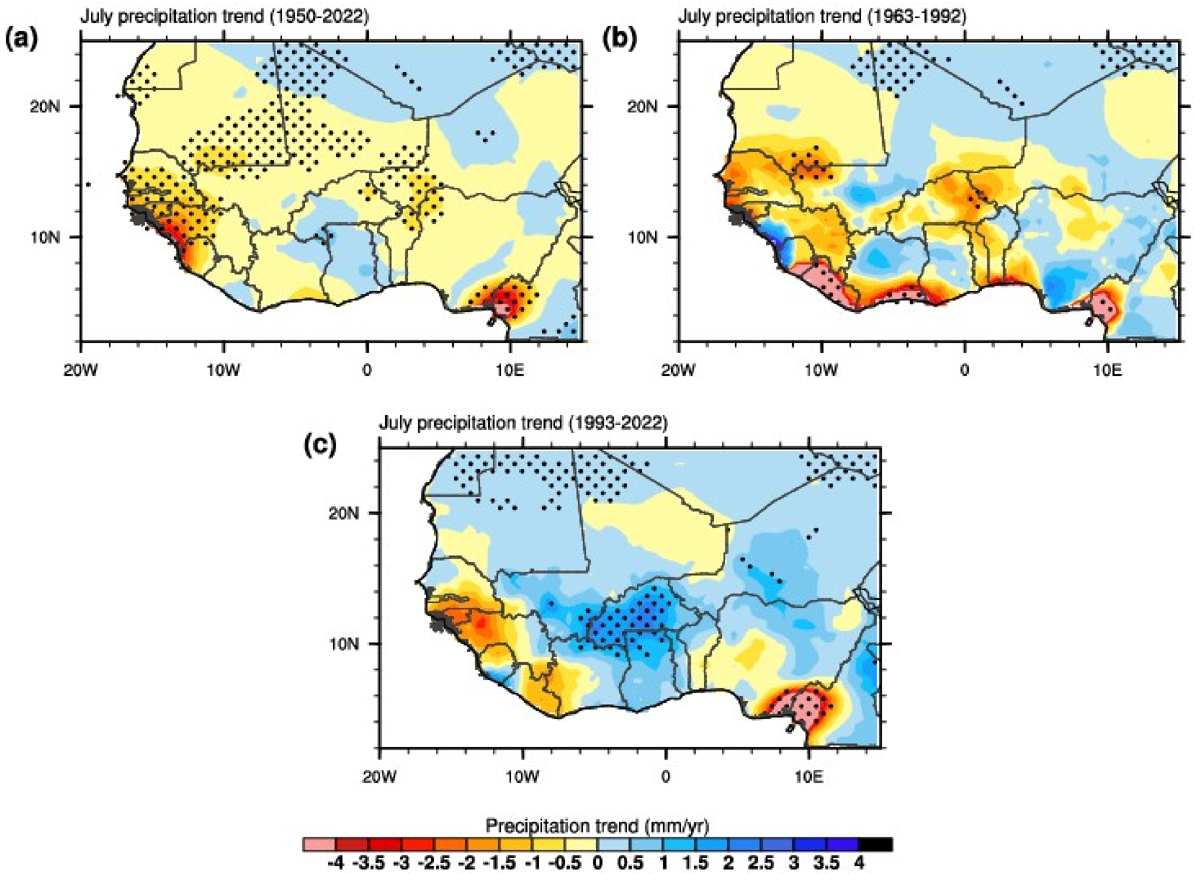

Figure 8: *Patterns of July precipitation trend over West Africa for a) 1950-2022, b)1963-1992, and c) 1993-2022*

Furthermore, in Figure 8b (1963-1992), slight increases are noted in southeastern Nigeria and some parts of the Sahel, while widespread decreases are evident across the Guinea coast, including southern Guinea, Sierra Leone, and Liberia, and extending into parts of southern Mali and Burkina Faso.

From 1993 to 2022 (Fig. 8c), notable trends are observed in central Niger, parts of southern Mali, Burkina Faso and the western Sahel. Decreases are prominent along the Guinea coast, especially in southwestern Ghana and southeastern Nigeria, with additional decline in northwestern Mali. Apparent differences and some consistent trends emerge when comparing the patterns across the three periods. The long-term period (1950-2022) reveals a mix of increasing and decreasing trends, with significant decreases along the coastal regions and some increases in the Sahel. 1963-1992 shows extensive decreases, particularly along the Guinea coast, reflecting the historical drought prevalent during this time. In contrast, the recent period (1993-2022) indicates a shift, with some areas in the Sahel and Nigeria experiencing increases, while the Guinea coast continues to exhibit significant decreases. This suggests a possible recovery in specific regions juxtaposed with ongoing drying in others.

Figure 9 presents the spatial pattern of August precipitation trends over West Africa. During 1950-2022 (Fig. 9a), notable significant increases in precipitation are observed in regions of northwestern Mali, central Niger and southern Algeria and Libya, with few isolated areas of substantial increase, mainly in the Sahel region. Precipitation decreases are seen along the Guinea coast (particularly between southwestern Nigeria and eastern Cote d'Ivoire), with a significant decline around the Adamawa axis of northeastern Nigeria.

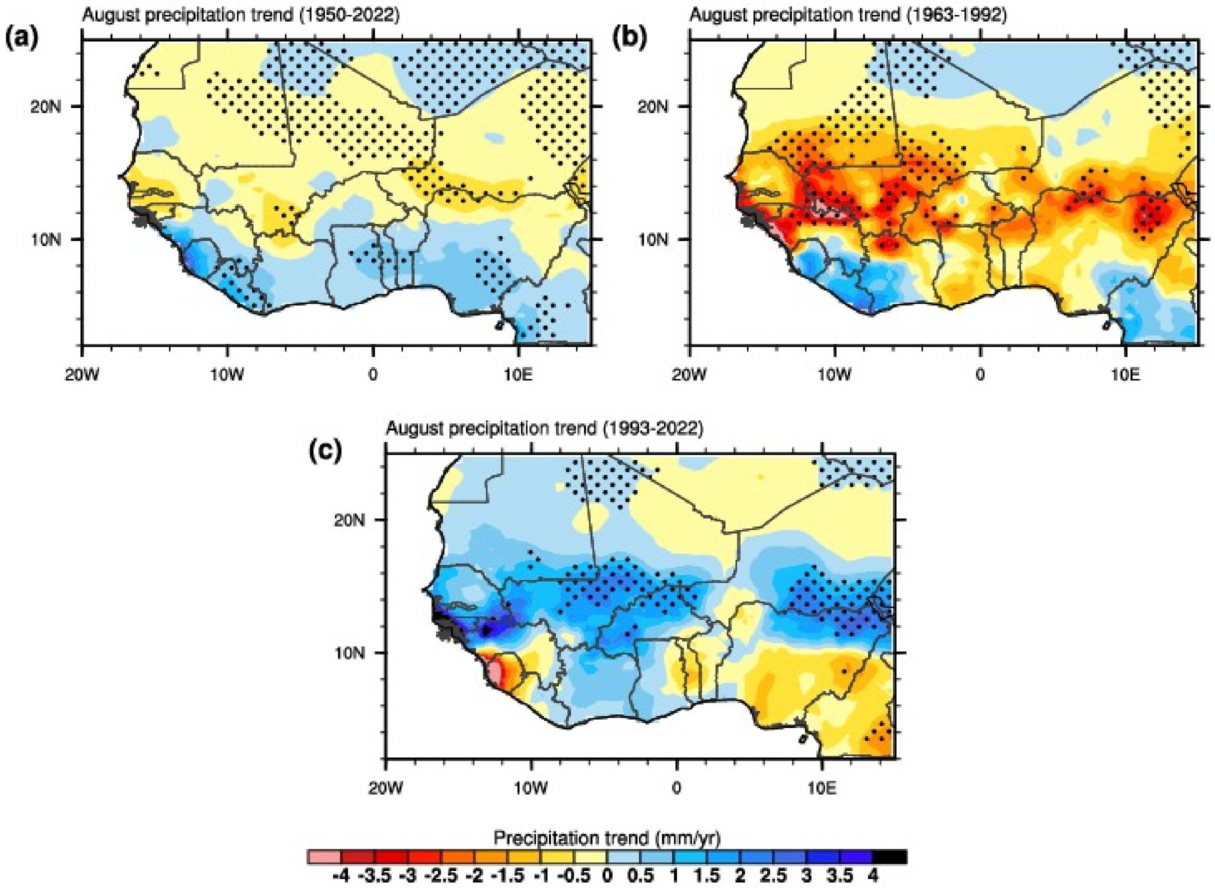

Figure 9: *Patterns of August precipitation trend over West Africa for a) 1950-2022, b)1963-1992, and c) 1993-2022*

For the 1963 to 1992 period (Fig. 9b), extensive decreasing trends are evident across the Sahel and Guinea coast regions, with few areas showing an increasing trend. Significant decreasing trend are evident in northern Nigeria, Guinea, Mauritania, Mali, Burkina Faso, north of Cote d'Ivoire and Niger. Nevertheless, Figure 9c show an increase in precipitation in most parts of the Sahel, especially around the eastern part of Niger extending to northeastern Nigeria and central Mali to northern Burkina Faso. The western part of Sierra Leone, central Ghana, up to Cameroon, show decreases in precipitation in August, with slight increases along the coastal areas of western Nigeria up to Liberia.

The spatial pattern of September precipitation trends over West Africa during the three periods is shown in Figure 10. From 1950 to 2022 (Fig. 10a), precipitation increased significantly in northern and eastern Mali and southwestern Nigeria, although most of the region shows non-significant increases and decreases.

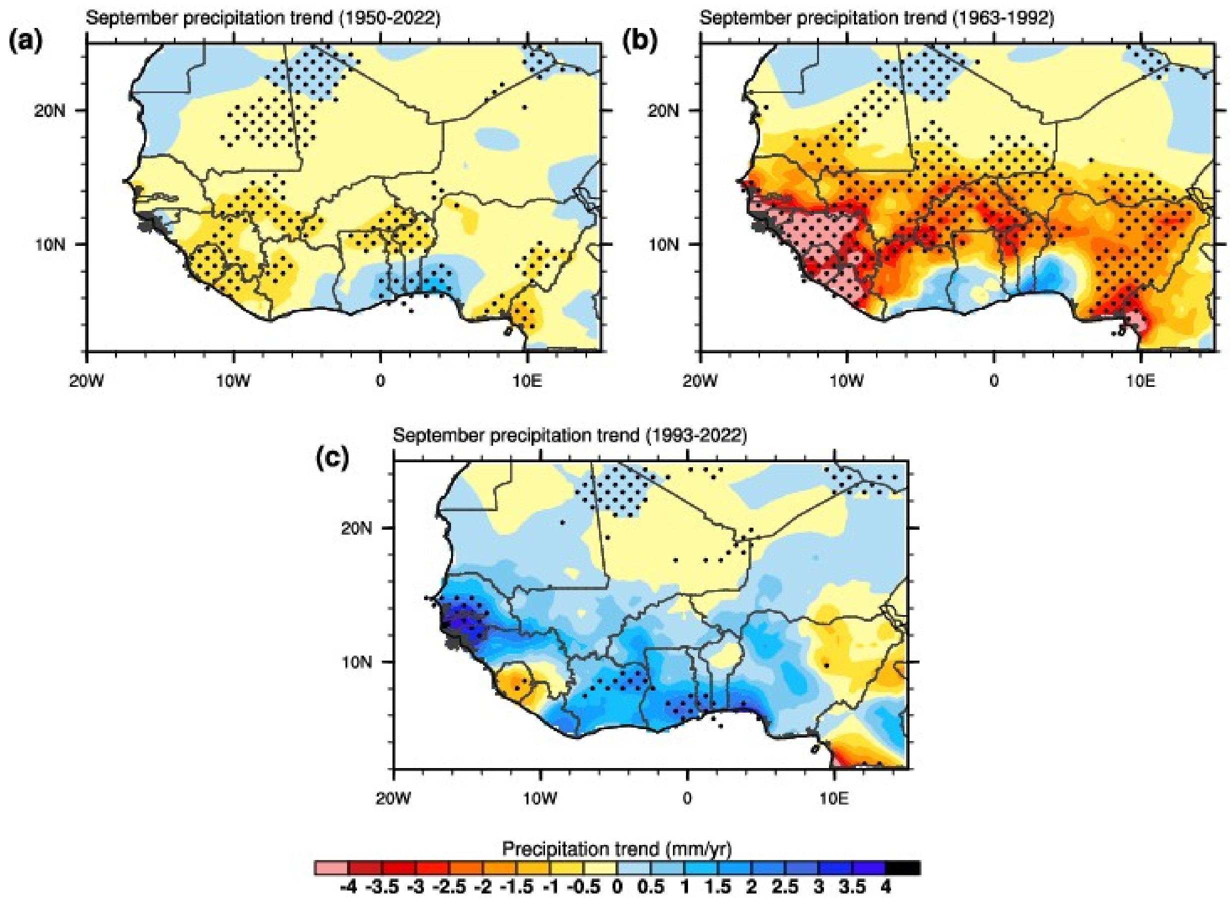

Figure 10: *Patterns of September precipitation trend over West Africa for a) 1950-2022, b)1963-1992, and c) 1993-2022*

During 1963 to 1992 (Fig. 10b), an extensive decrease in precipitation is observed across the Sahel and Guinea coast regions, with only a few isolated areas showing precipitation increases. Significant decreasing trends are widespread, especially in the southwestern part of West Africa, the Sahel, and eastern Nigeria. In the recent period from 1993 to 2022 (Fig. 10c), there is a notable increase in precipitation in most parts of the Sahel and

Guinea coast, with significant increases around the Sene-Gambia, northeastern Cote d'Ivoire, southern Ghana, and western Nigeria. However, significant decreases in precipitation also occurred in Liberia and northeastern Mali.

3.3. Evolution of the dominant modes of precipitation variability over West Africa

3.3.1. Modes of West African monsoon precipitation variability

Figure 11 depicts the percentage (%) variance of the top ten precipitation eigenvalues over West Africa based on season-reliant empirical orthogonal function (S-EOF) analysis.

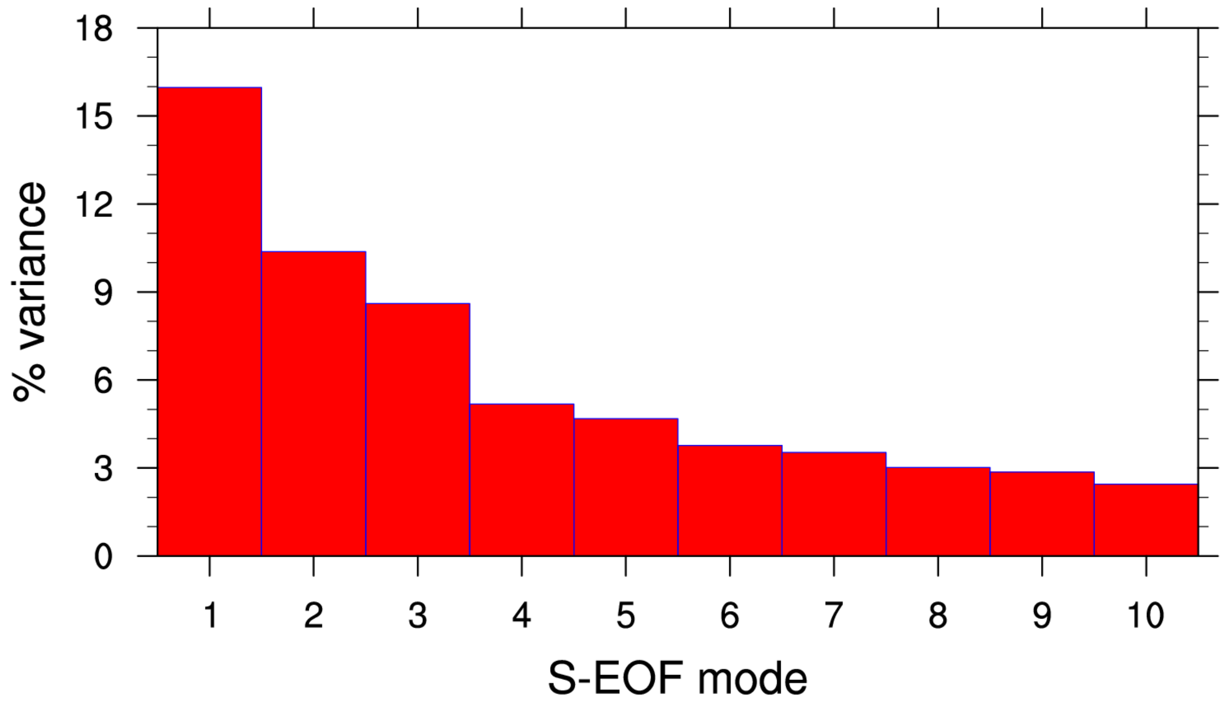

Figure 11: *Percentage (%) variance explained by the first ten leading S-EOF modes*

The first two leading modes, which account for 16.3% and 9.5% of the total variance respectively. These two modes explain about 26.38% of the rainy season variability and are distinguished from each other and the remaining S-EOFs based on the North et al. 1982 criteria. As a result, the first two S-EOF modes are selected for further examination since they exhibit physically and statistically significant patterns.

3.3.2. Spatial pattern of leading modes of precipitation variability

Figure 12 illustrates the evolving precipitation anomaly patterns during the summer monsoon period (June to September).

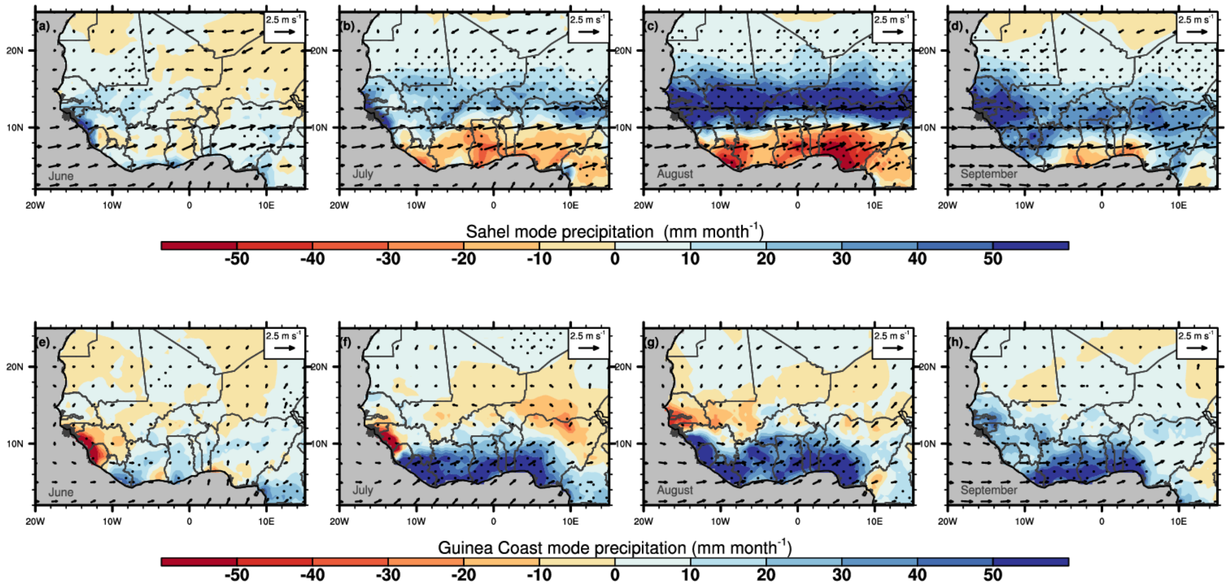

***Figure 12**: Rainy months evolving patterns of precipitation and wind (850 hPa) anomalies regressed onto the PCs of the top two S-EOF modes. (a-d) Sahel and (e-h) Guinean. Stipples denote statistical significance at the 90% confidence level.*

The Sahel mode reveals a distinctive south-north dry-wet seesaw pattern (Fig. 12a-d) with enhanced circulation pattern. During August and September, dry conditions dominate the Guinea coast, while areas between latitudes 10-20 degrees north experience wet conditions. In June and July, minor negative anomalies are present across the Sahel. However, dry conditions intensify in August, particularly over the Guinea coast domain.

In contrast, the Guinea coast mode of precipitation variability displays generally wet conditions across the Guinea coast region, with drier anomalies in the central and eastern Sahel (Fig. 12e-h). June and July exhibit positive anomalies along the Guinea coast, indicating enhanced precipitation. August stands out with a strong positive anomaly around the Guinea coast, which extends inland. The positive anomalies persist but are less intense and more localized in September.

The dipole pattern of precipitation anomalies is pronounced only during the Sahel mode of West African precipitation variability. Both modes, however, feature significantly wetter-than-normal conditions in September, indicating that most parts of the region are generally wet during this month. Notably, the coastal areas from Nigeria to Liberia are significantly drier in August compared to other coastal regions during the Sahel mode.

Comparatively, August and September emerge as the wettest months in the Sahel domain, while July and August are the wettest months in Guinean mode. Areas of significant extreme wet events span from Sene-Gambia to Ethiopia, while significant dry conditions are pronounced over southern Nigeria, Ghana, Côte d'Ivoire, and Liberia in August during the Sahel mode. The dry conditions observed in July and September over the Guinea coast are not significant. The Sahel region experiences relatively dry conditions in July, August, and September during the Guinea coast mode. The hotspot of extreme wet conditions is more pronounced over the central coastal areas in July, and southern Nigeria in August.

3.3.3. Temporal pattern

Figure 13 presents the time series of the two leading modes' principal components, with the magnitude indicating the strength of variation. Greater absolute values signify stronger variations and more typical spatial patterns. In Figure 13a, the PC1 time series and the Sahel index are positively correlated with a coefficient of 0.94, showing that it replicates the temporal pattern of precipitation in the Sahel region. The period 1950 to 1967 is characterised by primarily positive anomalies, except in 1962 and 1965; after that, it persisted mostly to the negative phase from 1968 to 2004, except in these six years (1988, 1994, 1998, 1999, 2003, and 2004). Since 2005, the Sahel region has consistently been positive, experiencing consistent wetter-than-average precipitation. Figure 13b shows the interannual series for the second leading mode; this region's precipitation has a pronounced interannual variability pattern characterised by alternating wet and dry years. The relationship between the second principal component time series and the Guinea coast region is also positively very strong, with a coefficient of 0.90.

