Impacts of Aerosols on Precipitation over West Africa

BY

POUYE Modou

B.Sc. (Physics and Chemistry), M.Sc. (Climate Change and Energy)

MET/19/3757

JULY, 2023

Impacts of Aerosols on Precipitation over West Africa

BY

POUYE Modou

B.Sc. (Physics and Chemistry), M.Sc. (Climate Change and Energy)

MET/19/3757

A Thesis of the Doctoral Research Programme of the West Africa Climate Systems, under the West Africa Science Service Centre on Climate Change and Adapted Land Use, in the Department of Meteorology and Climate Science Submitted to the School of Postgraduate Studies in Partial Fulfilment of the Requirements for the Award of the Degree of Doctor of Philosophy in Meteorology and Climate Science of the Federal University of Technology, Akure, Nigeria.

JULY, 2023

DECLARATION

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

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

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

Candidate's Name: POUYE Modou

Signature: Date ………/………/2023

CERTIFICATION

We certify that this Thesis entitled "Impacts of Aerosols on Precipitation over West Africa" is the outcome of the research carried out by Mr. POUYE Modou under the WASCAL DRP-WACS in the Department of Meteorology and Climate Science of the Federal University of Technology, Akure.

Prof. Emmanuel C. Okogbue ……………………………..

(Major Supervisor)

Signature Date

Department of Meteorology and Climate Science,
The Federal University of Technology,
Akure, Nigeria.

Dr. Johannes Quaas ……………………………..

(Co-Supervisor)

Signature Date

Institute for Meteorology
Universität Leipzig
Leipzig, Germany.

Dr. Vincent O. Ajayi ……………………………..

(Co-Supervisor)

Signature Date

Department of Meteorology and Climate Science,
The Federal University of Technology,
Akure, Nigeria.

Prof. Zachariah Debo Adeyewa ……………………………..

(Director)

Signature Date

Doctoral Research Program – West African Climate Systems
West African Science Service Center on Climate Change and
Adapted Land Use (DRP-WACS, WASCAL),
The Federal University of Technology,
Akure, Nigeria.

ABSTRACT

The aim of this study is to investigate the interaction between West African aerosols and convective, stratiform and shallow clouds, which affect precipitation quality and amount. Gridded satellite observation precipitation datasets Tropical Rainfall Measuring Mission (TRMM), in-situ precipitation data, reanalysis aerosol data ECMWF Atmospheric Composition Reanalysis 4 (EAC4) and rainwater samples were analysed to study the high aerosol concentration impacts on precipitation amount, frequency and quality over the Sahel and Guinea region. Mann-kendal Test was used to verify the trend in time series data. Sperman correlation was used to identify statistical links between aerosols and precipitation. To investigate the quantitative effects of aerosols on rain frequency over West Africa, the precipitation data was categorized into three groups: light ($r < 2.5$ mm/h), moderate (2.5 mm/h $\leq r <$ 10 mm/h), and heavy rain (10 mm/h $\leq r <$ 50 mm/h). Rain events from 12 stations located across West Africa were classified into two groups, based on aerosol concentration percentile. The first group contained precipitation data with the 10th percentile aerosol concentration considered as clean condition. While the second group contained data with the 90th percentile aerosol concentration considered as polluted condition. Each group was then further divided based on the percentile of aerosol events to obtain the rainfall frequency percentage. Precipitation reduction is observed during the seasons of December - January - February (DJF) and June - July - August (JJA) when black carbon and organic matter concentrations increased over West Africa. Additionally, results suggest that precipitation enhancement is observed during March - April - May (MAM) and September - October - November (SON) seasons when sulphate concentration increased. This may suggest that the West African atmospheric black carbon, organic matter and sulphate variation affect the amount of seasonal rainfall. However, the increase in sea salt particles during SON, when there is higher rainfall, could be related to the role of sea salt particles as cloud condensation nuclei, which could influence the amount and timing of rainfall in the region. Results show that dust is the dominant aerosol over all stations used in this study. Organic matter is the second most significant aerosol in

this region, which contributes to atmospheric pollution. A comparison between the Clean-case (C-case) and Polluted-case (P-case) shows that aerosol concentration variations affect precipitation class frequency over West Africa. Results suggest that aerosol pollution mostly decreases light rain and increases moderate and heavy rain over West Africa. Chemical laboratory rainwater quality analysis illustrates that Ouagadougou experienced acid rain during the rainy season of 2022. It indicates that there may be sources of sulphur emissions in these areas that are contributing to the elevated sulphate levels in the rainwater. The rainwater sample from Dakar showed sodium levels above the threshold, which could be an indication of potential sources of sodium contamination in the area. It indicates also that the levels of nitrate in the rainwater samples were within the normal range in most cities, but rainwater in some cities shows that the levels of nitrate in the rainwater samples were below the nitrate thresholds of 1.5 and 5 mg/L.