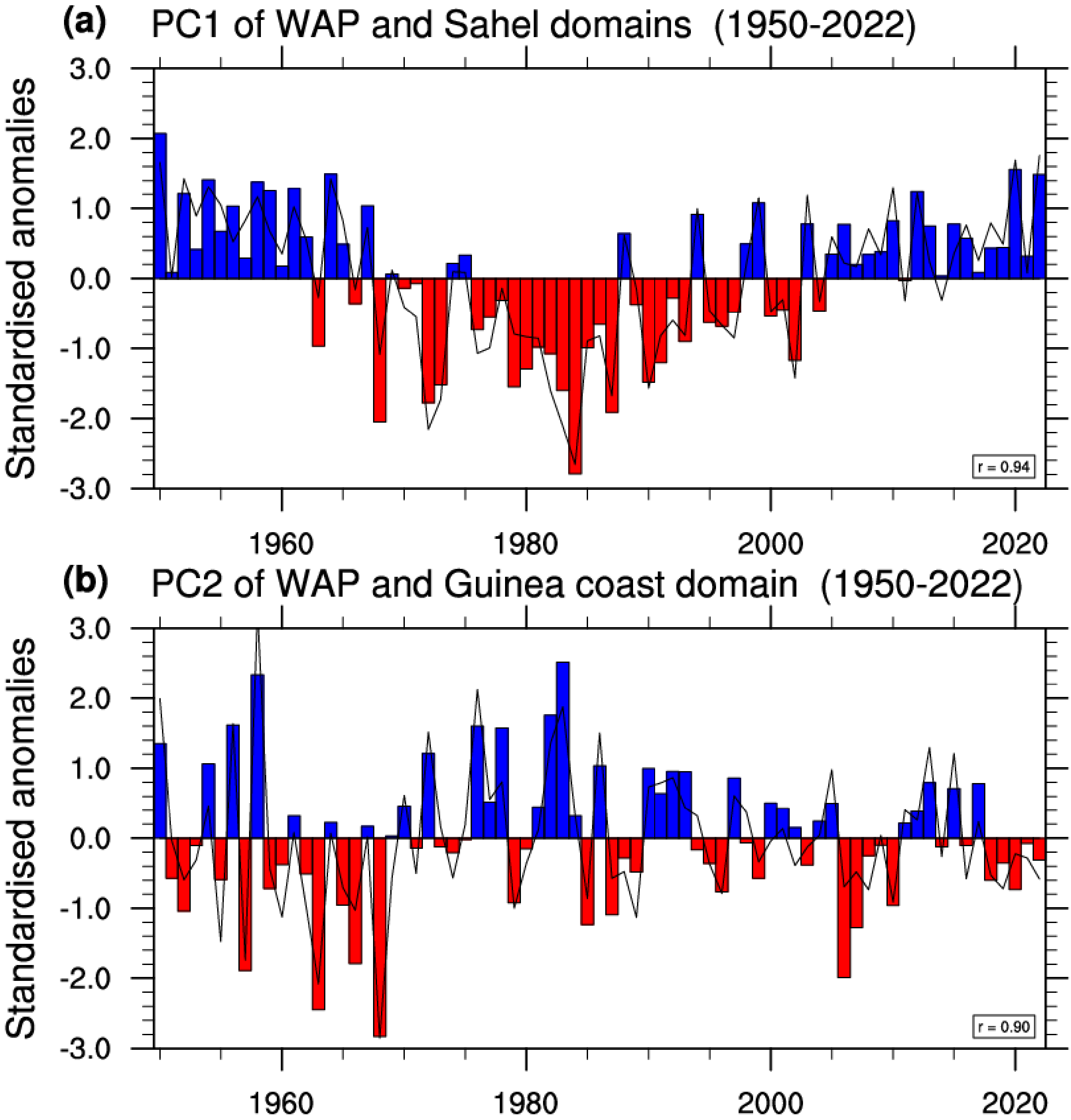

Figure 13: *Time series of expansion coefficients of the first two modes of precipitation variability, r represents the correlation coefficient between the PCs and the JJAS domain averaged precipitation (black thin line overlain on the bars)*

Comparatively, the driest (wettest) years over the Sahel and Guinea coast domain were 1984 (1950) and 1968 (1983), respectively, during the study period. Also, concurrent wet (dry) event years occurred in 1950, 1954, 1956, and 1958 (1968, 1985, 1987). Dipole years are 1952 for the wet Sahel and dry Guinea coast and 1972, 1982, and 1983 for the dry Sahel and wet Guinea coast.

3.4. Discussion

Previous studies in West Africa have reported changes in seasonal rainfall patterns, resulting in either increasing dryness or wetness. Precipitation variability in West Africa remains a profound challenge to the availability of water for agriculture, hydropower generation, and other ecosystem services and the occurrences of rainfall-related disasters. The characteristics (mean state, trend, change point, and spatial evolution) of monsoon precipitation variability over West Africa were presented. The result showed negligible changes on the domain-averaged mean rainfall seasonal cycle during the three periods, with notable variabilities in the rainy months. The absence of notable differences in the annual cycle of precipitation during the three periods buttresses the idea that the annual rainfall cycle has remained relatively the same during the three periods. The observed changes may be due to variability in intraseasonal rainfall properties such as frequencies, intensity, and duration of rains (Chagnaud et al., 2022; Obarein & Lee, 2022). The observed variability in the annual cycle (Fig. 6b) shows notable temporal changes in the three periods, as months and areas of higher rainfall occurrence depict higher variability. June, July, and September show a significant declining trend, while the August rainfall trend has remained relatively stable over the entire period. Since the Sahel pattern of rainfall variability is the leading mode of West African rainfall, this result supports the finding of Nicholson (2013) on the anomalies in August and September rainfall being the major contributor to the strong inter-annual variability in Sahel rainfall. A similar result was reported in Togo (Djaman et al., 2017).

The three change point methods detected significant shifts in rainy months rainfall in the late 1960s and early 1970s, with the statistically significant changes in June and September in contrast with the findings of Ilori and Ajayi (2020), where they detected no change point in rainfall over the Sahel region of West Africa during 1961-2000 in all three change point detection methods. The difference may be due to differing time periods and temporal scales.

The spatial pattern of the long-term analysis shows a mixed pattern of increasing and decreasing trends across West Africa. The western Sahel and part of central Nigeria exhibit increasing trends, indicating a general intensification of the monsoon rains in these areas. Conversely, the significant decreasing trends over the Guinea coast, highlight the region's exposure to drying conditions in the long term. The period (1963-1992) is marked by widespread decreasing trends, especially over the Sahel region in all months, which aligns with the known historical drought periods that affected the Sahel and surrounding regions (Bader & Latif, 2011; Ball, 1978; Biasutti, 2019; Ekwezuo & Ezeh, 2020; Hastenrath, 1990; Mohino, Janicot, et al., 2011; Nicholson, 2013; Vellinga et al., 2016). The recent period (1993-2022) depicts mixed trends, with some regions, particularly central Nigeria and parts of the western Sahel, showing increasing rainfall, while the Guinea coast shows significant decreasing trends (Ndehedehe et al., 2022).

Furthermore, interesting regional hotspots of increasing and decreasing precipitation is observed over West Africa for the different monsoon months. An increase in rainfall is consistently observed in parts of central Nigeria and the western Sahel especially between eastern Mali and Burkina Faso, indicating regions where the monsoon rains have been strengthening, especially in recent periods. This corroborates the findings of Daramola et al., (2023); Ndehedehe et al., (2022) on the intensification of extreme rainfall events in West Africa. Also, decreasing rainfall dominates the Guinea coast domain, especially southern Guinea, Sierra Leone, and Liberia, where persistent drying trends are observed (Araujo Bonjean et al., 2023). These mixed patterns of precipitation variability across different parts of West Africa raise serious concerns, to which the two dominant modes of precipitation variability provide a first- order explanation (García-Serrano et al., 2013; Moron, 1994; Mounier & Janicot, 2004). In recent years, the positive phase of the Sahel mode of precipitation variability has been dominant. The temporal evolution of these modes highlights alternating dry and wet years (Nicholson & Webster, 2007; Nnamchi et al., 2021; Paeth & Stuck, 2004; Worou et al., 2020), with more wet and dry event years in the Sahel mode than on the Guinea coast during the 73-year period. The significant wet regions during the Sahel modes includes the Casamance region of Senegal, areas situated between Latitudes 12 to 16 degrees north, Furthermore, the following areas are the driest: Southwestern Nigeria, Volta region in Ghana and some parts of Liberia. During the Guinea coast mode, the coastal areas from Sierra Leone to southwestern Nigeria are anomalously wet, especially from July to September, with very few significant dry areas.

3.5. Partial conclusion

The spatial and temporal variability of rainy season precipitation in West Africa underscores the critical need for adaptive strategies in water management, agriculture, and climate resilience. This study reveals significant regional and temporal trends in precipitation from 1950 to 2022, with areas like the western Sahel experiencing increased rainfall while parts of the Guinea coast exhibit a persistent decline. The severe drying period of 1963-1992, particularly during the Sahel drought, is contrasted by a partial recovery in rainfall post-1993, especially in the western Sahel. However, the mixed trends observed in August and September, alongside the regional patterns of increasing and decreasing trends, emphasise the complex nature of precipitation dynamics across West Africa.

The analysis identifies two dominant modes of precipitation variability: the Sahel and Guinea Coast modes. The Sahel mode, characterised by a dipole pattern, often results in extreme wet and dry event year that severely impact the region, highlighting the natural rainfall variability in the region. These findings suggest a strong link between large-scale dry and wet events and the variance in precipitation extremes rather than changes in the mean state. Future research should investigate the climatic drivers of these trends, particularly sea surface temperature anomalies, to improve predictive models and develop early warning systems. Enhanced understanding of these mechanisms is crucial for managing the risks associated with precipitation variability and developing robust climate adaptation strategies for West Africa.

CHAPTER 4: MECHANISMS ASSOCIATED WITH THE DOMINANT MODES OF WEST AFRICAN PRECIPITATION VARIABILITY

4.1. Introduction

The underlying physical mechanisms influencing the two dominant modes of precipitation variability over West Africa are examined using composite analysis. The composite mean difference of sea surface temperature, and circulation characteristics (vertically integrated moisture divergence anomalies, velocity potential, and divergent winds) during the Sahel and Guinea coast modes of variability were examined and presented in this chapter.

4.2. Mechanisms associated with West African extreme event years

4.2.1. Sea Surface Temperature Anomaly

The state of sea surface temperature in different oceanic basins is critical in modulating the West African monsoon system by affecting atmospheric circulation and moisture transport. Figure 14 show the oceanic basins and their relevant SST index, influencing extreme precipitation events during the Sahel and Guinea coast modes.

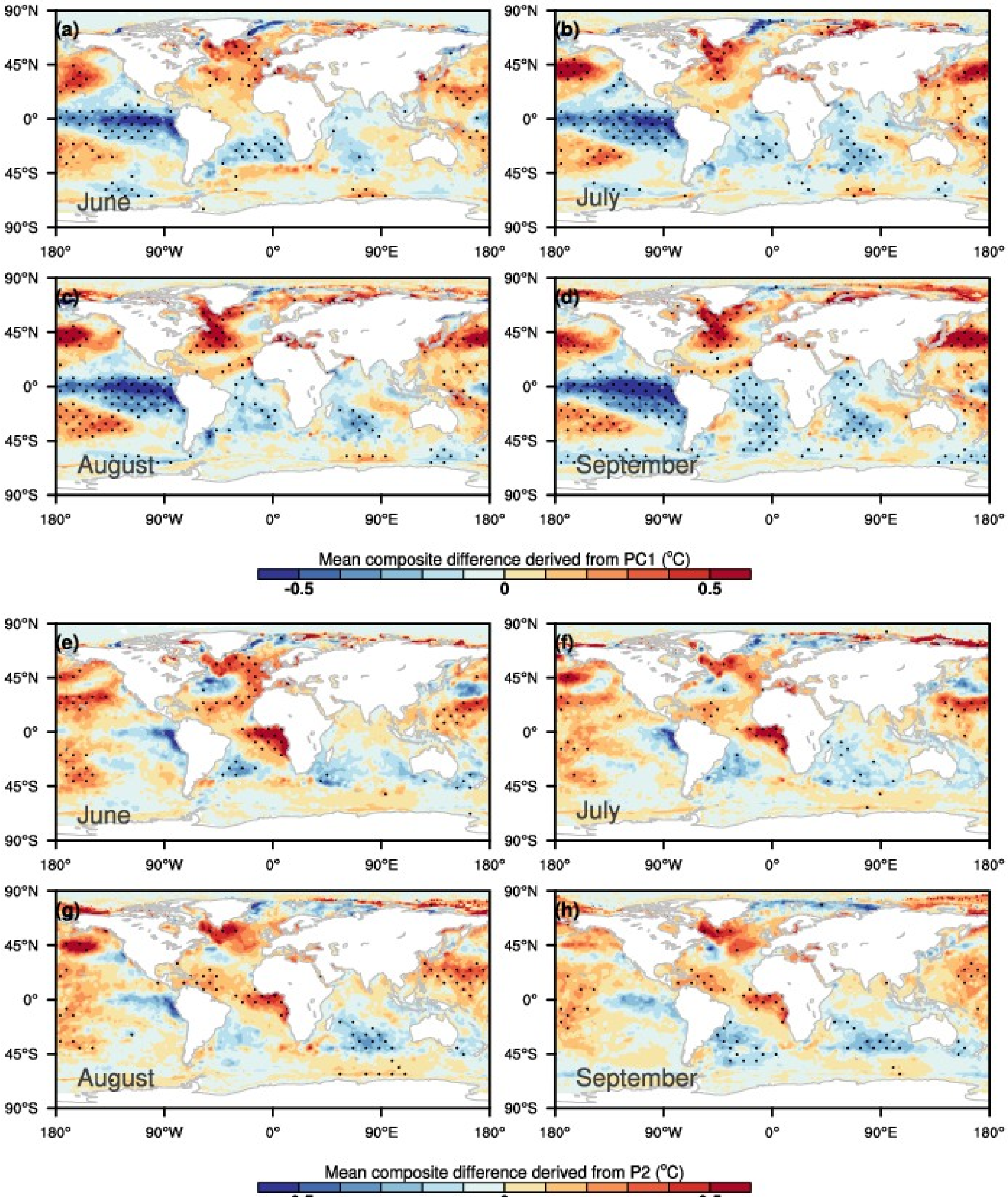

Figure 14: *Composite anomalies of the sea surface temperature pattern during the Sahel (a-d) and Guinea coast (e-h) modes (1950-2022). Black dots denote statistical significance at the 90% confidence level*

The Sahel mode is associated with warm SST anomalies in the North Atlantic and Mediterranean Sea. The equatorial Pacific exhibits a significant SST pattern comparable to a negative phase of ENSO and a positive phase of the Pacific Decadal Oscillation

(PDO) in the northern Pacific (Figures 14a-d), with the most robust connection to the equatorial Pacific in September. The Guinea coast mode shows a dipole structure, with pronounced warm SST anomalies in the Atlantic Niño region, especially in June and July, and cold anomalies along the coasts of Brazil, Uruguay, and Argentina (Figures 14e-h).

4.2.2. Velocity Potential and Divergent Winds

Velocity potential describes the irrotational component of winds, making it a powerful indicator of monsoon strength due to its ability to describe the convergence or divergence in the wind flow field. It is an indicator of subsidence and thus is commonly accepted as a strong proxy for ascending (descending) motion associated with anomalous Walker circulation (Zhang et al., 2014). At low latitudes, the velocity potential is preferred over other variables, such as pressure and geopotential heights, as it accurately captures the basic circulation pattern of monsoons (Ghil & Lucarini, 2020).

Based on the composites of the velocity potential and divergent/convergent winds in the lower (850 hPa) and upper troposphere (200 hPa) (Figures 15 and 16), we show how velocity potential anomalies influence large-scale divergence (convergence) that drives precipitation anomalies.

In the lower atmosphere, during the Sahel mode (Fig. 15a-d), a substantial divergence evolves over the Eastern hemisphere starting in June and peaking in July and August, with a strong convergence over the Western hemisphere with robust hotspots around Longitudes 60 to 140 west within the four rainy months. Similarly, a comparable pattern is observed during the Guinea coast mode (Fig.15e-h) with relatively weak velocity potential and divergent winds. Enhanced velocity potential occurs in July and September relative to the other months.

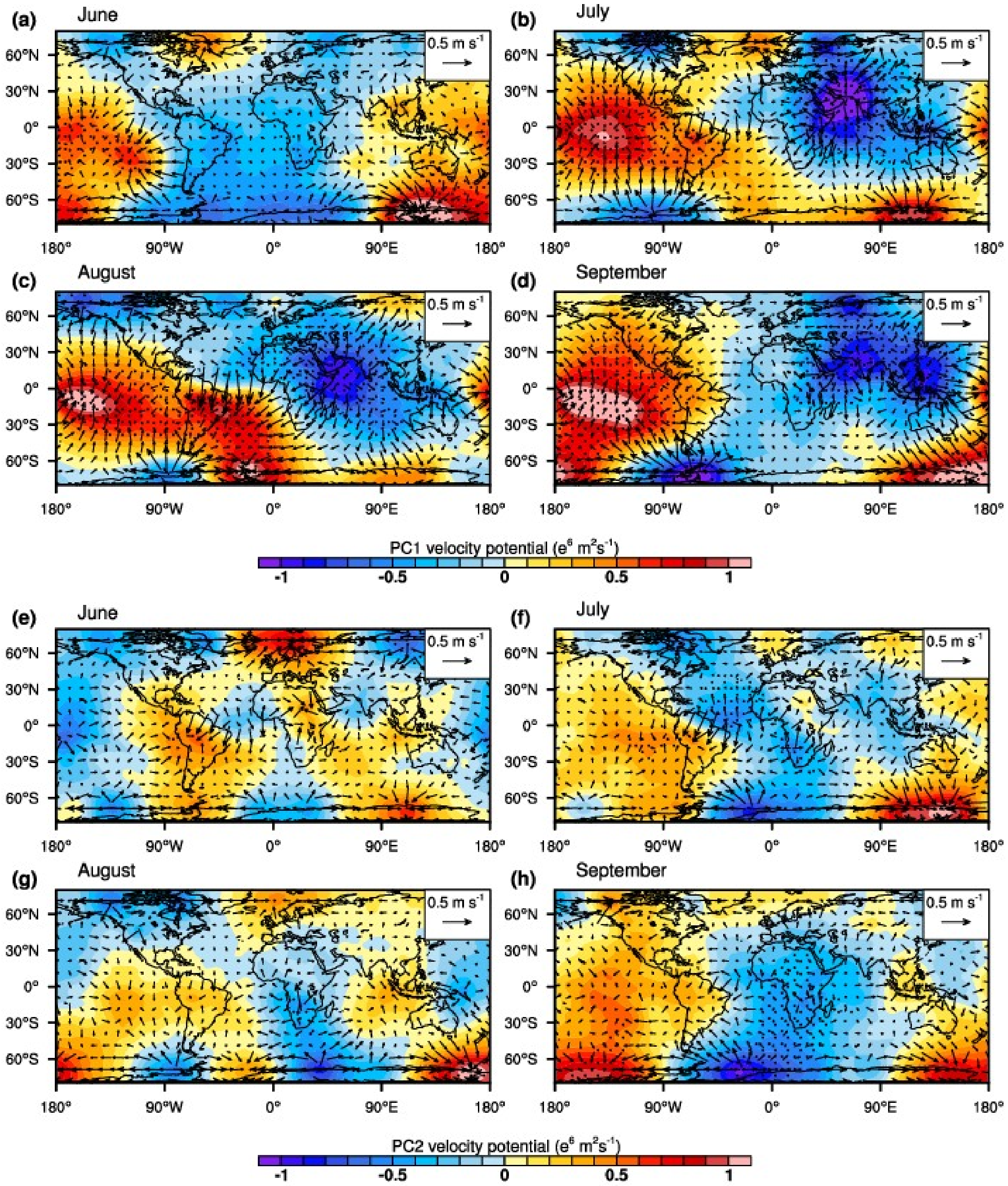

Figure 15: *Composite anomalies of the velocity potential (colour shading) and divergent winds (vectors) at the 850-hPa for the Sahel (a,d) and Guinea Coast (e,h) modes. Stipples denote statistical significance at the 90% confidence level. The rising (sinking) cells of the mean Walker Circulation occur over the continents (oceans)*

Figure 16 shows the composite anomalies of velocity potential and divergent winds in the upper atmosphere (200 hPa). A contrasting pattern with positive velocity (convergence) over the eastern hemisphere and a negative velocity potential (divergence) over the American continent is observed.

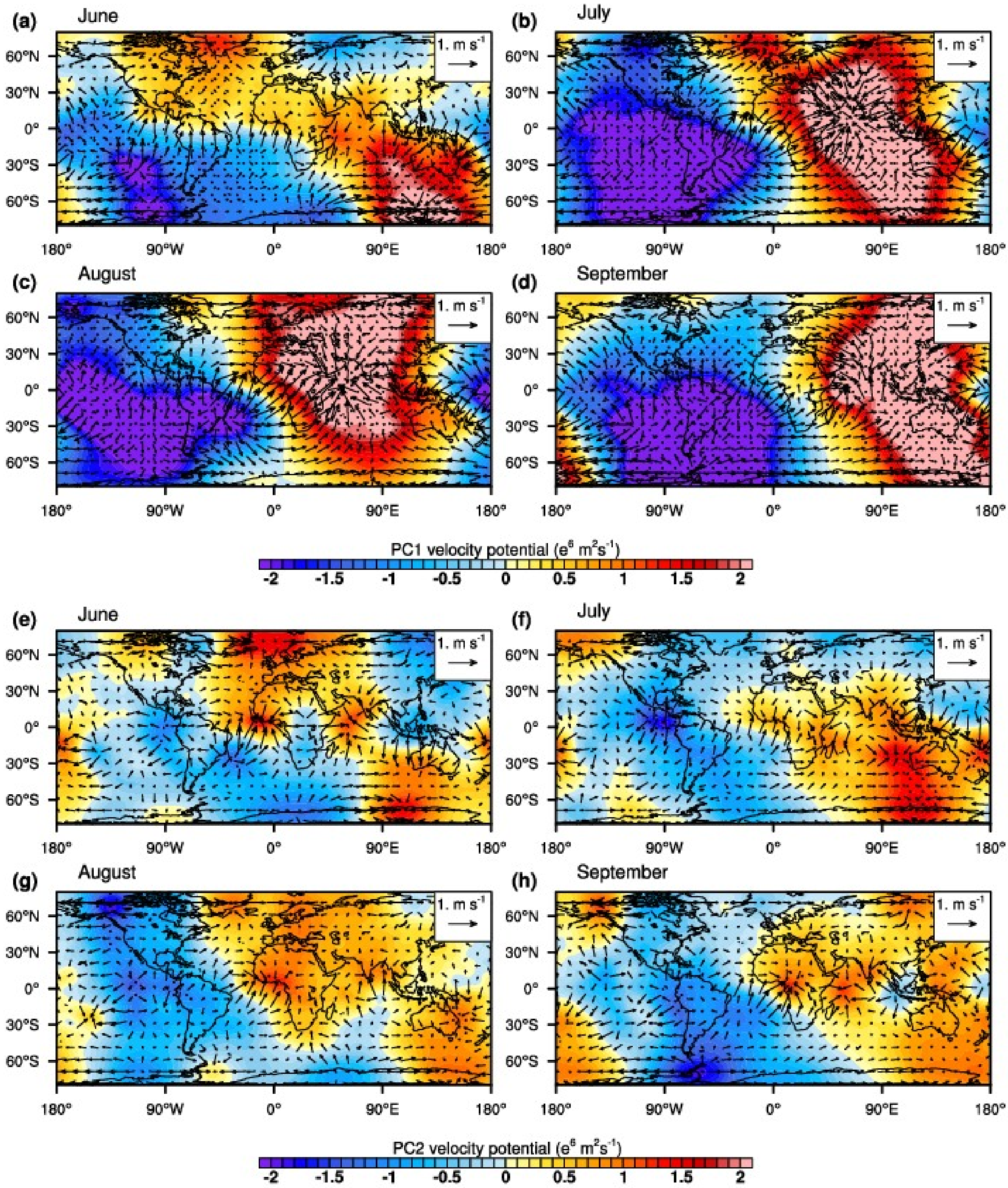

Figure 16: *Composite anomalies of the velocity potential (colour shading) and divergent winds (vectors) at the 200-hPa for the Sahel (a-d) and Guinea Coast (e-h) modes. Stipples denote statistical significance at the 90% confidence level*

During the Sahel mode, we observed two contrasting areas of enhanced convergence (divergence) zones in July-August and positive anomaly hotspots over the Indian sub-continent and the Maritime continents in September. The contrast between positive and negative anomalies is weaker during the Guinea coast mode, with solid convergence over the West African region, equatorial Pacific, and maritime continents. Due to the decreased intensity of the Walker circulation, the winds are generally weak and locally confined to the West African region.

4.2.3. Sources and sinks of moisture

The sources and sinks of moisture contributing to extreme precipitation events over the West African monsoon region are shown in Figure 17 using the vertically integrated moisture flux convergence (VIMFC) anomalies.

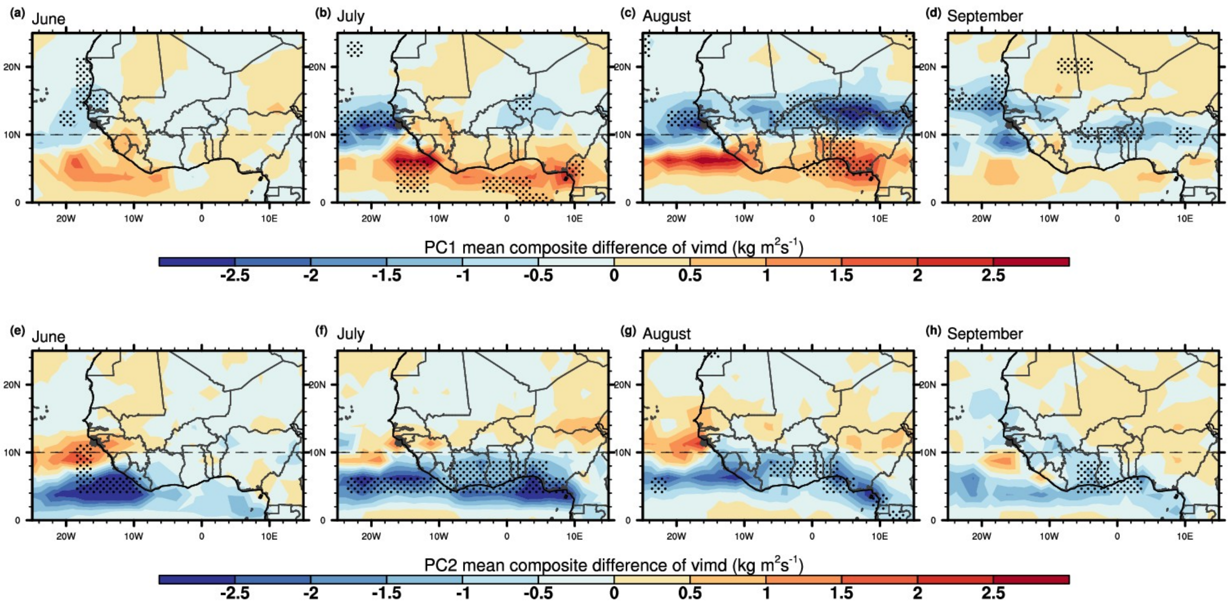

***Figure 17**: Composite anomalies of vertically integrated moisture showing the moisture sources and sinks during the Sahel (a-d) and Guinea coast(e-h) modes. Stipples denote statistical significance at the 90% confidence level.*

During the Sahel mode (Fig. 17a-d), significant moisture sources are observed over the coastal areas of Benin-Nigeria and Liberia-Sierra Leone. While significant moisture sink areas are found off the coast of Gambia-Senegal, as well as in Burkina Faso, Niger, the northern parts of Togo, Benin, and Nigeria. Moisture sinks in August are the most enhanced. Figures 17e-h show similar but more pronounced moisture source areas over the Gulf of Guinea, covering a greater area than those during the Sahel mode. The winds are mostly local, and no significant moisture sink areas exist except off the coast of Guinea and Guinea-Bissau. In June, the moisture source is well enhanced over the coast of Sierra Leone and Liberia, which reduces in intensity and expands to the coast of Nigeria in July. Also in August, the significant moisture source is reduced and limited to the tropical forest of Côte d'Ivoire and the coastal region of Nigeria.

4.3. Discussion

The influence of SST anomalies on West African precipitation variability is evident (Fontaine et al., 2010; Mohino, Rodríguez-Fonseca, et al., 2011). The Sahel mode's association with warm SST anomalies in the North Atlantic and Mediterranean Seas and a negative ENSO phase aligns with previous studies linking these regions to Sahelian rainfall variability (Biasutti, 2019; Giannini et al., 2003; Palmer, 1986; Pomposi et al., 2020; Rowell, 2001, 2003; Suárez-Moreno et al., 2018). The dipole structure of SST, with warm SSTs in the Atlantic Niño region and cold anomalies along South America's coast during the Guinea coast mode, highlights the Atlantic's critical role in modulating precipitation (García-Serrano et al., 2013; Nicholson & Webster, 2007; Nnamchi et al., 2021). Furthermore, during the warm SST phase of the Atlantic Niño mode, the trade winds relax, the thermocline is anomalously deep in the eastern basin, and the cold tongue of equatorial surface water does not appear, while convection is shifted southeastward. The shift weakens the equatorial trade winds in the west, leading to dry conditions observed over most parts of the Sahel (Frankignoul & Kestenare, 2005).

The analysis of vertically integrated moisture flux anomalies identifies significant sources and sinks contributing to extreme precipitation events (Kebacho, 2021, 2022; Lélé et al., 2015; Lélé & Leslie, 2016; Shelton & Dixon, 2023; Washington & Preston, 2006). From Benin Republic to Nigeria and Liberia to Sierra Leone, coastal areas are primary moisture sources during the Sahel mode, while inland regions act as sinks. The Guinea coast mode shows more pronounced moisture sources over the Gulf of Guinea, highlighting the region's importance in moisture supply. Compared to the Sahel mode, the local winds sink over the Guinea coast mode, suggesting different atmospheric circulation patterns driving moisture transport during the Guinea coast mode.

The obtained pattern of velocity potential and divergent/convergent winds in the lower and upper troposphere reveal novel insights into the large-scale atmospheric dynamics influencing WAM precipitation, especially the modulation of the Walker circulation (Choi et al., 2016; Crétat et al., 2017; Darmawan et al., 2021; Joly & Voldoire, 2009; Sharma T et al., 2023; Zhao et al., 2019). The weaker velocity potential and divergent winds during the Guinea coast mode indicate a less intense but significant Walker circulation influence on regional precipitation (Akinsanola & Zhou, 2020; Nnamchi et al., 2021). While the influence of sea surface temperature anomalies is very important, a study by Taschetto et al. (2016) revealed that extended extreme wet and dry episodes may result from internal atmospheric and land variability alone; however, these dry and wet events are less severe than in models that include ocean feedback. These ocean-atmosphere feedbacks are responsible for the large-scale spatially coherent rainfall pattern and impacts.

4.4. Partial conclusion

This study advances understanding of the seasonal dynamics and drivers of extreme precipitation events during the West African summer monsoon (WASM), particularly emphasising the influence of sea surface temperature (SST) anomalies on precipitation patterns. The analysis highlights how atmospheric and oceanic circulation patterns, including Walker and Hadley circulation variations, contribute to regional extreme precipitation conditions. Notably, July and August emerge as months with a higher propensity for extreme weather events, with the Sahel prone to flooding and regions like southwestern Nigeria and Ghana's Volta area experiencing extreme dry conditions.

These findings underscore the practical application of SST monitoring as a predictive tool. By enhancing early warning systems, it can help mitigate the impacts of extreme weather events. The potential benefits of improved seasonal forecasting, informed by these insights, are significant for agricultural planning and environmental sustainability. It could allow for better crop selection, timing of planting and harvesting, and irrigation planning, all of which are crucial for food security in West Africa. This chapter further highlights the need for continued research into the physical processes driving precipitation variability, as well as further investigation into how dominant SST anomalies influence summer precipitation patterns in the region.

CHAPTER 5: IMPACT OF DOMINANT OCEANIC BASINS ON WEST AFRICAN PRECIPITATION VARIABILITY

5.1. Introduction

This chapter explores the influence of key oceanic basins on the variability of West African precipitation. It examines how these regions' sea surface temperature anomalies (SSTA) affect precipitation patterns by modulating atmospheric circulation and moisture transport. The study identifies dominant oceanic modes that drive large-scale wet and dry years during the West African summer monsoon. Understanding these relationships is crucial for improving seasonal forecasting and climate adaptation strategies, particularly in a region where agriculture and water resources are highly sensitive to precipitation changes.

5.2. Influence of Sea Surface Temperature on West African precipitation

5.2.1 Dominant Oceanic Basins Influencing West African Precipitation

The significant oceanic basins influencing West African precipitation are illustrated in Figure 18. The Sahel mode (Figure 18a) is linked with SST variations across the Atlantic, Indian, and Pacific Oceans and the Mediterranean Sea. Positive SST anomalies in the eastern Mediterranean Sea are associated with increased precipitation over the Sahel, while negative anomalies have the opposite effect.

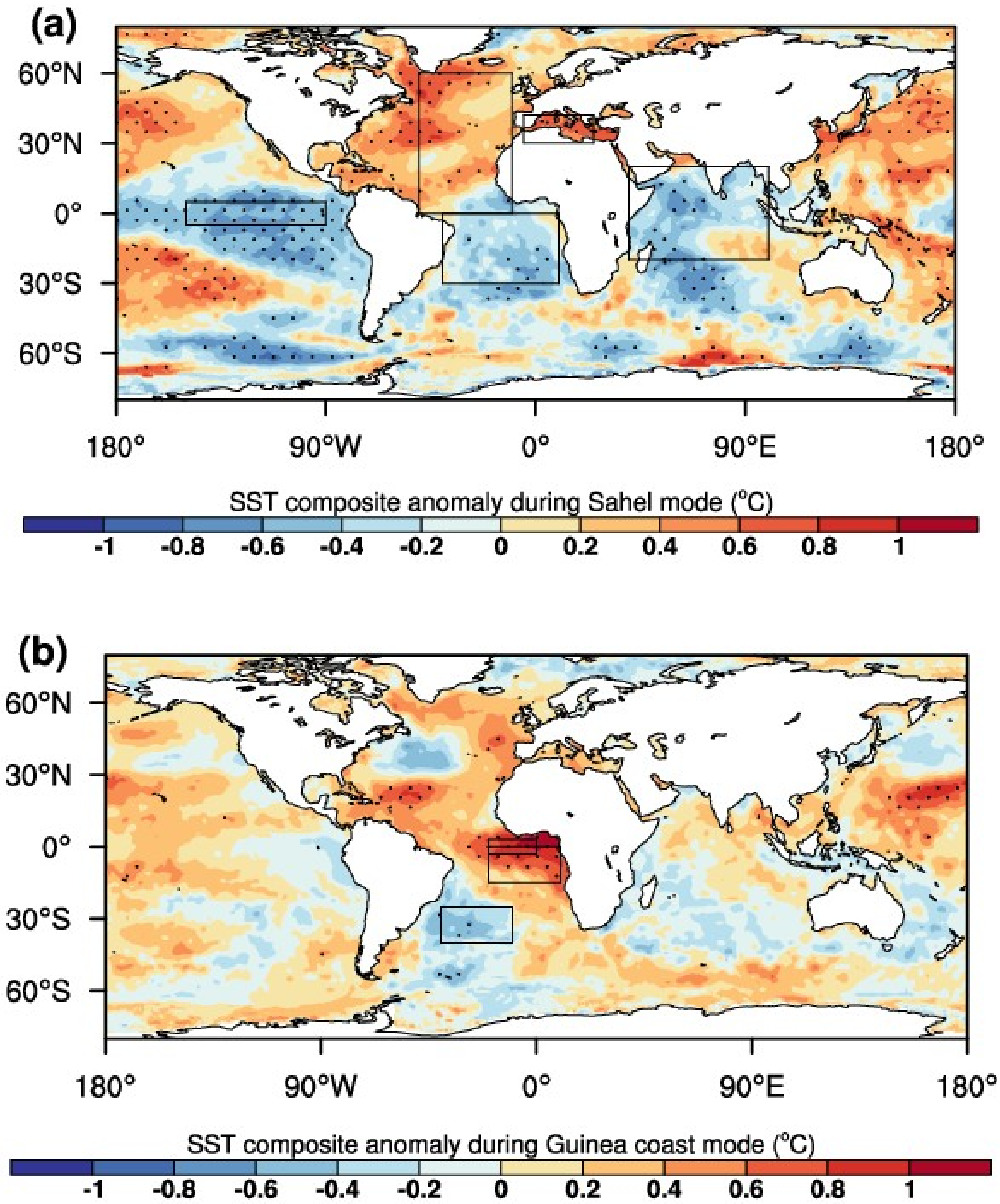

***Figure 18**: The composite anomalies of sea surface temperature pattern during the Sahel (a) and Guinea coast (b) modes (1950-2022). Stipples denote statistical significance at the 95% confidence level.*

The Guinea coast mode (Figure 18b) is primarily influenced by the Atlantic Zonal Mode (Atlantic Niño) and the South Atlantic Ocean Dipole (SAOD). The SAOD is characterised by a dipole structure of warm (cold) SST anomalies near the equator and cold (warm) anomalies along the South American coast. This pattern modulates rainfall over the Guinea coast and adjacent areas.

5.2.2. Spatial and temporal association between the dominant oceanic modes and West African precipitation variability

The relationship between the identified oceanic modes and West African precipitation from 1950 to 2022 is shown in Figures 19 and 20, respectively. Figure 19 shows the degree of association between the dominant sea surface temperature indices and regions in West Africa, with black dots depicting areas of significant relationship. The eastern Mediterranean Sea is positively associated with precipitation over most parts of West Africa. Strong association is observed over most parts of Mali and Burkina Faso, among others (Fig. 19a).

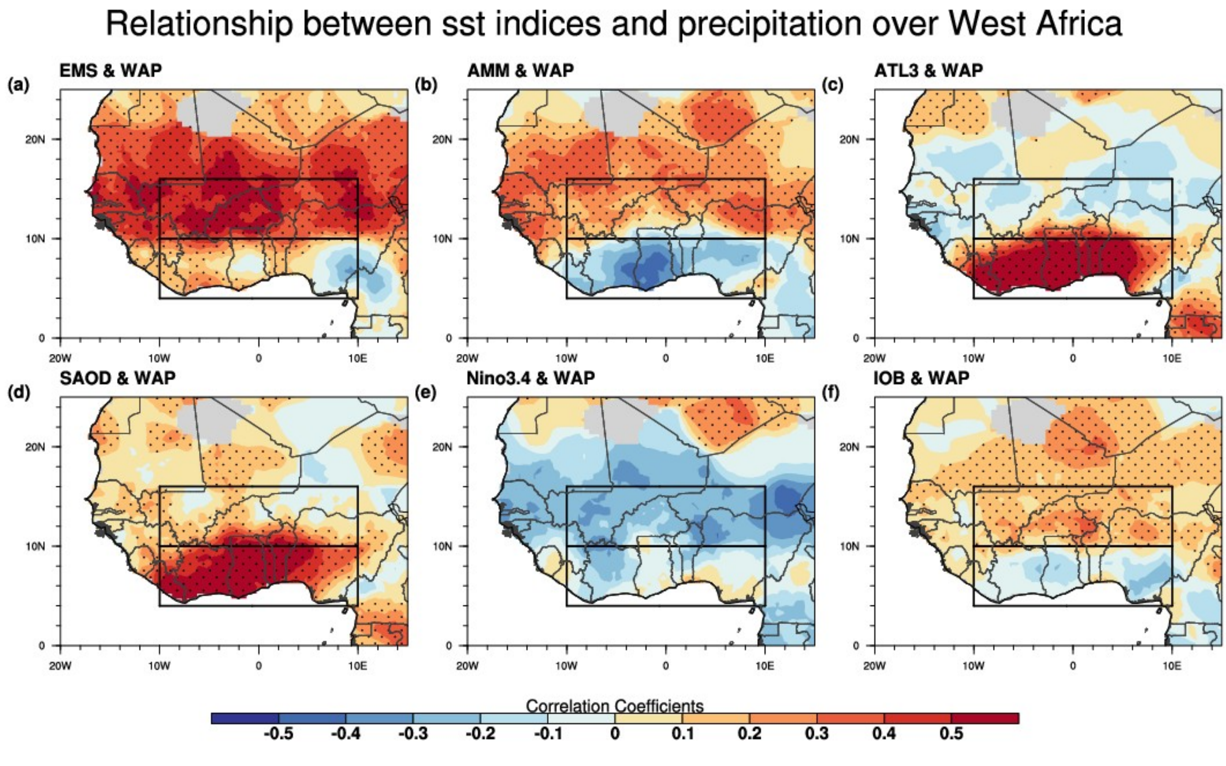

***Figure 19**: Relationship between dominant SST indices and precipitation over West Africa. Stipple represent grids of significant positive relationship at 95% confidence level.*

The relationship between the Atlantic meridional mode index shows a significant positive association over the Sahel region and around western Cameroon (Fig. 19b). While the Atlantic Niño index is strongly associated with precipitation variability over most parts of the Guinea coast region stretching from Liberia to western Nigeria and some mix patterns of insignificant association over the Sahel region. The SAOD depicts a more widespread, significant positive association over the West African region; over the Guinea coast areas, it depicts a similar pattern as the Atlantic Niño, though the degree of association is relatively weaker (Fig. 19d). There is no significant positive association between the equatorial Pacific index (Niño3.4) and West African precipitation variability. The Indian Ocean basin mode (IOB) is also significantly associated with precipitation variability over most parts of the Sahel. This oceanic mode, though significant, exerts the least influence over the teleconnection areas.

Figure 20 shows the association between the dominant oceanic modes and precipitation variability pattern over West Africa, emphasising areas of significant negative teleconnection. EMS is negatively associated with precipitation variability over southeastern Nigeria and the central part of Ghana. AMM is significantly negatively associated with most parts of the Guinea coast region, with few areas having a non-significant positive association. The ATL3 is also significantly negatively associated with most parts of the Sahel region, especially over the Niger Republic. SAOD is relatively not negatively associated with precipitation variability over West Africa except in few areas, such as the Western part of the Niger Republic and a few others. The equatorial Pacific Ocean (Niño3.4) is significantly negatively associated with precipitation variability over most parts of West Africa except in a few areas where a weak and non-significant positive association is found (Fig. 20e). The IOB shows a significant negative and weak association over most parts of the Guinea coast.