DEDICATION

The dedication honours those who supported the initiation and completion of the PhD's degree. These individuals include, but not only limited to:

- my wife Hadja Khadidiatou Toure who assisted me during this PhD and my son Mohamed Bassirou Pouye;
- my late father, who left us early and my mother, Aissatou Sarr. Thank you mother for bring us up. Caring for offspring has never been an easy task, but you have been striving and facing many challenges to make us steadfast on the right path.
- My brothers and sisters Ibrahima, Ousmane, Babacar, Omar, Ndeye Yacine and Fatima Pouye for their support.
- My late grandmother, Awa Diène, uncle Ibrahima Sarr, and all my family, and friends.

ACKNOWLEDGEMENTS

I want to acknowledge the full scholarship and financial support from the German Federal Ministry of Higher Education and Research (BMBF) and West African Science Service on Climate Change and Adapted Land Use (WASCAL) for my doctoral program.

I would like to thank the Executive Director and the staff of WASCAL Head office, Accra, Ghana and the Director, Prof. Z. D. Adeyewa and staff of WASCAL GRP-WACS, FUTA, Nigeria for their strong support and encouragement throughout this PhD work. I also appreciate Dr. A. Akinbobola, the Head, and Staff of the Meteorology Department and Climate Science, FUTA, Nigeria, for their cooperation.

I would like to sincerely thank my supervisors Prof. E. C. Okogbue and Dr. V. O. Ajayi from the Federal University of Technology of Akure (FUTA), Nigeria and Dr. J. Quaas from Universität Leipzig, Institute for Meteorology, Germany, who supervised this work. Thank you for your assistance and support through this research work. It has been difficult to organize this thesis but with your pieces of advice and comments, it has been possible. Thank you a lot. I really appreciate my advisors Dr. M. B. Sylla from the African Institute for Mathematical Sciences (AIMS), Rwanda and Prof. M. Fall from Cheikh Anta Diop University (UCAD) for all the supports, opportunities and facilities they provided me in order to carry out this work.

My special thanks go to my colleagues Laouali Ibrahim Tanimoune, Doumbia Boubacar and all others 4th West African Climate Systems (WACS) batch for their valuable contribution and support throughout this research work. Thanks again to my German supervisor for giving me the opportunity to spend 3 months in the Institute of Meteorology of the University of Leipzig. Thank you again for introducing me to the community of the institute of meteorology of the University of Leipzig. I express my gratitude to Dr. J. Quaas, Dr. A. Henkes, H. Wang, Dr. K. Haustein, Prof. M. Wendisch, Dr. M. Salzmann, Dr. J. Kretzschmar and others who helped me a lot during my stay in the institute.

I want to acknowledge the full cluster resources for the simulations supported by the European Union for climate and environmental research, with granted access to the HPC resources of Valence.

I would like to extend my appreciation to Dr. A. Faye and Lieutenant Diankha for their valuable help and useful pieces of advice.

I would like to appreciate my internal and external examiners for accepting to examine this work and for their valuable comments which contribute to improving this document.

I would like to address a particular thanks to all my family members for their support, patience encouragement and understanding during this long journey.

Glory be to the Almighty Allah for His Blessing and help.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ADW	Angular Distance Weighting
Al_2O_3	Aluminium Oxide
ANACIM	Agence Nationale de l’Aviation Civile et de la Meteorologie
ANAM-BF	Agence Nationale de la Meteorologie du Burkina Faso
ANAMET	Agence Nationale de la Meteorologie du Togo
ANAMET	Agence Nationale de la Meteorologie du Togo
ANMB	Agence Nationale de la Meteorologie du Benin
ANMM	Agence Nationale de la Meteorologie du Mali
AOD	Aerosol Optical Depth
AVHRR	Advanced Very High-Resolution Radiometer
C	Carbon
Ca^{2+}	Calcium
CAMS	Copernicus Atmosphere Monitoring Service
CaO	Calcium Oxide
CCN	Cloud Condensation Nuclei
CDNC	Cloud Droplet Number Concentration
CDS	Climate Data Store
CERES	Clouds and Earths Radiant Energy System
CESM	Community Earth System Model