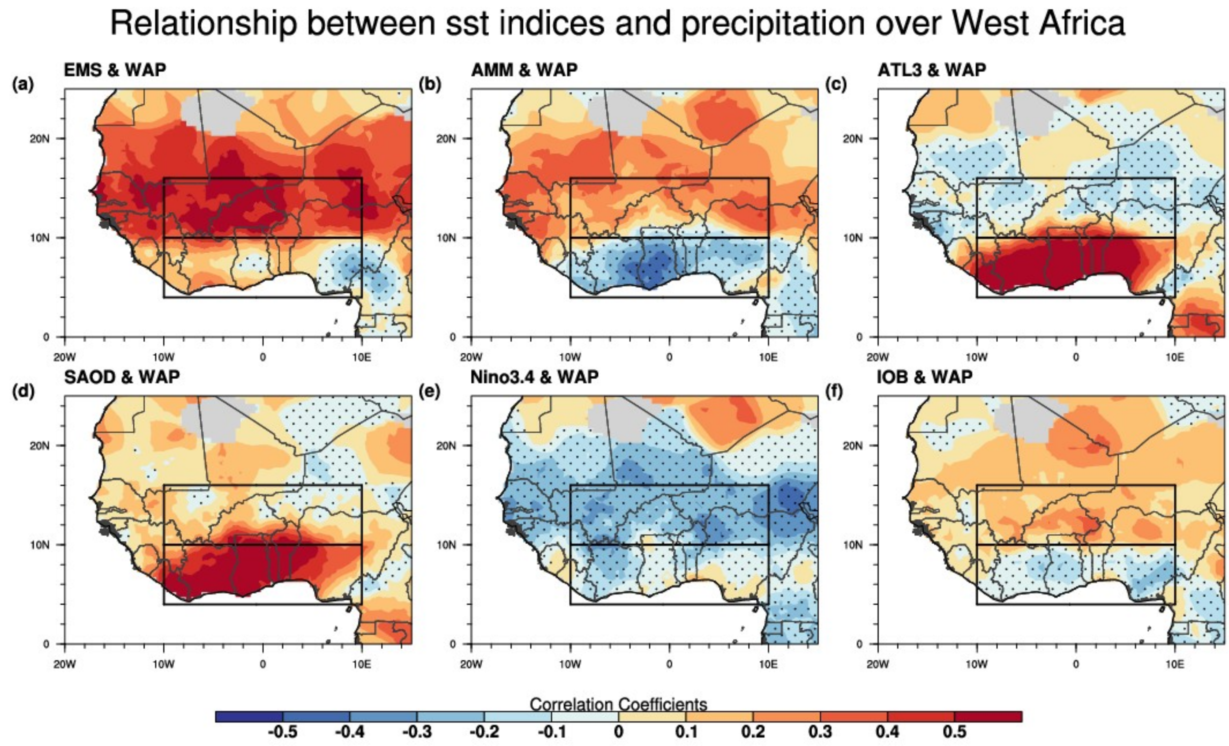

***Figure 20**: Relationship between dominant SST indices and precipitation over West Africa. Stipple represent grids of significant negative relationship at 95% confidence level.*

Table 7 shows the relationship between the identified oceanic basin SST indices and the dominant modes of precipitation variability in West Africa.

***Table 7:** Relationship between the SST indices and the leading modes of West African precipitation variability (those in bold are significant at 95%)*

WA modes	SST Indices					
	EMS	**ATL3**	**Niño3.4**	**SAOD**	**AMM**	**IOB**
Sahel	**0.60 (0.00)**	-0.01 (0.90)	**-0.33 (0.00)**	0.16 (0.18)	**0.26 (0.03)**	0.20 (0.09)
Guinea coast	0.14 (0.23)	**0.68 (0.00)**	-0.11 (0.35)	**0.62 (0.00)**	**-0.285 (0.02)**	-0.08 (0.52)

The identified SST indexes are all significantly related to precipitation variability in at least one domain of West Africa, with the EMS and ATL3 significantly correlated with precipitation in the Sahel and Guinea coast domains of West Africa. There is an inverse and significant influence of Niño3.4 SSTA on Sahel precipitation variability. Positive SSTA in the Niño3.4 region often corresponds to reduced Sahel precipitation. ATL3 and SAOD depict similar relationships with Guinea coast precipitation, although ATL3 had a higher level of relationship relative to SAOD. However, Nnamchi et al. (2017) assert that the SAOD is the dominant mode of variability in the South Atlantic Ocean. Lübbecke et al. (2018) explained that the characteristics of the SAOD seem to be intensely dependent on the study period and treatment of the data. There is no firm consensus on whether it should be viewed as a mode distinct from the Atlantic Niño. Therefore, we limited further analysis to the first three SST indexes (EMS, ATL3, and Niño3.4). Pomposi et al. (2020) obtained a similar correlation result of 0.33 for the Sahel-Niño3.4 relationship from the 1950-2015 period. Nevertheless, we present a higher yet significant relationship between Sahel precipitation and SSTA over the Mediterranean basin.

5.2.3. Joint impact of dominant Oceanic basins on West African precipitation variability

The extreme precipitation pattern due to the joint influence of leading oceanic basins SSTA on rainy season precipitation variability in West Africa is studied using the composite analysis technique. Table 8 presents the years used to derive the different joint effect phases.

Table 8*: Selected Event years based on a composite of different joint phases of SST Indices*

Basin index/Phases	**NN**	**NP**	**PN**	**PP**
ATL3-EMS	1969,1976,1978, 1983,1992	1964,1982,1994, 2012,2015	1974,1981,1984, 1996,2010	1952,1953, 1960,1963
ATL3-Niño3.4	1954,1964,1967, 1978,2000,2013	1965,1969,1976,1982, 1983,1997,2009,2012, 2014,2015	1952,1973,1984, 1988, 1999, 2010	1951,1953,1963 ,1979,1987
EMS-Niño3.4	1975,1978,1984, 2007,2010	1969,1972,1976,1983, 1991	1950,1952,1955, 1964,2022	1953,1963,1982 ,2012,2015

*NN is negative-negative, NP is negative-positive, PN is positive-negative, and PP is positive-positive

5.2.3.1 Eastern Mediterranean SSTA and Atlantic Niño

Sea surface temperature anomalies over the Mediterranean significantly influence the precipitation pattern in the West African Sahel. The joint impact of ATL3 and EMS is depicted in Figure 21.

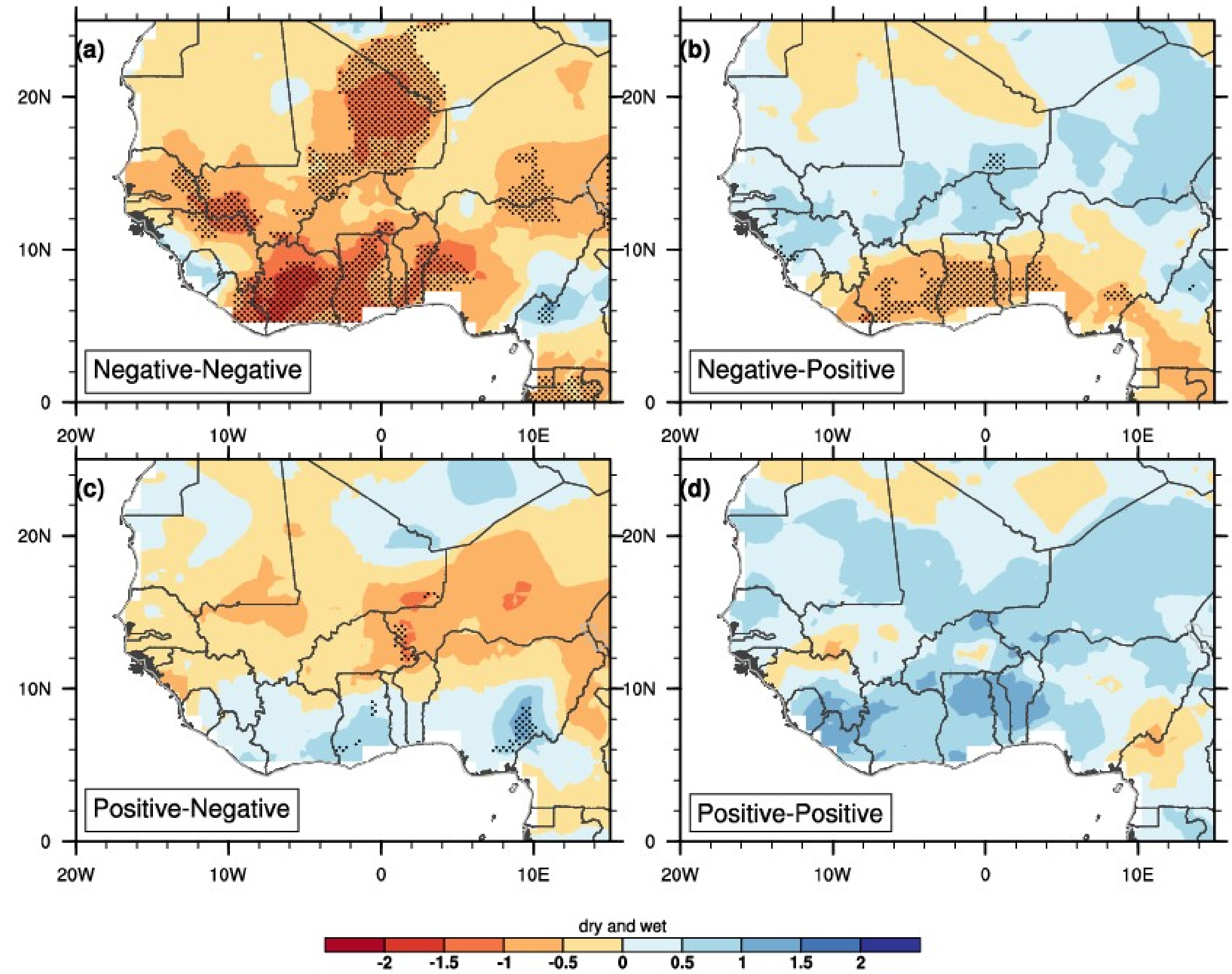

***Figure 21**: JJAS precipitation anomaly pattern based on the composite derived using ATL3 and EMS*

During simultaneous negative phases, the majority of the region experiences notably drier conditions, except for specific areas around Sierra Leone, Guinea, and Central Cameroon (Fig. 21a). Figure 21b illustrates significant drier-than-normal conditions over much of Cote d'Ivoire to Nigeria, with the Sahel region showing normal to wet conditions during a joint negative ATL3 and positive EMS phase. A general non-significant dipole pattern is observed during joint positive and negative phases, with some locations experiencing either significant wetness or dryness over the Guinea coast and Sahel region (Fig. 21c). When both oceanic regions are in their positive phase, a general, non-significant normal to wetter-than-normal precipitation condition prevails over most parts of the study area (Fig. 21d).

5.2.3.2 Atlantic Niño and Niño3.4

El Niño often brings drier conditions to West Africa, decreasing precipitation, while La Niña typically brings increasing moisture. Rainfall on the Guinea coast and Sahel regions is influenced by the positive and negative phases of the Atlantic zonal mode (Fig. 22a). During concurrent negative phases of ATL3 and Niño3.4, there is a dipole pattern with wetter conditions in the Tahoua region of Niger, southeast Mali's Ménaka region, and central Mauritania's Tagant region. Simultaneously, eastern Liberia, southwest Nigeria, and far north Cameroon experience significant dry spells.

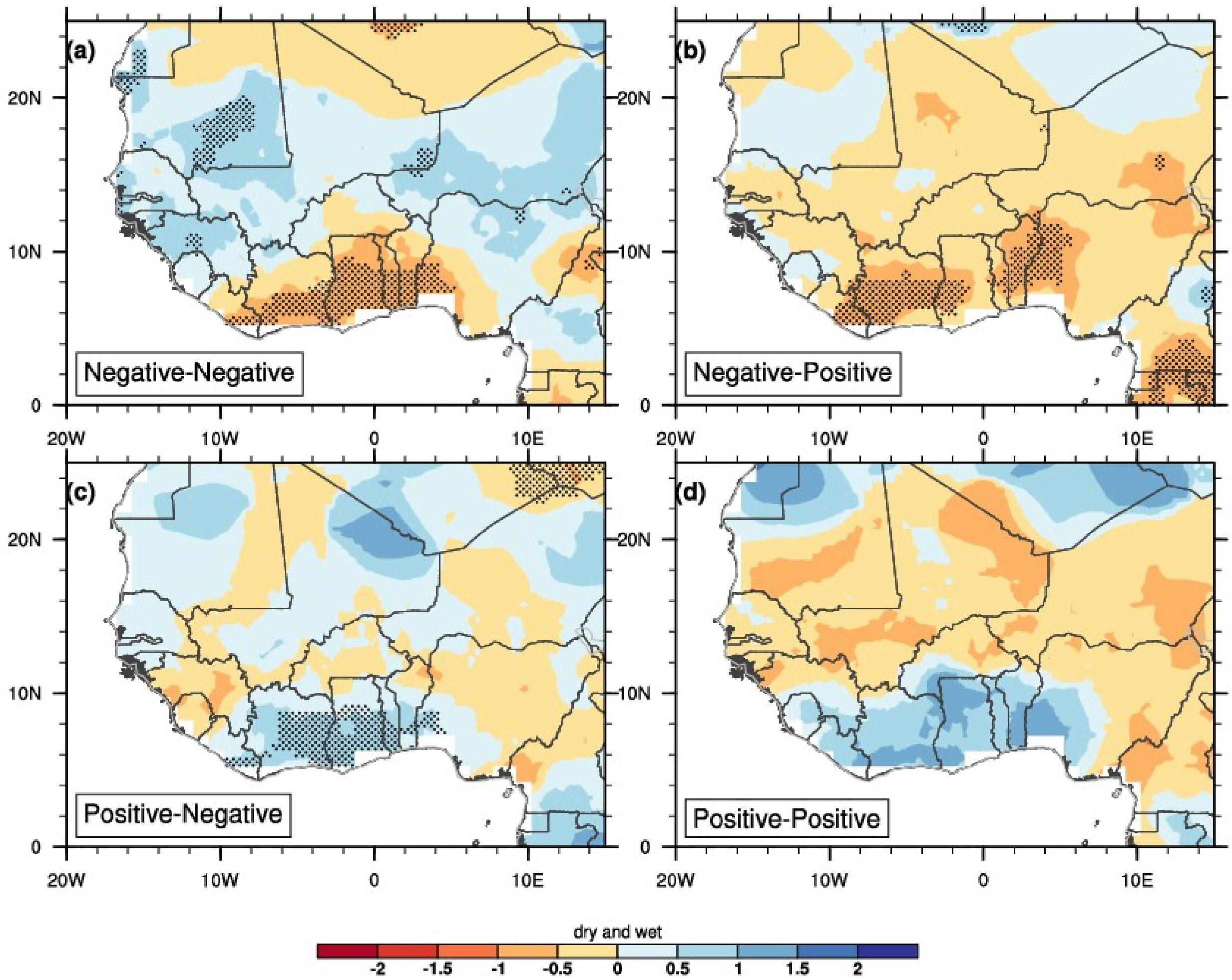

***Figure 22**: JJAS precipitation anomaly pattern based on the composite derived using ATL3 and Niño3.4*

The joint ATL3 and Niño3.4 negative and positive phases generally result in drier-than-normal conditions in most parts of West Africa. Central Cote d'Ivoire, northwest Nigeria, and Benin Republic are notable dry spots. At the same time, increased moisture is observed at the Cameroon, and Chad borders (Fig. 22b). Figure 22c illustrates the precipitation pattern during joint positive and negative ATL3 and Niño3.4 SSTA. Cote d'Ivoire and southwest Nigeria experience notably wetter-than-normal conditions. Overall, a dipole precipitation anomaly pattern, with a non-significant wet Guinea coast and dry Sahel, characterises West Africa during both oceanic basins' positive phases (Fig. 22d).

ENSO and Atlantic Niño jointly impact the distribution of precipitation in the region, and their respective combined phases influence their effects. Understanding these interactions is vital for enhancing seasonal climate predictions in the region. Previous research (Fontaine & Janicot, 1996) has highlighted the joint influence of the Tropical Pacific and Atlantic basins on West African precipitation variability. This relatively weak spatial effect occurs when ENSO's influence on the equatorial Atlantic is not robust due to the influence of tropospheric warming and oceanic downwelling in the North Tropical Atlantic propagating towards the ATL3 region (Cai et al., 2019).

5.2.3.3 Eastern Mediterranean SSTA and ENSO

Figure 23 shows the precipitation anomaly pattern associated with the joint impact of EMS and Niño3.4. Positive and negative SSTAs over the Mediterranean Sea are associated with wetter (drier) than normal conditions over West Africa. When both oceanic basins are in their negative phases, most parts of the West African region experience a relatively normal rainy season state (Fig. 23a). Figure 23b shows enhanced dryness over all parts of West Africa when both oceanic basins are in the phase inducing dry conditions. Consequently, most regions are significantly below-average during years with negative and positive phases of EMS and Niño3.4. The Sahel region exhibits significantly wetter-than-normal conditions when both basins are in wet-inducing phases (Fig. 23c). During this phase, southern parts of Ghana and Nigeria experience relatively normal to drier conditions. However, there is no significant anomalous precipitation pattern during concurrent positive phases of both oceanic basins (Fig. 23d).

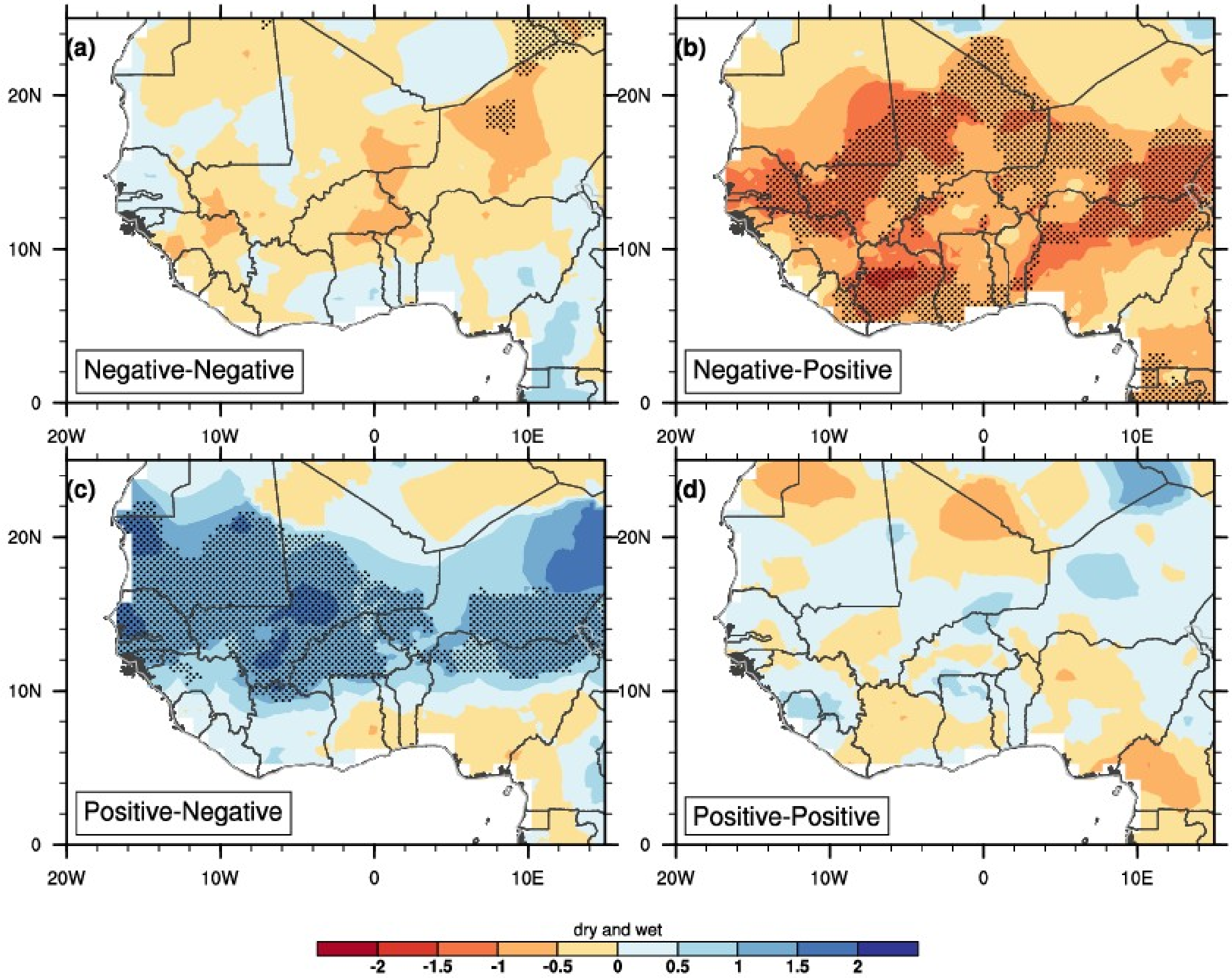

Figure 23: *JJAS precipitation anomaly pattern based on the composite derived using EMS and Niño3.4*

5.3. Discussion

This chapter investigates the influence of dominant sea surface temperature anomalies (SSTAs) on extreme precipitation events during the West African rainy season. The significant SST indices show different levels of association and areas of spatial relationships over the region, with the dominant ones including ATL3 (0.68), SAOD (0.62), EMS (0.60) and Niño3.4 (-0.33). The positive association between Guinea coast rainfall and ATL3 shows its importance. In recent years, studies have shown that a decrease in ATL3 variability has been linked to a weakening in the Bjerknes Feedback due to weaker thermocline feedback and increased net heat flux damping (Prigent et al., 2020; Silva et al., 2021).

Furthermore, the AMM significantly impacts the two modes of variability compared to the dominant SST indices that significantly impact one of the leading domains. AMM shows interannual to decadal scale variability and is connected to the ITCZ migration, affecting the precipitation pattern over West Africa and South America (Sobral Verona et al., 2023). This result supports the assertion of Wang (2006) that "the interbasin SST anomaly gradient is important for influencing tropical climate variability." Also, it corroborates Janicot et al.*'s* assertion that SST anomaly couplings in different oceanic basins, especially in the equatorial Pacific and Atlantic, could enhance or dampen their impact on the West African monsoon dynamics (Janicot et al., 1998). They further state that SST anomalies in the eastern equatorial Pacific tend to modulate the vertical motion over West Africa. This coupling makes relying only on the dominant SST drivers for predicting West African monsoon precipitation variability in specific years unreliable.