CH_4	Methane
Cl^-	Chloride
CMIP	Coupled Model Intercomparison Project
CN	Condensation Nuclei
CO_2	Carbon dioxide
CRM	Cloud-Resolving Model
CRU	Climate Research Unit
CR-WRF	cloud-resolving Weather Research and Forecasting
DER	Droplet Effective Radius
DJF	December - January – February
DMNN	Direction de la Meteorology National du Niger
DNMG	Direction Nationale de la Meteorologie Guineene
EAC4	ECMWF Atmospheric Composition Reanalysis 4
ECHAM	European Centre Hamburg Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño–Southern Oscillation
ESRL	Earth System Research Laboratories
FAO	Food and Agriculture Organization
Fe_2O_3	Ferric Oxide
GCCN	Giant Cloud Condensation Nuclei

GCM	Generation Circulation Models
GFDL-CM3	Geophysical Fluid Dynamics Laboratory Coupled Model 3
GISS-E2	Goddard Institute for Space Studies ModelE2
GMET	Ghana Meteorological Agency
H	Hydrogen atom
IN	Ice Nuclei
ITCZ	Convergent Tropical Zone
JJA	June - July – August
JJAS	June-July-August-September
K^+	Potassium ion
K_2O	Potassium Oxide
LIS	Lightning Imaging Sensor
LNMH	Liberian National Meteorological and Hydrological
LWP	Liquid Water Path
MADE	Modal Aerosol Dynamics Model for Europe
MAM	March - April – May
MCS	Mesoscale Convective System
Mg^{2+}	Magnesium
MgO	Magnesium Oxide
Mn_3O_4	Manganese (III) Oxide

MODIS	Moderate Resolution Imaging Spectroradiometer
MoFWR	Ministry of Fisheries and Water Resources
N	Nitrogen atom
Na^+	Sodium ion
NaCl	Sodium chloride
NAO	North American Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Centre for Atmospheric Research
NH_4^+	Ammonium ion
NMS	National Meteorological Services
NO_3^-	Nitrate ion
NOAA	National Oceanic and Atmospheric Administration
PC	Principal Component
PCA	Principal Component Analysis
PDF	Probability Distribution Function
PET	Potential Evapo-Transpiration
pH	Potential of Hydrogen
PM	Particulate Matter
PR	Precipitation Radar
RADM2	Regional Acid Deposition Model version 2

RCE	Radiative Cloud Equilibrium
RegCM	Community Regional Climate Model of ICTP
S	Sulphur
SAL	Saharan Air Layer
SiO_2	Silicon Dioxide
SLMet	Sierra Leone Meteorological Services
SO_2	Sulphur Dioxide
SO_2^{4-}	Sulphate ion
SODEXAM	Societe d'Exploitation de Developpement Aeroportuaire Aeronautique Meteo
SON	September - October – November
SORGAM	Secondary Organic Aerosol Model
SST	Sea Surface Temperature
TAV	Tropical Atlantic Variability
TMI	TRMM Microwave Imager
TMPA	TRMM Multi-satellite Precipitation Analysis
TRMM	Tropical Rainfall Measuring Mission
TS	Time Series
USAID	United States Agency for International Development
VIRS	Visible Infrared Scanner
WAM	West African Monsoon

WRF	Weather Research and Forecasting

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Precipitation plays an important role in rainfed agriculture (crop production and food security), which is commonly practised over West Africa. Changes in rainfall distribution strongly affect semi-arid regions like the Sahel and West Africa. During dry years known as periods of precipitation reduction, this region experiences food insecurity and heavy negative economic impact. The food and nutrition crisis affected 27.1 million people in those regions between 2021 and 2022 (USAID, 2022). The Sahel region in West Africa is experiencing a precipitation deficit since 1970. That deficit is the source of several socioeconomic problems, such as food insecurity, and water body depletion (Sylla *et al.*, 2018). Considering climate change and the projected population growth, ensuring sufficient water availability will be increasingly challenging in the future.