The joint effects of these anomalies result in distinct precipitation patterns across the region, offering a novel perspective on the drivers of West African Summer Monsoon (WASM) precipitation variability. While this study identifies clear patterns in the influence of SST anomalies on WASM precipitation, it is essential to acknowledge the complexities involved in these interactions. Previous research has shown that the response to large-scale climate variability, such as El Niño, can be non-linear and is influenced by interactions with other climate modes. For instance, Pomposi et al., (2020) found that the response to El Niño in regions like the Sahel might not be straightforward due to interactions with other climate modes, such as the Atlantic Meridional Mode (AMM) and the Indian Ocean Dipole (IOD). Similarly, Di Lorenzo et al., (2015) argue that the precipitation response to large-scale climate variability can be complex due to the interplay between different climate modes. These results show that while Mediterranean SST anomalies significantly influence Sahel precipitation. The combined effects of SST anomalies from different ocean basins can lead to non-linear and sometimes unexpected outcomes. For example, the positive phase of ENSO, typically associated with decreased precipitation in the Sahel, might interact with a warm Mediterranean SST anomaly to produce a different precipitation pattern than expected. This complexity underscores the need for more nuanced analyses considering the interplay between various climate modes.

The study emphasises the importance of considering the interactions between SST anomalies from different oceanic basins, corroborating Gao et al., (2022) assertion on the significance of these interactions in understanding regional precipitation extremes. Our findings align with this perspective, demonstrating that the combined effects of SST anomalies from the Mediterranean, Atlantic, and Pacific Oceans result in distinct precipitation patterns across West Africa. The SST anomalies that predominantly influence the Sahel mode are the Mediterranean and Atlantic Oceans. In contrast, the Guinea Coast mode is more affected by anomalies in the equatorial Atlantic Ocean. This finding suggests that regional precipitation patterns are not solely driven by anomalies in one ocean basin but by the combined effects of anomalies from multiple basins. This insight is crucial for improving climate predictions and developing more effective adaptation strategies. For instance, during years when warm SST anomalies are present in both the Mediterranean and the equatorial Atlantic, the Sahel region experiences significant reductions in precipitation. However, if a warm SST anomaly in the Mediterranean coincides with a cold anomaly in the Atlantic, the reduction in precipitation is less pronounced. This finding suggests that understanding the combined effects of SST anomalies can lead to more accurate predictions of precipitation variability and better-informed adaptation strategies.

These results also highlight the significant regional variability in precipitation responses to SST anomalies within West Africa. Okonkwo et al., (2015) suggested that the decline in Lake Chad's water level is linked to the combined effects of the cold phase of the AMM and the warm phase of ENSO, challenging the notion that Mediterranean SST anomalies alone can explain this phenomenon.

The findings highlight complex interdependencies between SST anomalies in different oceanic basins and West African precipitation. The Mediterranean Sea's influence on the Sahel is notable, particularly during positive SST phases, which enhance rainfall. This result aligns with previous studies suggesting that Mediterranean SSTs modulate monsoon circulation over West Africa by altering the thermal gradient between land and sea (Rowell, 2003).

The Atlantic Niño and SAOD are closely linked, as both involve SST variability in the equatorial Atlantic. However, their combined effect can differ from individual impacts due to interactions between atmospheric circulation patterns, such as the West African monsoon flow and the Intertropical Convergence Zone (ITCZ) position (Nnamchi et al., 2017). The lack of a strong correlation between Niño3.4 and precipitation suggests that ENSO's influence on West Africa is secondary to other modes like the Atlantic Niño and Mediterranean SST.

While the SAOD is considered a distinct mode, its dependence on study periods and data treatment raises questions about its stability and predictability (Lübbecke et al., 2018).

This uncertainty complicates efforts to forecast its impact on West African precipitation reliably. Further research is needed to clarify these dynamics and improve seasonal forecasting models.

5.4. Partial conclusion

This chapter has demonstrated the significant impact of SST anomalies in various oceanic basins on West African precipitation. The study highlights the need for integrated analysis of multiple oceanic modes to understand their joint influence on regional climate variability. While the Mediterranean Sea, Atlantic Niño, and SAOD are vital drivers, their interactions can lead to complex precipitation patterns. For example, the joint impacts of the Mediterranean Sea and equatorial Pacific SSTA on West Africa are associated with large-scale wet and dry events over West Africa. Future research should focus on disentangling these interactions to enhance the predictability of West African monsoon variability. This is crucial for effective climate prediction and modelling in the region.

CHAPTER 6: FUTURE TREND IN WEST AFRICAN PRECIPITATION IN CMIP6 MODELS

6.1. Introduction

Climate change science seeks to understand the physical, chemical, biological, and geological processes and the interactions among these processes that produce climate. It's goal is to predict future climates' based on natural variability and to project future climates based on assumptions of future human activities. These predictions and projections are determined from climate models and may be used to develop strategies for mitigating the effects of climate change and adapting to the expected changes. This chapter examines the effects of climate change on West African monsoon precipitation variability through a multi-scenario and multimodel mean approach by seeking to answer the question, "What will the future monsoon precipitation of West Africa look like?"

6.2. CMIP6 Model Evaluation

The Coupled Model Intercomparison Project Phase 6 (CMIP6) provides the latest climate model outputs, which are instrumental in projecting future climate scenarios. Two fundamental aspects of model validation are addressed here: the ability to simulate i) the rainy season long-term mean precipitation and ii) the two leading modes of precipitation variability. CRU precipitation is used as reference observation data. Evaluating these simulations performance during the historical period is vital for understanding potential future changes in precipitation extremes.

Figure 24 shows the CMIP6 multimodel mean bias and agreement. Generally, the models underestimate precipitation over the coastal areas compared to the Sahel region. In terms of model agreement, more than 95% of the analysed models agree on the sign of bias between the models and the observed dataset. There is less bias over the Sahel region than the Guinea coast region.

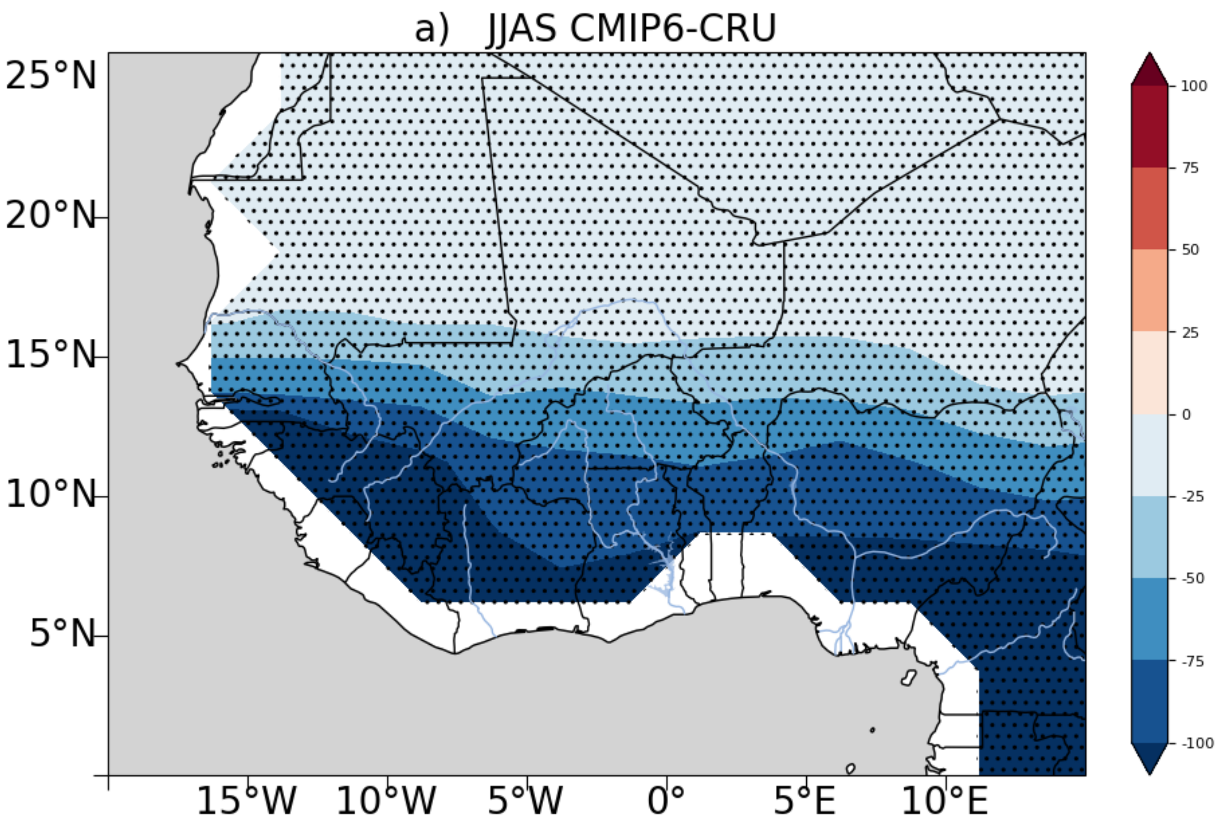

Figure 24*: CMIP6 ensemble mean JJAS precipitation bias over West Africa during the historical period (1950–2014). Black stippling indicates where at least 75% of the models show the same sign of bias.*

Furthermore, the ability of the multimodel mean of the 24 models to simulate the two leading modes of precipitation is shown in Figure 25. Figure 25a-d shows the bias during the Sahel mode of variability. Moreover, it is observed that in June, there was an overestimation (underestimation) over the Sahel (Guinea coast) region, respectively, with a general overestimation in the whole region in July. However, in August, there is an underestimation over the Sahel region and an overestimation over the Guinea coast; a reverse pattern is observed in September.

During the Guinea coast mode, the significance of the bias is less robust compared to that of the Sahel mode, with overestimations in August and September in greater parts of the region.

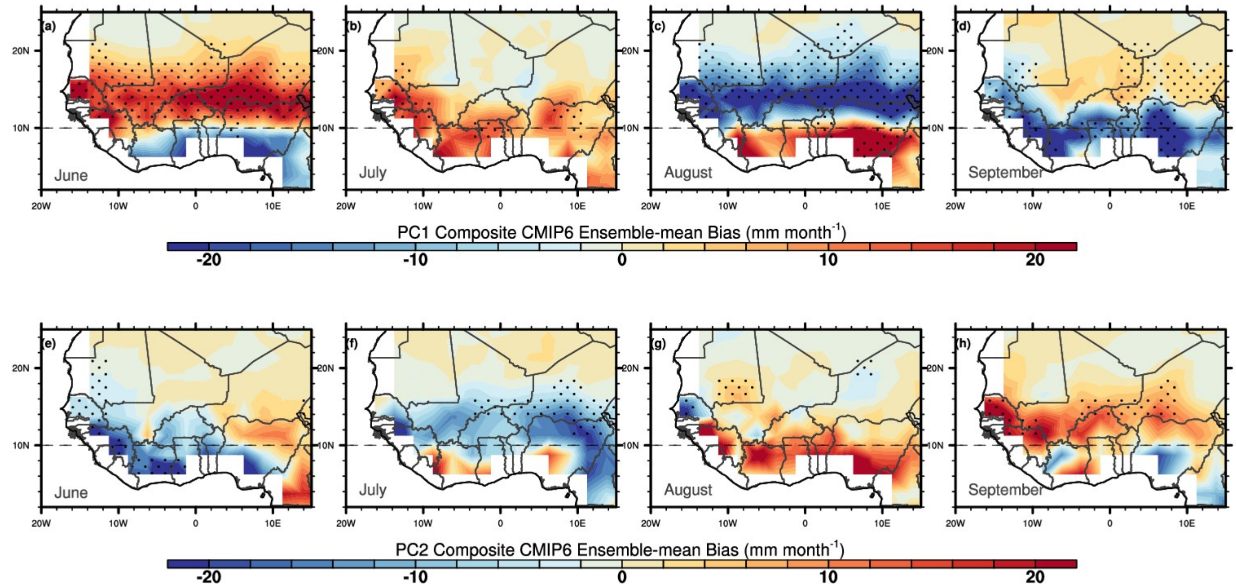

Figure 25: *CMIP6 multimodel-mean bias in simulating leading modes of precipitation variability over West African monsoon region*

Figure 26 shows the temporal relationship and biases between the CMIP6 MME and CRU precipitation over West African precipitation modes. In Figure 26a, the first principal component (PC1) shows a strong correlation ($r = 0.69$, $p < 0.01$), indicating that CMIP6 MME captures the dominant precipitation variability fairly well, especially after 1980. However, discrepancies are evident before 1980, when the CMIP6 model underestimates the observed negative anomalies in the 1970s. Figure 26b shows the second principal component (PC2), with a much weaker correlation ($r = 0.07$, not significant), suggesting that CMIP6 struggles to simulate the Guinea coast mode accurately, with significant mismatches across the entire period.

Figures 26c-d display the differences between the CMIP6 MME and CRU data for PC1 and PC2, respectively. For PC1, larger differences are concentrated in the earlier decades, especially pre-1980, where CMIP6 underestimates CRU's variability, while smaller discrepancies occur post-1980. In contrast, for PC2, the discrepancies are more evenly distributed across the entire period, with no clear improvement over time. This indicates that CMIP6 models better simulate the dominant mode of variability (PC1) but struggle with the secondary mode (PC2), which may be influenced by more complex, localised processes not well-represented in the models.

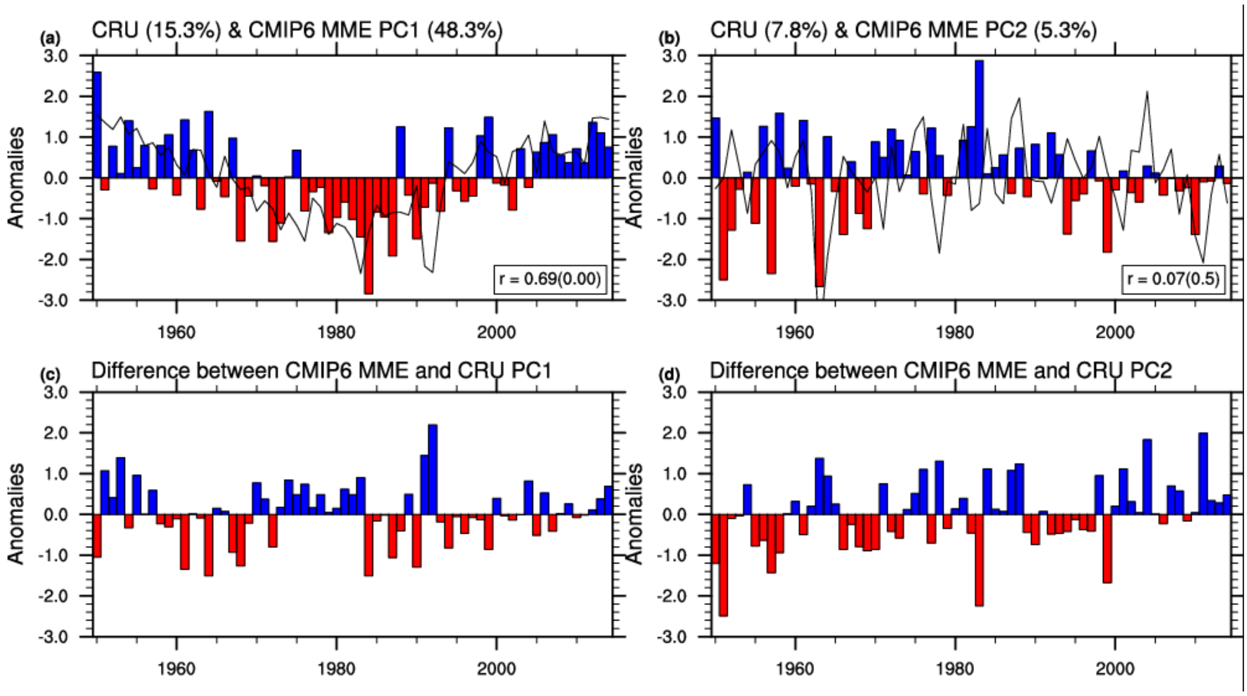

Figure 26: *Comparison between observed and CMIP6 MME temporal evolution of the West African leading precipitation modes (1950-2014)*

The individual models' ability to simulate the region's JJAS mean precipitation pattern was examined using root mean square error (RMSE) and correlation statistics. The smaller the RMSE score, the better the model simulation, while the higher the correlation coefficient, the more realistic the simulation.

Table 9 shows that the RMSE is relatively high over the two domains, with better performance over the Sahel domain.

***Table 9**: Root Mean Square Error between CMIP6 models and CRU precipitation*

Model	Sahel	Guinea coast
ACCESS-CM2	131.85	188.34
ACCESS-ESM1-5	130.57	186.14
BCC-CSM2-MR	130.8	186.22
CAMS-CSM1-0	130.65	187.61
CanESM5	130.05	184.25
CESM2	129.03	185.19
CESM2-WACCM	128.86	185.09
CMCC-CM2-SR5	129.21	186.16
CMCC-ESM2	129.81	186.7
EC-Earth3-Veg	131.7	186.36
FGOALS-f3-L	131.46	186.28
FGOALS-g3	131.86	188.49
FIO-ESM-2-0	128.98	187.77
GFDL-ESM4	127.01	182.64
IITM-ESM	131.22	188.17
INM-CM5-0	131.31	186.9
KACE-1-0-G	130.43	187.42
MIROC6	127.81	184.31
MPI-ESM1-2-HR	130.69	187.02
MPI-ESM1-2-LR	130.74	187.36
MRI-ESM2-0	130.19	186.1
NESM3	129.63	185.08
NorESM2-LM	129.72	187.06
NorESM2-MM	128.68	187.52

The top five performing models over the Sahel domain include: GFDL-ESM4, MIROC6, NorESM2-MM, CESM2-WACCM, and FIO-ESM-2-0, and the last five are FGOALS-g3, ACCESS-CM2, EC-Earth3-Veg, FGOALS-f3-L and INM-CM5-0. The five best models for the Guinea coast region are GFDL_ESM4, CanESM5, MIROC6, NESM3, and CESM2-WACCM, while the poor models are FGOALS-g3, ACCESS-CM2, IITM-ESM, FIO-ESM-2-0, and CAMS-CSM1-0.

Generally, the RMSE is higher over the Guinea coast, with a range of 188.49 to 182.64, compared to the Sahel region, which has a range of 131.86 to 127.01.

Furthermore, Table 10 shows the relationship between the simulated and observed (CRU) JJAS precipitation for the two leading domains over West Africa. It is observed that the 24 analysed models have a very strong positive correlation coefficient ($r >= 0.8$) over the Sahel domain, suggesting a satisfactory simulation of the spatial distribution of summer monsoon precipitation over the region. However, only seven models over the

Guinea coast domain have a r >= 0.5, suggesting a divergent and unsatisfactory simulation of the Guinea coast precipitation.

***Table 10**: Correlation coefficients between observed and simulated JJAS precipitation during the period 1950–2014 over the two leading sub-domains of West Africa*

Model	Sahel	Guinea coast
ACCESS-CM2	0.84	-0.02
ACCESS-ESM1-5	0.91	0.33
BCC-CSM2-MR	0.85	0.25
CAMS-CSM1-0	0.96	-0.24
CanESM5	0.84	0.23
CESM2	0.95	0.52
CESM2-WACCM	0.95	0.54
CMCC-CM2-SR5	0.96	0.31
CMCC-ESM2	0.95	0.31
EC-Earth3-Veg	0.85	0.13
FGOALS-f3-L	0.86	-0.1
FGOALS-g3	0.8	0.56
FIO-ESM-2-0	0.93	0.4
GFDL-ESM4	0.91	0.53
IITM-ESM	0.92	-0.26
INM-CM5-0	0.83	0.04
KACE-1-0-G	0.92	0.31
MIROC6	0.93	0.42
MPI-ESM1-2-HR	0.9	-0.2
MPI-ESM1-2-LR	0.93	-0.51
MRI-ESM2-0	0.83	0.64
NESM3	0.94	0.31
NorESM2-LM	0.96	0.64
NorESM2-MM	0.96	0.61

Based on the different metrics used in assessing the bias in the CMIP6 models, it is observed that the models performed better over the Sahel region relative to the Guinea coast. Using a correlation coefficient of >=0.5 in both domains, the models that best reproduce the observed pattern of JJAS precipitation are CESM2, CESM2-WACCM, FGOALS-g3, GFDL-ESM4, MRI-ESM2-0, NorESM2-LM, and NorESM2-MM. The future trend of the leading mode of precipitation variability is, therefore, presented in the next section for two future periods using the multimodel mean of the good models.

6.3. Future trend of precipitation variability over West Africa

Information about future regional precipitation patterns is crucial for planning and managing critical infrastructure, such as hydropower plants, water reservoirs, and city planning. Unpreparedness for changes and variations in regional precipitation regimes may disrupt the water-food-energy supply chains and lead to avoidable deaths and damages from precipitation-induced disasters.

6.3.1. Temporal trend of leading modes precipitation

The different scenario simulations of the temporal evolution of the leading modes of precipitation variability are presented in Figure 27. Future evolution of the Sahel mode (Fig. 27a) shows the persistence of extreme wet phase from 2015 to 2045 under SSPs 3-70 and 5-8.5 and a change in phase to drier than normal conditions from 2060 to 2100. In contrast, SSP 1-2.6 depicts a near-normal condition with drier-than-normal conditions from 2015 to 2035 and a wetter-than-normal condition towards the end of the century. SSP 2-4.5 depicts a general wetter-than-normal pattern from 2015 to 2045, which switches to a drier-than-normal phase and a wetter-than-normal phase from 2085 to 2097. While the lower SSPs project a wetter-than-normal precipitation in the far future, the higher scenarios project a wetter-than-normal 2020s that gradually change to normal conditions and a drier-than-normal state from 2075 onwards. However, the Guinea coast mode (Fig. 27b) depicts a general inter-annual variability pattern with no general trend among the different scenarios. They generally project fluctuations within the normal condition (=< ±1 SD).

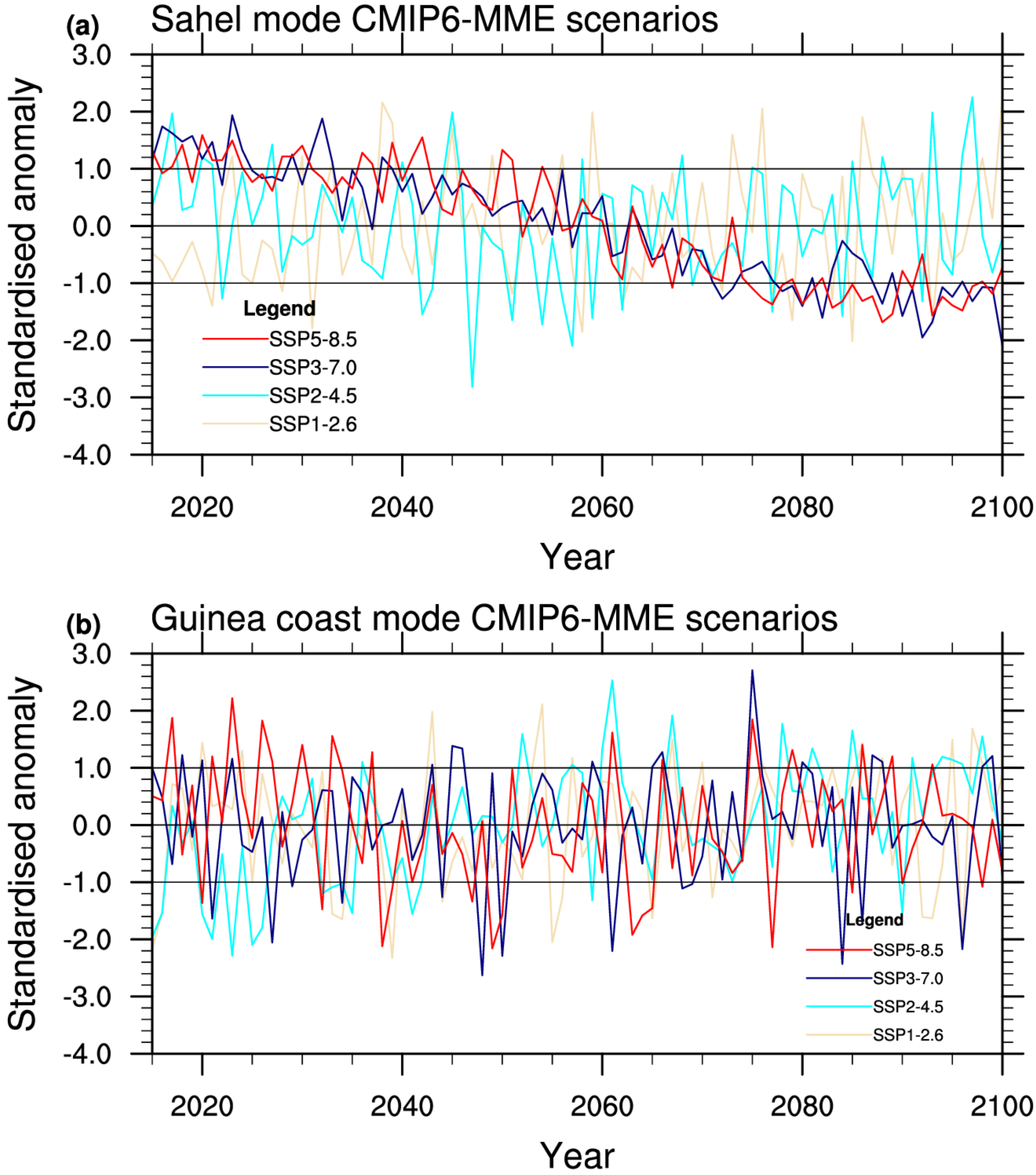

Figure 27: *Multimodel mean projected precipitation variability over West Africa based on the two leading PCs (2015-2100)*

6.3.2. Spatial pattern of near-future precipitation trend over West Africa (2020-2059)

The near future projected trend during the Sahel mode of precipitation variability is shown in Figure 28. The figure was derived based on the season-reliant empirical orthogonal function analysis leading principal component regressed unto the monthly precipitation; red and blue shadings represent drier and wet conditions, respectively. Figures 28a-d show the projected trend for SSP1-2.6; it is observed that June will be relatively normal with a slight significant increase in precipitation around the Guinea highlands. In July, a dipole pattern with significantly wetter conditions over most parts of the Sahel, especially in Mali, Burkina Faso, Niger, Benin, and Nigeria, is observed. A wetter-than-normal trend is projected for August, with the most increase occurring in Cote d'Ivoire, Guinea, Sierra Leone, and Liberia. A similar pattern is also observed in September, though with less intensity. SSP2-4.5 projects a drier pattern that is significant over the Guinea coast region in June, which progresses to a near-normal condition in July. A slight, significant increase is projected over Guinea highland areas and some parts of Niger and Mali. This pattern of increase intensifies in August over the Guinea coast region with near-normal dry, insignificant conditions over most parts of the Sahel, which progresses into September.

Under SSP3-7.0 (Fig. 28i-l), a significant increase in precipitation is observed over most parts of the Guinea coast and southern parts of the Sahel region. However, under this scenario, the eastern part of the Sahel is projected to be significantly drier than normal in August and September. SSP5-8.5 projects wetter-than-normal conditions over the western part of the study area and drier-than-normal conditions over the eastern part, with a significant decline over the northeastern part of Nigeria in June, July shows a tendency towards wetter conditions over most parts of the region, especially between latitudes 8 and 14 degrees. A similar pattern is projected in August and September, with an insignificant decrease in precipitation over most parts of the Niger Republic in August (Fig. 28m-p).

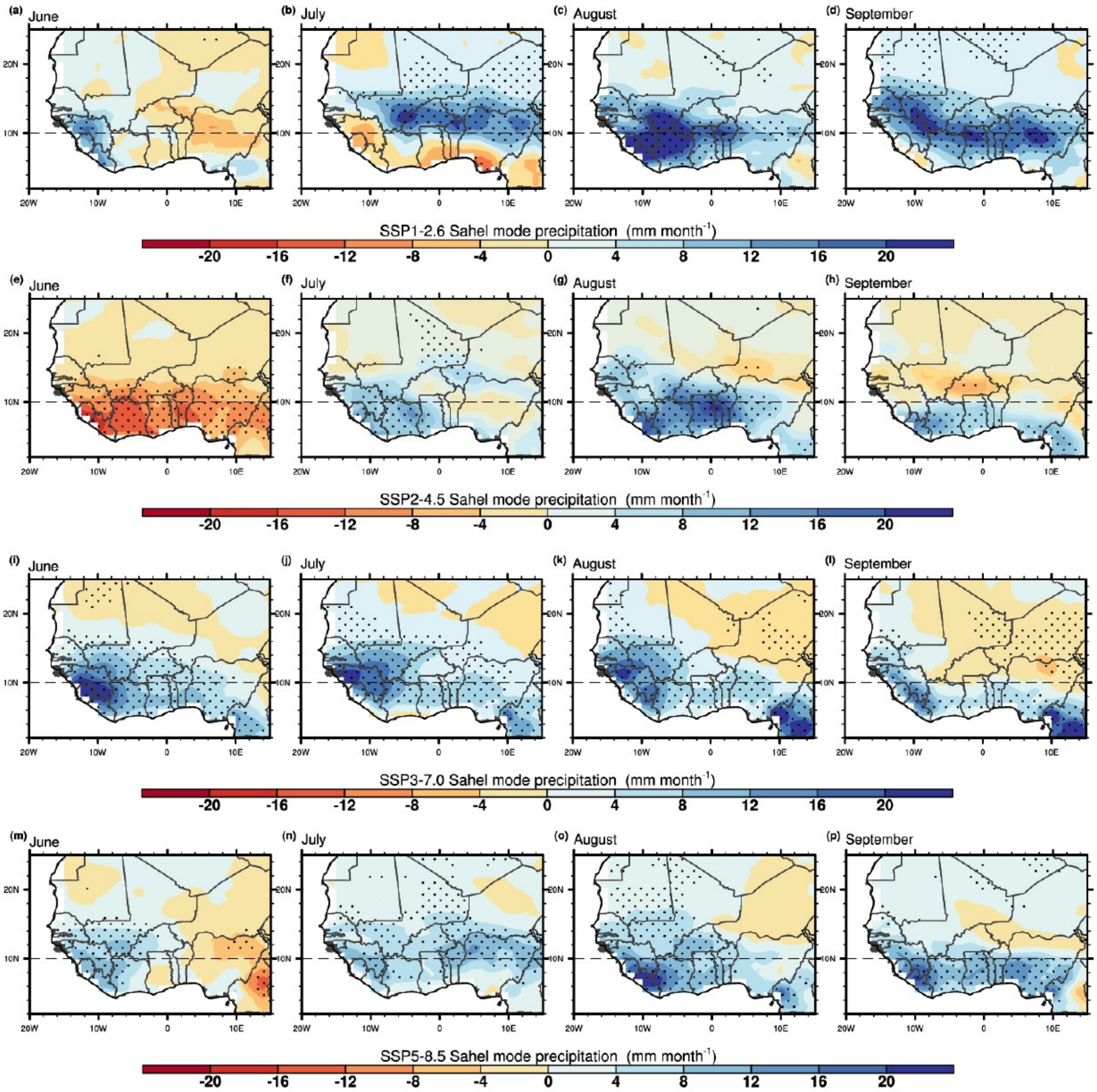

Figure 28: *Projected trend in leading mode of precipitation variability over West Africa based on ensemble mean of the good models (2020-2059)*

The near future is generally projected to experience wetter-than-normal conditions in July-August and September over most parts of West Africa, especially the Guinea coast region, with insignificant drier trends over the eastern parts of the Sahel.

6.3.3. Spatial pattern of far future precipitation trend over West Africa (2060-2099)

The far-future trend in the leading mode of precipitation variability over West Africa is presented in Figure 29. SSP1-2.6 shows a clear decline in precipitation, especially over the Sahel region, suggesting a significant drying trend over Mali, Burkina Faso, Niger and northern Nigeria, particularly during July and August and wetter than normal Guinea coast, especially in August and September (Fig. 29a-d). At the same time, the SSP2-4.5 scenario (Fig. 29e-h) shows an overall drying trend over West Africa. Significant areas of wet trend are observed over the central Sahel, especially around Mali, Burkina Faso, Niger and Nigeria in August. Furthermore, Figure 29i-l shows that under the SSP3-7.0 scenario, a more extensive and severe drying trend is observed over West Africa during the monsoon months. The drying trend is significant over most parts of the Guinea coast relative to the eastern Sahel region. This scenario signals an intense reduction in precipitation, indicating a significant risk of drought during the rainy season if emissions continue to rise. Under SSP5-8.5 (Fig. 29m-p), the worst-case scenario, the West African region is projected to face severe and widespread precipitation decline. From June to September, drying intensifies, particularly over most parts of the Sahel, except around the Lake Chad and Guinea coast regions in August.

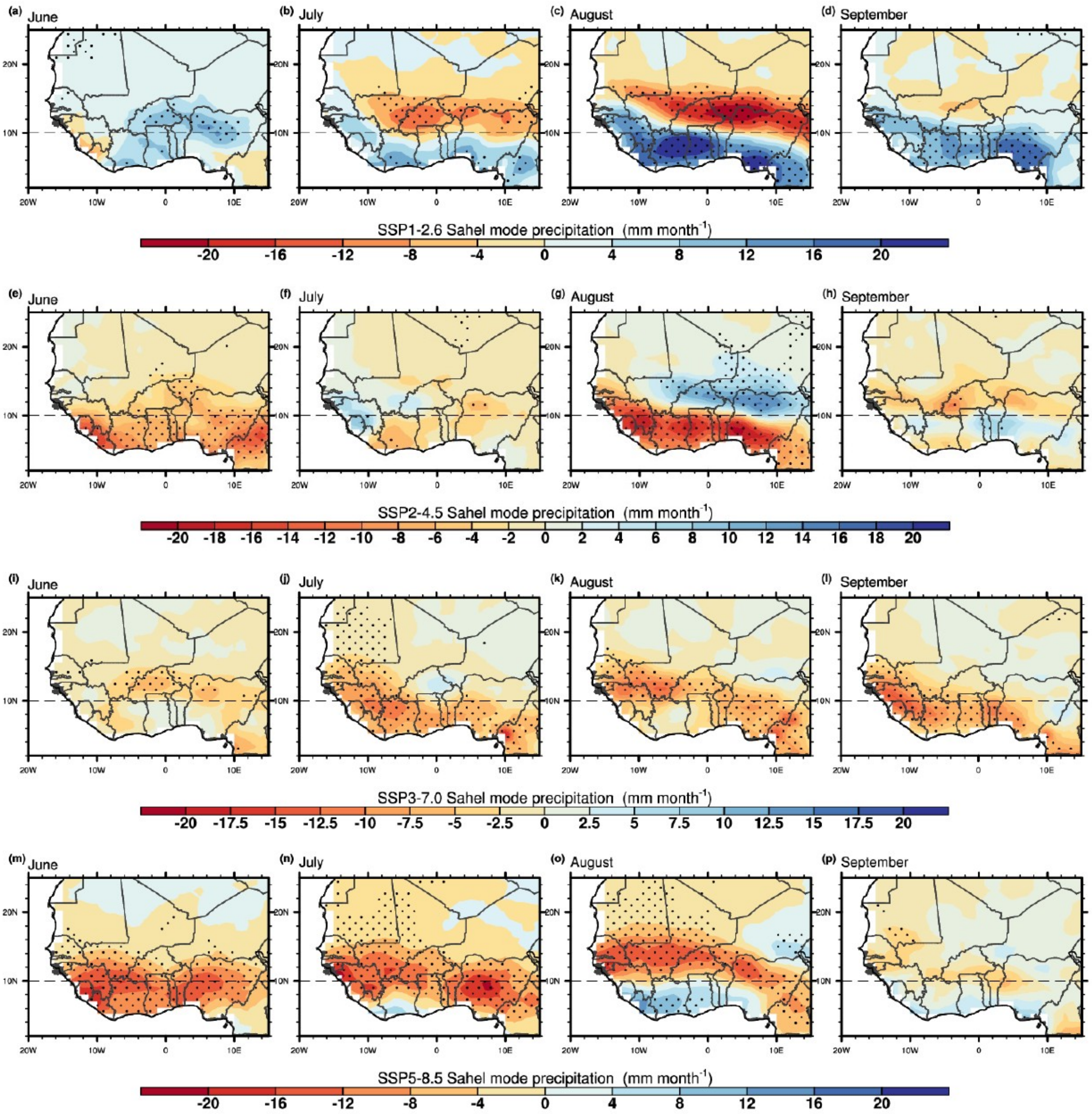

Figure 29*: Projected trend in leading mode of precipitation variability over West Africa based on MME of the good models (2060-2099)*

During the Sahel mode of precipitation variability, a drier trend is projected over the West African region from 2060 to 2099.

6.4. Discussion

This chapter investigates the future trend in monsoon season precipitation over West Africa using MME derived from CMIP6 model outputs. The model's simulations of precipitation characteristics performed better over the Sahel region and during the Sahel mode of variability compared to the Guinea coast domain and mode, where their performance is relatively poor. The inability to realistically replicate the observed precipitation characteristics has been observed by (Agyekum et al., 2018, 2023; Ajibola et al., 2020; Cook & Vizy, 2006; Faye & Akinsanola, 2022; Nworgu et al., 2024; Tamoffo et al., 2023; Worou et al., 2022). For instance, Ajibola et al., (2020) found that High-Resolution Model Intercomparison Project (HighResMIP) simulations underestimate the annual peak of rainfall during August, though they were able to captured the general rainfall pattern and the spatial daily pattern of precipitation in the monsoon season (from June to September) over West Africa, with a high correlation coefficient exceeding 0.8 for the mean field and a relatively lower correlation coefficient for extreme events. Their result shows that merely improving the horizontal resolution of GCMs may not remove biases from the CMIP6. Faye and Akinsanola, (2022) show that the performance of the CMIP6 models differ considerably between Sahel and Guinea coast subregions. The persistent biases in capturing the region's extreme precipitation characteristics is consistent with previous multi-model ensemble studies (e.g. Ajibola et al., 2020; Akinsanola et al., 2021; Ayugi et al., 2021; Bouramdane, 2023; Faye & Akinsanola, 2022; Hamed et al., 2022; Kurniadi et al., 2022; Mathbout et al., 2023; Nooni et al., 2023; Rivera & Arnould, 2020).

Base on this multimodel mean is suggested to be used in studying future trend in climate variables (Abatan et al., 2017; Agyekum et al., 2018; Fotso-Nguemo et al., 2019; Izumo et al., 2020; Lim et al., 2023; Martinez-Villalobos & Neelin, 2023; Narsey et al., 2020; B. Wang et al., 2021; Zittis et al., 2021). The future trends of monsoon precipitation over the Sahel indicate that, under higher-emission scenarios (SSP3-7.0 and SSP5-8.5), the region is expected to experience widespread and severe declines in rainfall, particularly in the northern Sahel. Conversely, lower-emission scenarios (SSP1-2.6 and SSP2-4.5) show less drastic drying, with potential increases in precipitation during peak rainy months, especially in the southern Sahel. As emissions rise, the drying trends intensify, leading to greater risks of drought, with the northern Sahel being the most vulnerable to arid conditions. In conclusion, the future of West African monsoon precipitation hinges heavily on global emission trajectories, with high emissions amplifying drought risks and low emissions allowing for more stable or even increased precipitation during the rainy season.

6.5. Partial conclusion

This chapter has evaluated and show that CMIP6 models tend to perform better over the Sahel region and the Sahel mode of West African precipitation variability. Possible reason for this may be due to the improved simulations of the drivers of Sahel precipitation variability such as ENSO, IOB, North Atlantic modes among others relative to the main driver of the Guinea coast mode: the Atlantic Nino. While the near future state of precipitation variability will gradually switch to a near normal state. Drier conditions are projected to occur in the far future under higher emission scenarios.

CHAPTER 7: IMPACTS AND RISK REDUCTION STRATEGIES TO EXTREME WET AND DRY CONDITIONS IN WEST AFRICA

7.1. Introduction

Climate variability and changes are perceived as a new challenge due to their ability to exacerbate existing dysfunctionalities, especially among the most exposed groups and regions. Historically, seasonal precipitation variability has significantly impacted agriculture and water-dependent sectors in several regions globally (Guido et al., 2020), and, in recent times, has exacerbated disaster occurrences. The previous results have established the trend and dominant modes of precipitation variability over West Africa using climatological analysis. This chapter seeks to ascertain the validity of the results based on the perceptions and experiences of respondents in selected countries of West Africa. In addition, their observed impacts and possible risk-reduction strategies are presented.

7.2. Perception of monsoon season precipitation variability

7.2.1. Perceptions and knowledge of monsoon season precipitation variability

Understanding perceptions and knowledge of monsoon season precipitation variability is crucial, especially in regions heavily reliant on rainfed agriculture and for disaster management. Based on the cross-sectional survey, Table 11 presents respondents' perceptions of the dominant pattern of extreme rainy season events in various countries over the past five years.

***Table 11**: Dominant pattern of rainy season extreme events in the last five years*

Dominant pattern	Frequency	Percent
More extreme wet events	139	32.9
About the same (Normal)	132	31.3
More extreme dry events	128	30.3
Not sure	23	5.5
Total	422	100

A total of 422 participants responded, with 32.9% reporting more extreme wet events and 30.3% reporting more extreme dry events. Also, 31.3% observed the same pattern of rainy season variability, and 5.5% were uncertain of the dominant pattern of rainy season extreme events. The almost equal proportion of respondents' view of the dominant pattern of rainy season extreme events indicates the diverse experiences of precipitation variability across West Africa, confirming the importance of understanding the spatiotemporal modes of precipitation variability over the region, with the Sahel and Guinea coast modes often experiencing divergent extreme precipitation conditions with the transition (Sudanian) zone experiencing a near-normal variability pattern.

To further establish the commonly observed characteristics of rainy season precipitation pattern in the study area, Figure 30 presents perceived monsoon season characteristics, with the three most common characteristics being heavy rainfall (45.7%), delayed onset of rains (35.3%), and prolonged dry spells (25.4%).

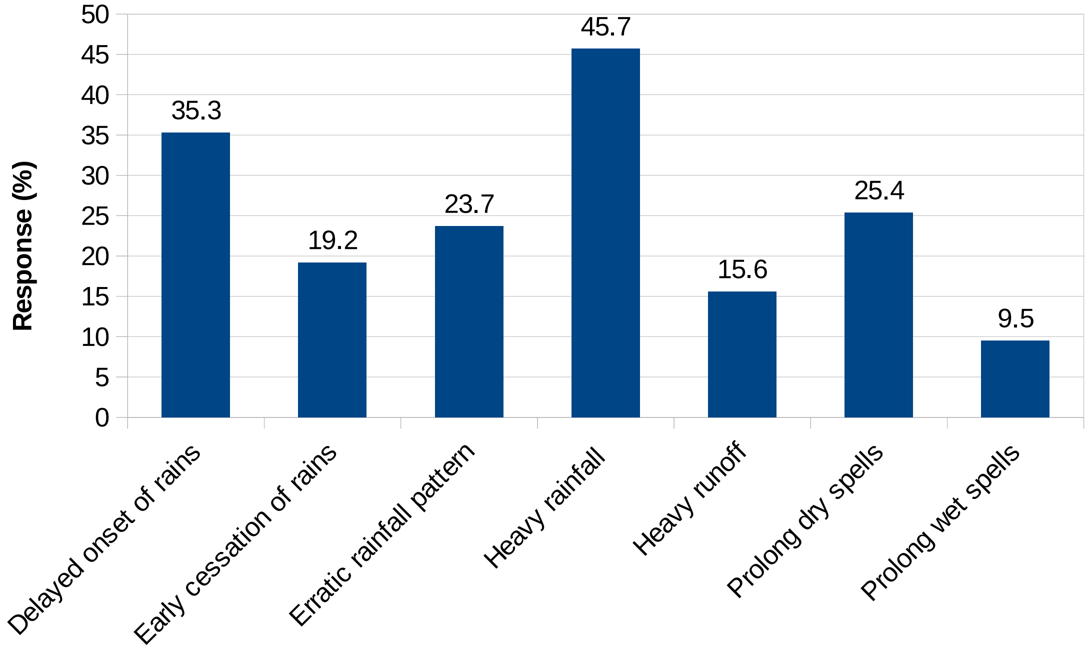

Figure 30: *The common characteristics of rainy season extreme events in the study area*

This result further confirms the previous climatological result, where it was reported that there had been significant changes in the intraseasonal variability pattern relative to the mean state over different parts of West Africa on an annual or seasonal basis.