Precipitation is an important process in regulating the atmosphere, spherical humidity, heat balance and local water circulation. From a microphysical point of view, aerosol excess is known to reduce warm precipitation efficiency by creating much more and smaller cloud droplets (Stier *et al.*, 2022). Aerosol pollution leads to more graupels with smaller sizes at higher altitudes (Zhang *et al.* 2021). In contrast, droplet size and concentration depend on Cloud Condensation Nuclei (*CCN*) from the aerosol. An increase in CCN concentration increases cloud droplets and also reduces their radii preventing them from reaching the size threshold which is 500 μm for small rain, 1000 μm for typical rain and 2500 μm for large rain (Stull, 2017). An increase in the number of cloud droplets, or when the droplets become smaller in size, leads to an increase in the clouds' lifetime. Smaller cloud droplets have a larger surface area relative to their volume. This increased surface area enhances the interaction between the droplets and the surrounding air, promoting the condensation of water vapour onto the droplets. As more water vapour condenses onto the smaller droplets, they grow in size, increasing the clouds' overall water content. This process is known as the condensation coalescence mechanism. The larger droplets fall more slowly through the cloud, allowing them to collide and merge with other droplets, further increasing the clouds' water content and sustaining its lifetime. Aerosol pollution changes (positive or negative shift) rainfall onset, cessation, intensity and frequency. Meaning that precipitation changes are linked to aerosol variability. The impact of aerosol excess varies among different types of clouds, such as stratiform, shallow, and convective clouds. Aerosol negative effects on precipitation are proved by observation data, although climate models predicted an increase in rainfall due to global warming (Salzmann, 2016).

Aerosol particles from hygroscopic materials are good surfaces for the condensation of water vapour and are therefore called Condensation Nuclei (CN). The CCN is part of the CN and is capable of initiating cloud droplet formation. This ability is closely related to the quality and composition of its water-soluble components. To understand the factors that contribute to CCN and cloud interaction, it is important to consider precipitation formation impact on forecast hydrology and local climate. Precipitation is the most difficult component of the West African climate system to predict because of the complex interactions between aerosols and clouds in this region. Accurate precipitation prediction allows policymakers to plan alternatives for rain reduction and abundance for the sake of economic activities. In contrast, excess aerosols in some areas reduce precipitation amount or suppress clouds, preventing them from raining. Changes in the climate system can cause precipitation reduction in some regions and an abundance of rainfall in others.

1.2 STATEMENT OF PROBLEM

Aerosol can exert a strong influence on the formation of warm rain, mainly through its influence on Cloud Condensation Nuclei (CCN). Aerosol tends to increase with CCN especially in a region like West Africa. Due to the competition of water vapour among cloud droplets, a higher CCN number inevitably leads to smaller cloud droplets. Small cloud droplets are ineffective in collisions, partly due to lower falling velocities and partly due to smaller collision efficiencies. It is difficult for cloud droplets to grow into raindrops only by condensation (usually defined as water droplets with a radius or diameter greater than 100mm), and collision coalescence is considered to be a necessary process for the formation of warm rain. But the collisional coalescence process is inefficient unless some cloud droplets can grow by condensation up to the so-called Hawking limit (about 19 mm radius) (Hocking, 1959). Once a raindrop has started to form, its further growth occurs mainly through cloud droplet collection, and the efficiency of this process is highly dependent on cloud droplet size.

Another effect of increased CCN on warm rain formation is the narrowing of the cloud droplet size spectrum (Fitzgerald and Spyers-Duran, 1973; Martin *et al.*, 1994; Liu and Daum, 2002; Andreae *et al.*, 2004). If we assume that the shape of the cloud droplet size spectrum remains constant, increasing the cloud droplet number concentration leads to decrease droplet radii, so a larger cloud droplet activation cut-off size. Smaller droplets grow faster in size than larger droplets. This means that increasing the cut-off size (representing the smallest cloud droplets) can result in a narrower range of cloud droplet sizes. The difference in cloud droplet size (and thus descent velocity) is important to the collision process because it requires significant relative motion of the two colliding droplets. Therefore, the narrower spectral width will also suppress the formation of warm rain. Note that suppressing collisional coalescence further improves the reduction of the cloud droplet size spectrum.

Note that the warm rain suppression effect may not appear if the increase in CCN is accompanied by a change in the spectral shape of the cloud droplet. An extreme example is the addition of some very large CCNs, often called giant CCNs (GCCNs), with radii in the micrometre range or larger. Natural GCCNs are large grains of sea salt formed by the collapse or ripple of air bubbles in the ocean (de Leeuw *et al.*, 2011). Due to its inherently large size, GCCN can be directly activated in rain embryos and can easily initiate the warm rain process (Johnson, 1982; O'Dowd *et al.*, 1997; Feingold *et al.*, 1999; Lasher-Trapp *et al.*, 2001; Cheng *et al.*, 2007). Furthermore, since they also compete for water vapour, GCCNs can lower cloud droplet numbers, depriving small CCNs of the opportunity to activate into cloud droplets. Also, since there are fewer cloud droplets, each cloud droplet can grow larger and thus be more efficiently converted into rain by collisional coalescence. Thus, GCCN counteracts the first and second indirect effects of Twomey. Large insoluble particles such as mineral dust have similar capabilities, especially when coated with hygroscopic materials. The GCCN effect is used for artificial precipitation. In a process called warm cloud seeding, GCCN-sized salt particles are introduced into clouds to speed up rainfall. However, the effectiveness of GCCN depends on the efficiency of raining without it.