7.2.2. Perception of causes of extreme wet and dry conditions during the rainy season

Understanding the perceived causes of extreme rainy season precipitation in different parts of West Africa is also very crucial as it aids attribution and prediction of a given extreme condition. Figure 31 displays respondents' views on the causes of extreme wet and dry rainy seasons.

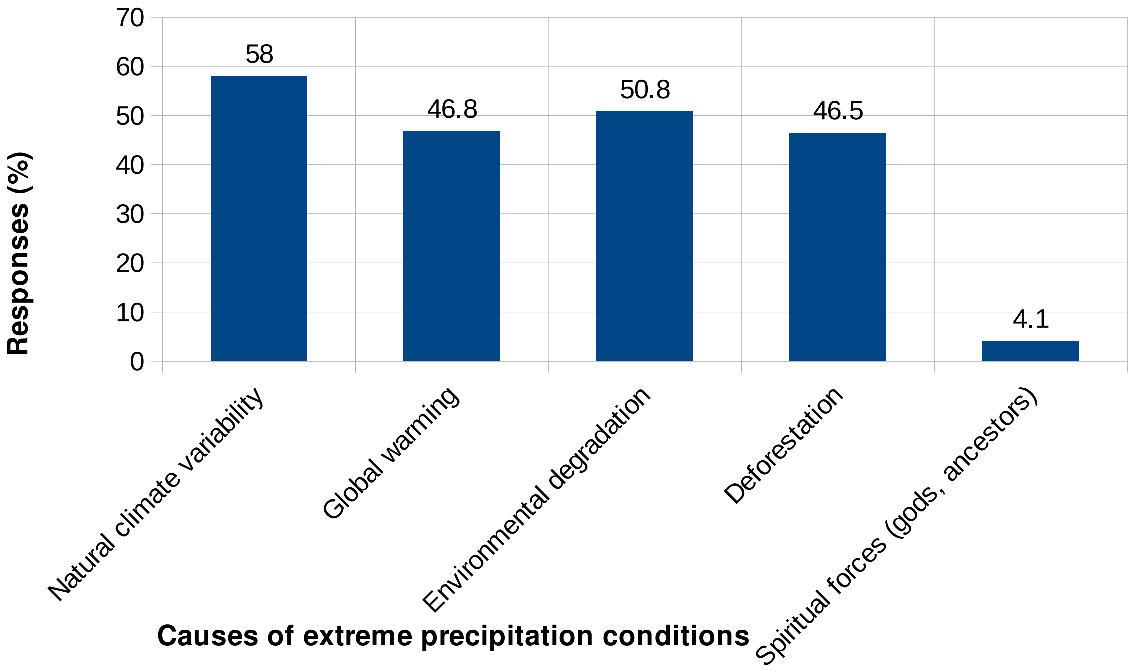

***Figure 31**: Perceived causes of extreme precipitation conditions in West Africa*

Fifty eight percent (58%) of the respondents attribute the variability to natural climate causes driven by the interactions within the climate system, while 50.8% to environmental degradation. These two causes are perceived as the primary causes, followed by global warming (46.8%) and deforestation (46.5%). A smaller proportion (4.1%) attribute the extreme events to spiritual forces. These highlight a broad awareness of environmental factors, though a minority still relies on traditional beliefs.

7.2.3. Impacts of extreme precipitation events

Extreme precipitation conditions exert adverse impacts on different parts and socioeconomic sectors of West Africa. Table 12 shows the primary impacts of extreme wet conditions as reported by the respondents.

Table 12: *Impacts of Extreme Wet conditions in West Africa*

Impacts	Frequency	Percent
Infrastructural damage	257	61.5
Crop damage	255	61
Displacement of people	204	48.8
Increase in food prices	194	46.4
Loss of livelihood	148	35.4
Loss of livestock	135	32.3
Water quality degradation	128	30.6
Decline in health due to water related diseases	127	30.4
Psychosocial effect	109	26.1
Death	101	24.2

Key impacts include infrastructural (61.5%) and crop damage (61%), followed by displacement of people (48.8%) and increased food prices (46.4%). Other significant effects include loss of livestock, degraded water quality, and various health and psychosocial effects, underscoring the wide-ranging consequences of extreme wet conditions.

The cross-tabulation (Table 13) provides a detailed understanding of country-wise perceptions regarding the impacts of extreme wet events. Crop damage is widely recognised as a major impact, particularly in Burkina Faso and Niger (83.3% each), while Côte d'Ivoire (50%) and Ghana (51.1%) report lower impacts, possibly reflecting varying levels of agricultural vulnerability. Increased food prices are moderately perceived across all countries, generally around 50%, though the impact appears less intense in Nigeria (45.2%) and The Gambia (40.2%), suggesting that these regions might experience or perceive food price inflation differently during extreme wet events. Infrastructural damage also ranks as a significant concern, with very high percentages in Niger (94.4%) and Burkina Faso (83.3%), underscoring the infrastructural risks associated with extreme precipitation. However, Benin (55.6%) shows a comparatively lower concern, potentially indicating lesser perceived impacts on infrastructure.

Impacts such as loss of livestock, health decline due to water-related diseases, and death show varying degrees of perception across countries. Livestock losses are notably high in Mali (69.2%) and Niger (61.1%), but low in Côte d'Ivoire (12.5%), suggesting a greater dependency or vulnerability in certain areas. Health declines related to waterborne diseases vary, with Niger (50%) reporting a substantial impact, while Burkina Faso (8.3%) perceives it as minimal, perhaps reflecting disparities in healthcare and water sanitation. The perception of death as an impact of extreme wet events is particularly high in Niger (77.8%), contrasting with lower perceptions in The Gambia (13.1%) and Ghana (15.6%), which may highlight regional differences in mortality risk to extreme climate conditions. Displacement, water quality degradation, psychosocial effects, and loss of livelihood also vary, with Niger consistently reporting high percentages, indicating significant regional vulnerabilities. Overall, crop damage, infrastructural damage, and displacement are widely perceived impacts across most countries, while health-related impacts and psychosocial effects show more localised concerns, reflecting unique environmental and socioeconomic factors in each country.

***Table 13**: Country-wise perception of impacts of extreme wet events (frequency and percentages)*

	Country of Residence								
Impacts of extreme wet events	**Benin**	**Burkina Faso**	**Cote d'Ivoire**	**Ghana**	**Mali**	**Niger**	**Nigeria**	**The Gambia**	**Togo**
Crop damage	7 (77.8%)	10 (83.3%)	4 (50.0%)	23 (51.1%)	9 (69.2%)	15 (83.3%)	101 (60.8%)	60 (56.1%)	26 (65.0%)
Increased food price	5 (55.6%)	7 (58.3%)	4 (50.0%)	21 (46.2%)	6 (46.2%)	10 (55.6%)	75 (45.2%)	43 (40.2%)	23 (57.5%)
Infrastructural damage	5 (55.6%)	10 (83.3%)	6 (75.0%)	27 (60.0%)	9 (69.2%)	17 (94.4%)	91 (54.8%)	67 (62.6%)	25 (62.5%)
Loss of livestock	4 (44.4%)	5 (41.7%)	1 (12.5%)	10 (22.2%)	9 (69.2%)	11 (61.1%)	51 (30.7%)	25 (23.4%)	19 (47.5%)
Decline health due to water related disease	4 (44.4%)	1 (8.3%)	1 (12.5%)	10 (22.2%)	4 (30.8%)	9 (50.0%)	54 (32.5%)	38 (35.5%)	6 (15.0%)
Death	4 (44.4%)	5 (41.7%)	4 (50.0%)	14 (77.8%)	6 (46.2%)	14 (77.8%)	40 (24.1%)	14 (13.1%)	7 (17.5%)
Displacement of people	4 (44.4%)	6 (50.0%)	3 (37.5%)	18 (40.0%)	8 (61.5%)	17 (94.4%)	85 (51.2%)	45 (42.1%)	18 (45.0%)
Water quality degradation	4 (44.4%)	4 (33.3%)	0 (0.0%)	7 (15.6%)	6 (46.2%)	9 (50.0%)	57 (34.3%)	27 (25.2%)	14 (35.0%)
Psychosocial effects	4 (44.4%)	5 (41.7%)	3 (37.5%)	11 (24.4%)	3 (32.1%)	11 (61.1%)	38 (22.9%)	20 (18.7%)	14 (35.0%)
Loss of livelihood	2 (22.2%)	5 (41.7%)	4 (50.0%)	11 (24.4%)	7 (53.8%)	13 (72.2%)	64 (38.6%)	27 (25.2%)	15 (37.5%)

Source: Authors fieldwork (2024)

The Pearson Chi-Square test was used to assesses whether there is a statistically significant association between a respondent's country of residence and their perception of the impacts of extreme wet events (Table 14). The Chi-Square value is 203.88, with 80 degrees of freedom and a p-value of 0.000. Since the p-value is less than 0.05, the null hypothesis is rejected. Thus, the perception of the impacts of extreme wet events vary significantly across countries.

***Table 14**: Hypothesis on impacts of extreme wet events*

Pearson Chi-Square Tests		
		Country of residence
Impacts of extreme wet events	Chi-square	203.88
	df	80
	sig.	.000*

Results are based on nonempty rows and columns in each innermost subtable.
*.The Chi-square statistic is significant at the .05 level.

Furthermore, Figure 32 presents the perceived impacts of extremely dry conditions in West Africa. The three most perceived impacts are crop failure (78%), increase in food prices (58.9%), and water scarcity (44.2%). Other impacts include loss of biodiversity, depletion of groundwater, and loss of livelihoods.

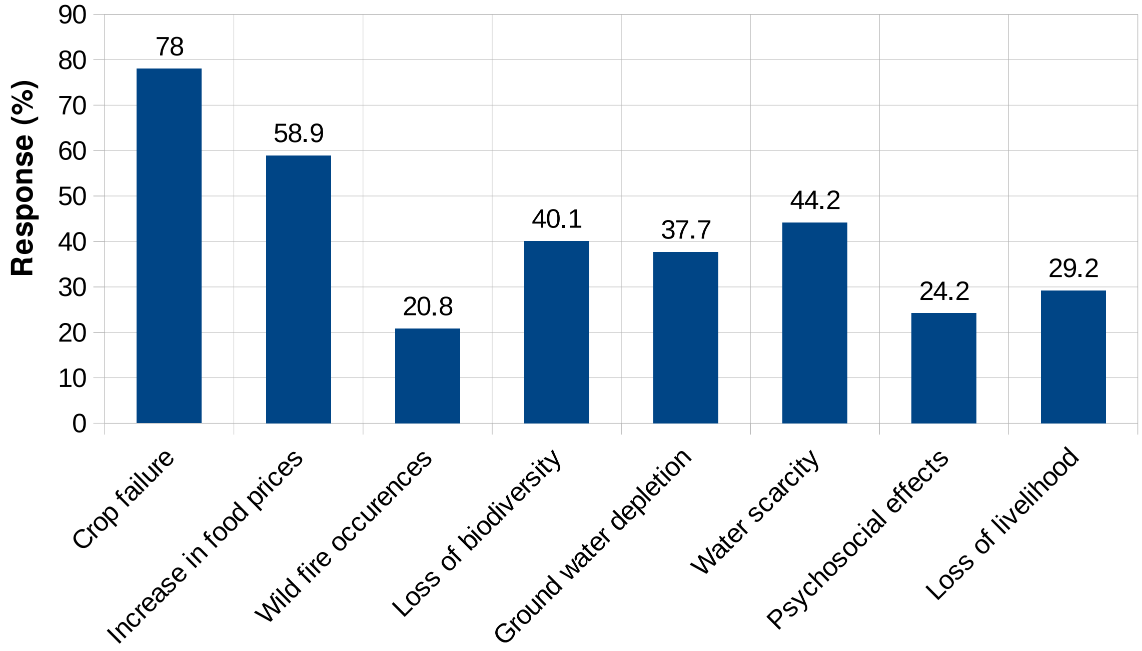

***Figure 32:** Perceived impact of extreme dry conditions over West Africa*

These adverse impacts of extreme dry conditions mainly affect those engaged in agriculture-related activities and those living in areas with limited water sources, as most surface water bodies dry up during prolonged dry periods.

The cross-tabulation table (Table 15) illustrates the percentage of respondents in various countries who identified specific impacts of extreme dry events. Crop failure emerges as a widely acknowledged impact, with particularly high percentages in Burkina Faso (92%) and Benin (89%), signifying widespread recognition of its severity. Similarly, increased food prices are broadly perceived as a major consequence, with countries like Burkina Faso (83%) and Niger (72%) showing strong agreement. While the impact of wildfires appears more localised as it is most pronounced in Mali (46%). Other impacts, such as biodiversity loss, show moderate perceptions with Niger (61%) and Côte d'Ivoire (71%) reporting higher concerns, suggesting region-specific environmental exposure and vulnerabilities.

Surface and groundwater depletion reflect varying levels of concern, with countries like Niger (56%) and Mali (54%) reporting higher percentages, while Togo (28%) and Ghana (27%) indicate lower impact, possibly due to differences in water resource conditions. Water scarcity is another significant concern, especially in Benin (89%) and Mali (69%), but less so in Togo (31%) and Ghana (32%), which may be attributed to differences in regional water availability. Psychosocial effects and livelihood loss are less frequently reported impacts. However, Niger and Côte d'Ivoire indicates relatively higher concerns. Overall, the data reveals that crop failure, increased food prices, and water scarcity are the most consistently perceived impacts of extreme dry conditions across the sampled countries, while wildfires, psychosocial effects (such as anxiety, worry and fear), and loss of livelihood show greater variation, highlighting how environmental conditions and adaptive capacities differ across the region.

Table 15: *Country-wise perception of impacts of extreme dry events*

	Country of Residence								
Impacts of extreme dry events	**Benin**	**Burkina Faso**	**Cote d'Ivoire**	**Ghana**	**Mali**	**Niger**	**Nigeria**	**The Gambia**	**Togo**
Crop failure	8 (89%)	11 (92%)	4 (57%)	33 (75%)	9 (69%)	15 (83%)	131 (79%)	83 (78%)	29 (74%)
Increased food price	3 (33%)	10 (83%)	5 (71%)	29 (66%)	7 (54%)	13 (72%)	96 (58%)	54 (50%)	27 (69%)
Wildfires	2 (22%)	2 (17%)	0 (0%)	12 (27%)	6 (46%)	3 (17%)	31 (19%)	26 (24%)	4 (10%)
Loss of biodiversity	4 (44%)	7 (58%)	5 (71%)	13 (30%)	7 (54%)	11 (61%)	51 (31%)	49 (46%)	19 (49%)
Surface and ground water depletion	4 (44%)	4 (33%)	2 (29%)	12 (27%)	7 (54%)	10 (56%)	65 (39%)	41 (38%)	11 (28%)
Water scarcity	8 (89%)	7 (58%)	1 (14%)	14 (32%)	9 (69%)	8 (44%)	81 (49%)	43 (40%)	12 (31%)
Psychosocial effects	3 (33%)	3 (25%)	2 (29%)	9 (20%)	4 (31%)	8 (44%)	39 (24%)	24 (22%)	8 (21%)
Loss of livelihood	2 (22%)	4 (33%)	5 (71%)	9 (20%)	4 (31%)	12 (67%)	43 (26%)	29 (27%)	13 (33%)

Source: Authors Fieldwork (2024)

Furthermore, the Pearson Chi-Square test was used to examine if there is a statistically significant association between a respondent's appraisal of the impact of extreme dry spells and their country of residence. Table 16 shows the Chi-Square statistic of 107.37, with 64 degrees of freedom and a p-value of 0.001. The p-value is less than 0.05, hence the null hypothesis is rejected. There is a significant association between country of residence and perceptions of the effects of extreme dry events.

Table 16*: Hypothesis on impacts of extreme dry events*

Pearson Chi-Square Tests		
		Country of residence
Impacts of extreme dry events	Chi-square	107.37
	df	64
	Sig.	0.001*

Results are based on nonempty rows and columns in each innermost subtable.
*. The Chi-square statistic is significant at the .05 level.

Risk reduction strategies to extreme precipitation conditions

There are two common risk reduction strategies often employed in disaster risk management. They are structural and non-structural measures (Fernandez Milan & Creutzig, 2015; Hemmati et al., 2022; IPCC, 2014; Ortega-Gaucin et al., 2018; Yang & Liu, 2020). The United Nations General Assembly (2016) defined structural measures as "any physical construction to reduce or avoid possible impacts of hazards, or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems" (P. 23), while non-structural measures are "measures not involving physical construction which use knowledge, practice or agreement to reduce disaster risks and impacts, in particular through policies and laws, public awareness raising, training and education" (P. 23).

Tables 17 and 18 present risk reduction measures that could enhance the effectiveness of adaptation strategies to extreme precipitation conditions in West Africa. Table 17 shows the non-structural measures that could enhance the region's resilience to extreme precipitation conditions. The most frequently recommended measures include climate prediction and early warning systems (61.6%), public awareness programs (46.5%), research, monitoring, evaluation and training (42.8%) and spatial planning (40.1%). These measures aim to build community resilience by improving preparedness and adaptive capacity.

Table 17: *Non-structural risk reduction measures*

Measures	Frequency	Percent
Climate prediction and early warning systems	252	61.6
Public awareness and sensitisation outreaches	190	46.5
Research, monitoring, evaluation and training	175	42.8
Spatial (rural and urban) planning	164	40.1
Contingency planning for hazard occurrences	148	36.2
Improved water re-utilisation and recycling	147	35.9
Weather risk insurance	117	28.6
Enactment and enforcement of building codes	107	26.2

Table 18 lists the structural interventions considered effective for reducing risks associated with extreme precipitation conditions. Key measures include the construction and maintenance of drainage systems (75.8%), the construction and maintenance of dams and water reservoirs (61.6%), and the establishment of irrigation systems in all climatic zones (46.7%). These infrastructural solutions are critical to managing water resources and mitigating regional flood risks.

Table 18*: Structural risk reduction measures*

Measures	**Frequency**	**Percentage**
Construction and maintenance of drainage systems	320	75.8
Construction and maintenance of dams and water reservoirs	260	61.6
Establishing irrigation systems in all climatic zones	193	46.7
Wetland restorations and afforestation	172	40.8
Construction of flood walls	150	35.5
Improved access roads and connectivity	139	32.9

Barriers to mitigating the adverse impacts of extreme wet and dry conditions

The key barriers to effectively mitigating the adverse impacts of extreme wet and dry conditions in West Africa are multifaceted and deeply rooted in environmental, socio-economic, and infrastructural challenges. Figure 35 summarises the key barriers to effectively mitigating the impacts of extreme precipitation conditions in West Africa. The most perceived challenges identified are poor infrastructure (62.3%), lack of technical capacity at the local level (60.4%), and inadequate funds (57.3%). Others are policy and governance issues due to poor political will which manifest as insufficient and/or weak climate change policy frameworks. Lack of local awareness and limited investment in climate resilience measures. These barriers, amongst others, hamper effective responses to climatic extremes in the region.

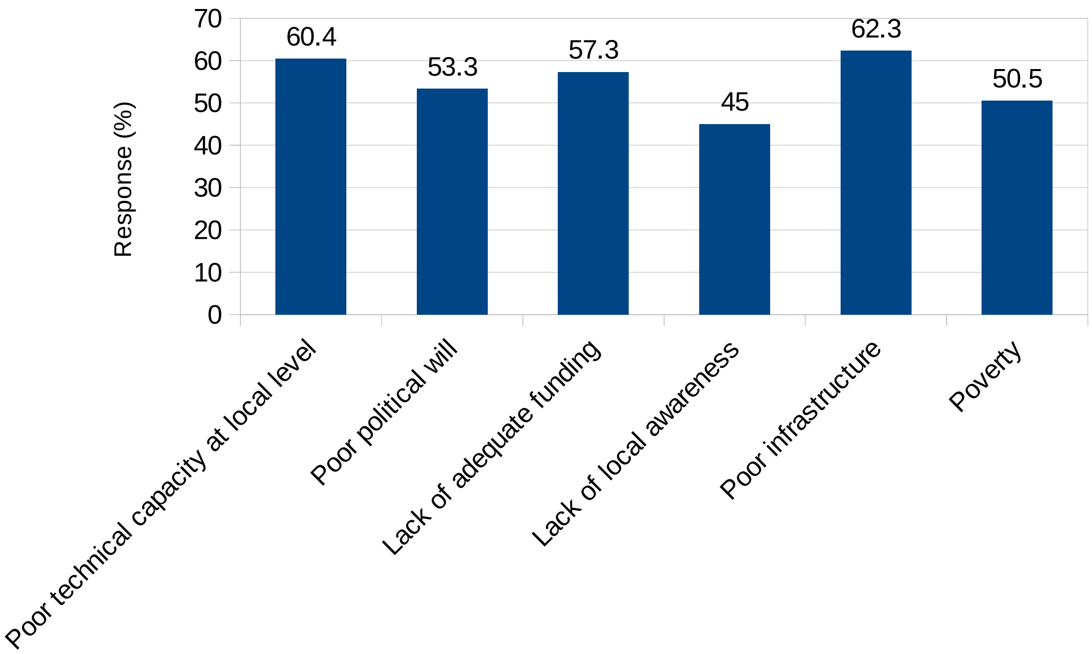

***Figure 33**: Key barriers to effect climate risk reductions in West Africa*

7.3. Discussion

The increasing uncertainty surrounding the monsoon season in West Africa has raised concerns among residents of the region, as evidenced by the survey results. The perception of dominant precipitation patterns varies considerably across different countries and climatic zones. Respondents from Niger described the rainy season as marked by intense downpours, often resulting in flash floods and storm water surges. As one participant noted, "When it rains, the heavens pour a large amount of water within a short period" (Niger, 9 September 2024). This assertion and findings corroborate Elagib et al., (2021); Tarhule, (2005) findings in the Sahel. Conversely, a key informant from Lomé, Togo, remarked on a lack of a distinct rainy season, describing it as "drier than expected, making reliance on the monsoon season risky especially for crop production purposes" (Togo, 20 September 2024). These contrasting perspectives illustrate the complex nature of precipitation variability and its impacts across the region.