Aerosol effects on precipitation depend on four (4) parameters such as cloud types, air humidity, buoyancy and wind shear. Aerosol impact on deep convective clouds is investigated in three places - south Florida, Oklahoma, and the Central Pacific. Cloud-Resolving Model (CRM) simulation experiments low and high Cloud Condensation Nuclei (CCN) environment. These studies found that Relative humidity and evapourative cooling are important in determining the positive or negative response of precipitation to aerosol pollution (Tao *et al.*, 2007, Khain, 2009). Observational datasets are used to show that excess aerosol suppresses precipitation from convective clouds (Liu *et al.*, 2019). Precipitation, from deep clouds with high water content, is enhanced by aerosol pollution in the Southern Great Plains in the United States (Li *et al.*, 2011).

Warm Precipitation suppression during high aerosol concentration periods occurs in both convective and stratiform rain (Barthlott and Hoose, 2018, Huang *et al.*, 2009). Ground-based PM10 and (Tropical Rainfall Measuring Mission) TRMM along with ERA-Interim data are used to investigate the aerosol effects on shallow, stratiform and convective rain over the Pearl River Delta region of China. It found that the top height (1 to 27 km) of convective rain increased by about 29% and the one (0 to 47 km) of stratiform rain decreased by about 10% to 8%. But no changes are noticed in shallow rain (Guo *et al.*, 2018). Aerosol Optical Depth (AOD) $\geq$ 0.5 decreases precipitation frequency in Eastern China (Sun *et al.*, 2022). Black carbon from biomass burning suppresses convective precipitation over Nanjing, China (Huang *et al.*, 2016). Black carbon and sulphur dioxide emissions reduction from Europe and the United States enhance precipitation in three models NOAA Geophysical Fluid Dynamics Laboratory Coupled Model 3 (GFDL-CM3), NCAR Community Earth System Model (CESM1), and NASA Goddard Institute for Space Studies ModelE2 (GISS-E2)

(Westervelt *et al.*, 2018). Aerosol also affects radiative transfer through clouds via absorption of solar light (semi-direct effect), which may accelerate cloud dissipation (cloud burning effect). A study over the Amazon Forest reported that smoke reduced daytime boundary layer cloud cover, from 38% in clean conditions to 0% in heavy smoke (Koren *et al.*, 2004). An increase of anthropogenic aerosols over the Southern China reduced significantly precipitation associated with mesoscale convective systems (MCSs) (Zhang *et al.* 2020). Polluted areas in South Australia did not develop any precipitation due to aerosol pollution (Ayers, 2005). A precipitation negative response is noticed in the extra-tropics during high aerosol concentrations (Dagan *et al.*, 2021). High aerosol concentration decreases precipitation from clouds with low water content in the Southern Great Plains in the United States (Li *et al.*, 2011). Analysis of convective clouds over the Atlantic Ocean shows systematic effects of pollution, desert dust and biomass-burning aerosols on their development and coverage, and found a decrease of cloud droplet sizes by 20% in high aerosol concentrations (Koren *et al.*, 2005). Dust emission over West Africa affects both monsoon development and its precipitation. Precipitation increased with dust pollution in the Western Ghats in India (Prashantha Kumar & Manjunatha, 2021). Aerosols from that emission interact with shortwave and longwave radiation and lead to changes to clouds' physical and radiative properties (Lau *et al.*, 2009). Ten Generation Circulation Models (GCM) are used to investigate aerosol-cloud-radiation interaction on the international AEROCOM initiative. It is proven that aerosol forcing on clouds is -1.5 ± 0.5 W/m^2 (Quaas *et al.*, 2009).

An increase of 13% more precipitation in the polluted aerosol case was predicted on the southern plains of the United States. Aerosol Optical Depth (AOD) ≤ 0.5 increases precipitation frequency in Eastern China (Sun *et al.*, 2022). A precipitation positive response is noticed in the tropics during high aerosol concentrations (Dagan *et al.*, 2021). This study used a cloud-resolving Weather Research and Forecasting (CR-WRF) model with a two-moment bulk microphysical scheme (Li *et al.*, 2009). A study done in the Pearl River Delta region in China showed an increase of precipitation by about 16% in the polluted case by a Cloud Resolving – Weather Research and Forecasting (CR-WRF) simulation. It showed light and moderate suppression and heavy rain enhancement (Wang *et al.*, 2011).