The variation in perceived extreme precipitation conditions reflects the complex interplay between geographic, climatic, and socio-cultural factors ranging from the arid Sahel to the humid Guinea Coast. Residents in these regions experience and interpret extreme precipitation events differently. The Sahelian region, accustomed to droughts due to its traditionally low and erratic rainfall, often views dry extremes as the primary risk. However, this expectation has been challenged by the dominance of the active phase of the Sahel precipitation mode of West African precipitation variability. Now, areas historically accustomed to dry spells are experiencing extreme wet events, while regions with traditionally wetter seasons face prolonged dry periods. This pattern reversal has tested long-standing adaptation measures, emphasizing the need for updated strategies to handle both droughts and floods.

The adverse impacts of extreme dry monsoon seasons are particularly severe for agriculture, leading to crop failures and rising food prices due to decreased availability and often unaffordable by the poor. This is consistent with Yiran and Stringer, (2016) finding in the savanna ecosystem of Ghana. Although the immediate consequences of such dry spells are dire, structural and non-structural adaptive measures, such as improved irrigation systems and water storage facilities, could mitigate these effects (Ghelli et al., 2012; Gupta & Nair, 2012; Yang & Liu, 2020). Meanwhile, extreme wet monsoon seasons are more frequently associated with infrastructural damage, crop destruction, and population displacement relative to extreme dry conditions. The observed impacts corroborate findings by other similar studies in different geographic regions for example in Argentina (Naumann et al., 2019), East Africa (Chen & Georgakakos, 2015) amongst others. Priority adaptation strategies include constructing and maintaining drainage systems, dams, and water management facilities across all climatic zones to reduce vulnerability to both extremes. The lack of environmental strategy and development focus on dealing with extreme dry and wet events in West Africa, has led to pervasive maladaptation and unpreparedness in region which corroborates the assertions of Adaawen, (2021); Ikeme, (2003); Yengoh et al., (2017). The complexity and difficulty of adapting to and developing local capacity for climate change-related hazards need urgent and continuous actions (Wilk et al., 2022). Both structural and non-structural actions should be taken to adapt most West African settlements, including farmlands, to climate changes and its impacts; more non-structural measures geared towards improving the living standard and spatial planning will aid adaptation to precipitation-induced risks. Furthermore, the construction of resilient infrastructures, such as runoff retention ponds and good infrastructures, as observed in

Lome, helps to mitigate urban flooding due to heavy rainfall events while providing water for use during the dry season, amongst other measures. Poverty is a significant barrier and incentive for maladaptation in the region. Thus, there is a need for targeted action to address climate vulnerability (Wilk et al., 2022).

This information underscores the importance of proactive adaptation measures that address drought and flood risks instead of relying on reactive responses to confine damages after they occur. Anticipatory actions can limit the socio-economic ripple effects of extreme precipitation events, ultimately fostering resilience across the region.

7.4. Partial conclusion

This chapter provides a comprehensive view of the regional perceptions, impacts, and risk reduction strategies associated with extreme wet and dry conditions in West Africa. The respondents' diverse perspectives underscore how precipitation variability affects different regions, with impacts ranging from agricultural losses to infrastructural damage and water scarcity. The significant regional differences in perceptions of extreme events suggest that adaptation strategies must be context-specific. Non-structural measures, such as enhanced climate prediction systems through increasing the spatial coverage of meteorological stations and improved and sustained public awareness programs and training, along with structural interventions, like the construction and maintenance of drainage systems, dams and irrigation facilities, are widely recognised as essential for building resilience to precipitation variability. Nonetheless, the effectiveness of these measures is hindered by persistent barriers, including inadequate infrastructure, insufficient technical capacity, and limited funding, highlighting the urgent need for more robust policy frameworks and resource allocation to address these challenges effectively in the region especially by investing in adequate resilient infrastructures and planned urbanisation.

GENERAL CONCLUSION AND PERSPECTIVES

SUMMARY OF THE RESEARCH FINDINGS

Climate variability and extreme weather events significantly impact West Africa's socio-economic systems, ecosystems, and public health. Anticipating the impacts of future climate change, particularly in regions heavily dependent on monsoon rains, is critical for ensuring sustainable development and risk management. This thesis examined extreme wet and dry conditions over West Africa during the monsoon season, assessing their characteristics, drivers, projections and challenges to effective climate risk reduction.

This study provides new insights into the mechanisms driving monsoon variability and its extremes by analysing historical precipitation patterns from 1950 to 2022 and large-scale atmospheric-oceanic interactions. The findings contribute to a deeper understanding of the climate system's complexities in West Africa and offer actionable knowledge to guide climate risk management in the region. The key findings based on the objectives of the study are:

1. Trends and dominant patterns of large-scale wet and dry conditions

The study reveals distinct regional and temporal trends in monsoon precipitation across West Africa. Areas like the western Sahel have experienced increased rainfall, while persistent drying trends dominate parts of the Guinea coast. Two dominant modes of precipitation variability, the Sahel and Guinea Coast modes, were identified. These modes are critical in explaining the region's extreme wet and dry events dynamics. The Sahel mode, characterised by a dipole pattern, drives significant intra- and interannual variability in rainfall, underscoring the need for enhanced predictability and resilience strategies across the region. The mixed patterns of rainfall variability highlight the complex nature of monsoon dynamics, with important implications for agriculture, water resources, and disaster management.

2. Drivers of West African precipitation variability

Sea surface temperature (SST) anomalies in the equatorial Pacific, Mediterranean, Indian, and Atlantic Oceans strongly influence precipitation variability over West Africa. The Sahel mode, which is highly correlated with these SST anomalies, demonstrates the vital role of ocean-atmosphere interactions in driving the region's extreme wet and dry conditions. This study reinforces the importance of understanding the seasonal evolution of these interactions for improved predictions of extreme weather events. Variations in large-scale circulation systems, such as the Walker and Hadley cells as depicted by the velocity potential and divergent winds pattern, are shown to be pivotal in determining regional precipitation outcomes, particularly during the peak monsoon months of July and August.

3. Joint influence of climate modes on extreme precipitation conditions

Large-scale extreme precipitation events are often linked to the joint phases of climate modes, particularly interactions between Mediterranean and equatorial Pacific SST anomalies. When acting together, these modes alter the Walker circulation, directly influencing the West African monsoon rainband migration. This joint interaction is a significant contribution of this research, emphasising the need to consider multiple modes of variability for more accurate seasonal forecasting.

4. Future projections and implications

The CMIP6 models used in this study generally captured the dominant modes of precipitation variability over West Africa. However, their performance varies, with better reliability in simulating the Sahel mode than the Guinea Coast. Future projections show divergent patterns, with the higher-emission scenario predicting drier conditions during the late 21st century, while lower-emission scenarios suggest near-normal precipitation conditions. This discrepancy highlights the challenges decision-makers face in planning for future climate risks. Nonetheless, the models underscore the need for continuous improvement and re-assessment, especially considering West Africa's vulnerability to climate-induced disasters.

5. Impacts and barriers to climate risk reduction

Extreme precipitation events in West Africa cause widespread damage, including crop failure, infrastructural damage, loss of livelihoods, displacement, and water shortages. However, the region's adaptive capacity is hampered by inadequate infrastructure, limited technical expertise, poor governance, and a lack of financial resources. Addressing these barriers will require sustained investment in capacity building, resilient infrastructure development, and political will. The study stresses the importance of transitioning from reactive crisis management to proactive risk management in order to mitigate the adverse impacts of adverse climate variability.

POLICY IMPLICATIONS

This thesis offers practical insights that can guide policymakers in designing more effective disaster risk management strategies. The findings highlight the critical need for integrating climate-informed decision-making into all sectors: agriculture, water resources, infrastructure, regional planning and public health. Key recommendations include:

Enhanced climate monitoring and data sharing: Expanding the spatial coverage of meteorological observatories across West Africa is crucial for improving climate monitoring. While a lot of initiatives with cooperation from international and developmental partners are trying to bridge the data gap, the National Meteorological Agencies need to enhance their relevance to the region by encouraging data sharing, accessibility, and affordability among relevant stakeholders and digitising meteorological and hydrological records into spatio-temporal format will significantly enhance forecasting capabilities and research outcomes.

Proactive risk management: Governments and individuals must prioritise preparedness, planning, and early warning systems. This can minimise the destructive effects of extreme weather events by focusing on pre-event activities such as climate impact projections , risk assessments and behavioural modifications.

Climate-resilient infrastructure: Investing in climate-resilient infrastructure, especially in urban planning and water management systems, will reduce vulnerability to adverse flood and drought impacts. This includes enforcing building codes, constructing proper drainage systems, and promoting sustainable land use practices.

Inclusive policy frameworks: Incorporating Indigenous knowledge systems, promoting gender mainstreaming in climate risk management, and streamlining bureaucratic hurdles within environmental agencies are essential for developing localised and equitable solutions. Policies should also address the needs of vulnerable communities, ensuring that adaptation strategies are inclusive and participatory.

PERSPECTIVES

This thesis highlights several avenues for future research:

1. Further analysis of climate mode interactions: Understanding how different modes of climate variability (e.g., Mediterranean, Pacific) interact to influence large-scale

circulation and feedback mechanisms is critical. Future studies should explore these interactions in more detail to refine predictive models.

2. Drought-to-flood interactions: Investigating the transitions between drought and flood conditions during the monsoon season will improve risk assessments for these dual hazards, as most flood events over the Guinea Coast areas often increase after the monsoon break.

3. Intraseasonal precipitation dynamics: More detailed analysis using daily rainfall datasets is needed to understand the fine-scale dynamics of precipitation within the monsoon season. This will provide insights into intraseasonal variability and help refine early-warning systems.

4. Vulnerability and exposure studies: Future research should incorporate vulnerability and exposure dimensions into climate studies. These factors are crucial in determining the socio-economic impacts of extreme events and designing appropriate and sustainable adaptation measures.

5. Model development: Continuous re-assessment of climate models is necessary to reduce biases and improve model and projection reliability. Efforts should focus on enhancing the models' ability to simulate the complex climate processes unique to the West African monsoon system, especially over the Guinea coast domain, where the performance and reliability of the CMIP6 models are relatively poor compared to the Sahel domain. Currently, there is a dearth of West African-hosted climate models; regional climate centres and organisations should strive to bridge this model development gap in the region.

CONCLUSION

The findings of this thesis underscore the urgency of addressing climate risks in West Africa. As the frequency and intensity of extreme wet and dry events continue to rise, building resilience across all sectors is paramount. By combining scientific knowledge with inclusive policy frameworks and proactive risk management strategies, West Africa can better prepare for the future impacts of climate change. However, this will require collaboration among governments, international organisations, and local communities to foster sustainable development and reduce climate vulnerability.

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APPENDICES

Appendix I: Questionnaire

Climate Change and Disaster Risk Management Program,
WASCAL,
Universite de Lome, Togo.
August, 2024.

Dear Sir/ Madam,

Survey of Risk Reduction Strategies to Extreme Wet and Dry Rainy Season in West Africa

My name is Chukwudi Ekwezuo, a postgraduate student at the WASCAL Doctoral Research Program in Climate Change and Disaster Risks Management at the Universite de Lome, Togo. I am currently working on a research project on the above named topic. This study aims to provide information on risk reduction strategies for flood and dry conditions during the rainy season in West Africa. Findings from this study will drive policy and behavioural changes to improve disaster risk management. Data gathered will be securely stored and used only for academic research purposes; no personal identifiers will be taken. Therefore, your full participation in completing this form within 10 minutes is the surest way to success for this study. Your participation is utterly voluntary.

Thank you so much for this support.

C. S. Ekwezuo

Section A. Demographic characteristics

1. Gender: Male [ ] Female [ ] Prefer not to say [ ]

2. Age (completed years) :……………………………….

3. Country of Residence: ……………………………….

4. Type of settlement: Urban [ ] Rural [ ] Peri-urban [ ]

5. How long have you lived here (in years)? Less than 5 years [ ] 6 to 10 year [ ] 11 to 15 years [ ] 16 to 20 years [ ] More than 20 years [ ]

6. What is your highest qualification? None [ ] Primary [ ] Secondary [ ] Tertiary (Graduate) [ ] M.Sc or Ph.D [ ]

7. What is your marital Status? Single [ ] Married [ ] Divorced [ ] Prefer not to say [ ]

8. If married, what is the level of education of your spouse? None [ ] Primary [ ] Secondary [ ] Tertiary (Graduate) [ ] M.Sc or Ph.D [ ]

9. What is your current employment status? Never employed [ ] Student [ ]

Self employed [ ] Employed (Salary/wage earner) [ ]

Section B. Perception of extreme rainy season condition

10. How would you describe the dominant pattern of rainy season extreme events in the last five years? (select only one option)
More extreme wet events [ ] More extreme dry events [ ] About the same (Normal) [ ] Not sure [ ]

11. What are the common characteristics of rainy season extreme events in your region? (select all that apply)
Prolong dry spell [ ] Heavy rainfall [ ] Heavy run-off [ ] Delayed onset of rains [ ] Early cessation of rains [ ] Erratic rainfall patterns [ ] Prolong wet spell [ ]

12. What impacts have you observed from extreme wet conditions during the rainy season? (Select all that apply)
Crop damage [ ] Increased food prices [ ] Infrastructure damage [ ] Loss of livestocks [ ] Decline in health (through malnutrition or spread of waterborne diseases) [ ] Death [ ] Displacement of people [ ] Water quality degradation [ ] Psychosocial effects [ ]

13. What are the main causes of extreme wet or dry conditions during the rainy season in your area? (Select all that apply)
Natural climate variability [ ] Environmental degradation [ ] Global warming [ ] Spiritual entities (God, Ancestors) [ ] Deforestation [ ]

14. What impacts have you observed from extreme dry conditions during the rainy season? (Select all that apply)
Crop failure [ ] Increased food prices [ ] Wildfires [ ] Loss of biodiversity [ ] Surface and ground water depletion [ ] Water scarcity [ ] Psychosocial effects [ ] Loss of livelihood [ ]

15. Which risk reduction strategies are currently being employed in your region to mitigate the adverse impacts of extreme dry conditions? (Select all that apply)
Early warning systems [ ] Improved drainage systems [ ] Water storage and conservation [ ] Use of drought-resistant crops [ ] Community awareness and preparedness programs [ ] Livelihood diversification [ ] Crop diversification [ ] Adoption of soil conservation techniques (e.g. No tillage) [ ] Mixed farming [ ] Changes in agricultural calendar [ ]

16. Which risk reduction strategies are currently being employed in your region to mitigate the adverse impacts of extreme wet conditions? (select all that apply)
Early warming system [ ] Community awareness and preparedness programs [ ] Improving infrastructure for flood management [ ] Land-use planning and management [ ] Stay away from hazardous areas [ ]

17. What non-structural measures could effectively reduce the risk associated with extreme wet and dry conditions during the rainy season?
Weather risk insurance [ ] Climate prediction and early warning systems [ ] Proactive spatial planning to avoid high-risk areas [ ] Improved water reutilisation and recycling [ ] Enactment and enforcement of building codes [ ] Research, assessment and training [ ] Information resources and public awareness outreaches [ ] Contingency plans for minimizing losses when a hazardous event does occur [ ]

18. What structural measures could be effective in reducing the risks associated with extreme wet and dry conditions during the rainy season? (Select all that apply)
Construction and maintenance of effective drainage systems [ ] Improved traffic access roads [ ] Construction and maintenance of dams and water reservoirs [ ] Construction of flood walls [ ] Wetland Restoration and Afforestation [ ] Establishing efficient irrigation systems [ ]

19. What are the barriers to addressing drought and flood impacts in your area? (Select all that apply)
Lack of technical capacity at the local level [ ] Lack of political will [ ] Lack of funding [ ] Lack of local awareness [ ] Poor infrastructure [ ] Poverty [ ]

20. How vulnerable are you to the negative impacts of extreme wet conditions during the rainy season? *Do you suffer great loss when floods or drought occur in your area or surrounding areas?*
Vulnerable [ ] Not vulnerable [ ]

21. Who is more at risk during extreme wet and dry events in your area?
Woman [ ] Children [ ] Men [ ] Dependents (sick, elderly, disabled, infants) [ ]

Appendix II: Publications and Conferences

Ekwezuo, C. S., Ezeh, C. U., Sogbedji, Jean M., Phil-Eze, P. O. (2024) Analysing Spatial Variability of Monsoon Rainfall over West Africa. *International Journal of Environment and Climate Change*, 14 (9), 77-91. https://doi.org/10.9734/ijecc/2024/v14i94394

Conferences

C. S. Ekwezuo, and J. M. Sogbedji (2024): Enhancing Resilience to Monsoon Extremes in West Africa through Innovative Climate Prediction and Adaptation Strategies. A paper presented at the First International Conference of the Pan African University held on 19 - 21 November 2024 at the Pan African University Life and Earth Sciences Institute (Including Health & Agriculture) PAULESI, University of Ibadan, Ibadan, Nigeria

C. S. Ekwezuo, and J. M. Sogbedji (2024): Rainy Season Precipitation Variability and Possible Causes over West Africa from 1950 to 2022. A paper presented at the xxth edition of the international scientific days of Lomé (JSIL-2024), Du 08 au 11 Octobre 2024, Lome, Togo

C. S. Ekwezuo, J. M. Sogbedji, P. O. Phil-Eze and H. C. Nnamchi (2024): Dynamics of the Dominant Modes of Rainy Season Extreme Pluvial Events Over West Africa. A paper presented at the Troisième Conférence scientifique Internationale sur le Changement Climatique en Afrique de l'Ouest et au Sahel (CICC2024), Du 09 au 11 Septembre 2024, Niamey, Niger.

C. S. Ekwezuo, J. M. Sogbedji and C. U. Ezeh (2024): Mechanisms Causing Rainy Season Extreme Precipitation Events over West Africa. A paper presented at the 2024 International Annual Conference on Climate Change, Migration and Security, held 12th - 15th March, 2024 at the University of Nigeria, Nsukka, Nigeria.

C. S. Ekwezuo, P. O. Phil-Eze, J. M. Sogbedji, and J. C. Ekwezuo (2023): Concurrent precipitation and temperature extremes in Nigeria from 1981 to 2021. A paper presented at the 62nd Association of Nigerian Geographers national Conference held at the University of Nigeria, Nsukka, Nigeria from 7-11 February, 2023.

Abstract

Extreme precipitation during the West African summer monsoon causes significant flooding and drought, impacting food security, infrastructure, and regional socioecological systems. This thesis examines monsoon precipitation's dynamics, variability, and future projections using gridded climate (1950–2022) and survey data. Results show spatially heterogeneous trends, with significant changes detected in monsoon precipitation variability, except in August. Two dominant precipitation modes were identified using season-reliant empirical orthogonal function (SEOF) analysis: the Sahel mode (16.3% variance) linked to equatorial Pacific, Mediterranean, Indian, and North Atlantic sea surface temperature (SST) anomalies and the Guinea coast mode (9.5% variance) influenced by equatorial and South Atlantic SST. Wet years exhibit strong low-level convergence over Africa and upper-level divergence over the Pacific, driven by Walker circulation changes. CMIP6 models perform better over the Sahel than the Guinea coast, projecting future drying trends. Extreme precipitation events impact agriculture, infrastructure, and food security, with adaptation hindered by poor infrastructure, technical capacity gaps, and funding constraints. These findings are crucial for climate adaptation, informing policymakers on resilient infrastructure and adaptive strategies to mitigate adverse impacts of climate extremes in West Africa.

Keywords: *Anomalous precipitation, climate change projections, CMIP6 models, sea surface temperature, West Africa*.

Comprendre les extrêmes de précipitations en Afrique de l'Ouest: Caractéristiques, facteurs et projections

Résumé

Les précipitations extrêmes pendant la mousson d'été en Afrique de l'Ouest provoquent des inondations et des sécheresses importantes, qui ont un impact sur la sécurité alimentaire, les infrastructures et les systèmes socio-écologiques régionaux. Cette thèse examine la dynamique, la variabilité et les projections futures des précipitations de mousson en utilisant des données climatiques maillées (1950-2022) et des données d'enquête. Les résultats montrent des tendances spatialement hétérogènes, avec des changements significatifs détectés dans la variabilité des précipitations de mousson, sauf en août. Deux modes dominants de précipitations ont été identifiés en utilisant l'analyse de la fonction orthogonale empirique (SEOF) basée sur la saison : le mode Sahel (16.3% de variance) lié aux anomalies de température de surface de la mer (SST) du Pacifique équatorial, de la Méditerranée, de l'Inde et de l'Atlantique du Nord et le mode côte guinéenne (9.5% de variance) influencé par les SST de l'Atlantique équatorial et de l'Atlantique Sud. Les années humides présentent une forte convergence des basses couches sur l'Afrique et une divergence des hautes couches sur le Pacifique, sous l'effet des changements de la circulation de Walker. Les modèles CMIP6 sont plus performants sur le Sahel que sur la côte guinéenne, projetant des tendances futures à l'assèchement. Les précipitations extrêmes ont un impact sur l'agriculture, les infrastructures et la sécurité alimentaire, l'adaptation étant entravée par des infrastructures médiocres, des lacunes dans les capacités techniques et des contraintes de financement. Ces conclusions sont cruciales pour l'adaptation au climat, car elles informent les décideurs politiques sur les infrastructures résilientes et les stratégies d'adaptation visant à atténuer les effets négatifs des extrêmes climatiques en Afrique de l'Ouest.

Mots clés: *Précipitations anormales, projections de changement climatique, modèles CMIP6, température de surface de la mer, Afrique de l'Ouest*.