Even though measurements and model simulations show the strong pollution interaction with cloud microphysics, the magnitude or direction of the effect on precipitation and its variations with meteorological conditions have not been identified. Aerosols' effects on precipitation frequency over West Africa have not been examined or understood. This study used high-resolution satellite data to supply a quantitative evaluation of aerosols (dust, black carbon, organic matter, sulphate and sea salt) effects on precipitation frequency over West Africa.

The following questions are addressed:

(i) What are the trends and spatiotemporal variations in the chemical components of aerosols and precipitation over West Africa?

(ii) What are the dominant aerosol and the precipitation time response to aerosol over West Africa? And

(iii) What are the effects of atmospheric aerosols on precipitation?

1.3 AIM AND OBJECTIVES

1.3.1 Aim

The aim of this study was to investigate the impacts of aerosols on precipitation in West Africa.

1.3.2 Objectives

To achieve the main purpose cited above, this study is going to:

(i) examine the trends and spatiotemporal variations in the chemical components of aerosols and precipitation over West Africa;

(ii) examine the precipitation time response to aerosol and the dominant aerosols over West Africa; and

(iii) identify the effects of atmospheric aerosol on West African precipitation.

1.4 MOTIVATION FOR THE STUDY

Good food security management always goes with good water resources policies. It is well known that precipitation reduction has a negative effect on economic activities in West Africa. Considering changing climate and population growth, improvement of precipitation efficiency should be one of the priorities in developing countries. Moreover, most of the socioeconomic problems in West Africa come from precipitation reduction. In the Sahel, where many economies depend on rain-fed agriculture, increasing occurrences of extreme climate events, such as precipitation reduction and drought, threaten crop production and food security (FAO, 1996). Nevertheless, a good understanding of complex atmospheric chemistry, especially chemical interactions between aerosols and clouds is the overwhelmingly most important knowledge to well predict rainfall in order to better build economic improvement policies for this region. Excess is always harmful, meaning that excess of Cloud Condensation Nuclei (CCN) may reduce cloud efficiency. Due to the aerosols-clouds interactions, many global climate models estimate the global mean change in precipitation due to the aerosol effect (Menon *et al.*, 2002; Menon and Del Genio, 2007; Takemura *et al.*, 2005; Lohmann and Diehl, 2006). Results from this study will be useful in weather modification for getting more precipitation by applying cloud seeding or less rain by applying cloud dissipation.

1.5 JUSTIFICATION OF THE STUDY

The purpose of this study is to examine the chemical interactions between aerosols, clouds and precipitation over West Africa. Chemical interaction between aerosols and clouds plays an important role on precipitation in West Africa. High concentration of aerosols over the Sahel proliferates some chemical reactions in clouds which prevent some of them from raining and reduce the precipitation amount of others. From a microphysical point of view, the aerosol is known to reduce precipitation efficiency by creating much smaller cloud droplets. Few studies about aerosols' effects on precipitation were done in West Africa, but several investigations on it were carried out in some other regions in the world. It is proved that suppression of precipitation during months of high aerosol concentration occurs in both convective and stratiform rains. This suggests the suppression of deep convection due to the aerosol (Huang *et al.*, 2009). The start and peak times of convective and stratiform precipitation are delayed by aerosols in the North China Plain, the Yangtze River Delta, and the Pearl River Delta (Sun and Zhao, 2021). Using Tropical Rainfall Measuring Mission (TRMM) measurements, Ayers, 2005 claimed that polluted area in South Australia did not develop any precipitation, and concluded that rainfall was suppressed by excess aerosols. Aerosol also affects radiative transfer through clouds via absorption of solar light (semi-direct effect), which may accelerate cloud dissipation (cloud burning effect). A study over the Amazon Forest reported that smoke reduced daytime boundary layer cloud cover, from 38% in clean conditions to 0% in heavy smoke (Koren *et al.*, 2004). Analysis of convective clouds over the Atlantic Ocean shows systematic effects of pollution, desert dust and biomass-burning aerosols on the development and coverage of them and found a decrease of cloud droplet sizes by 20% in high aerosol concentrations (Koren *et al.*, 2005). Chemical reactions between aerosols and cloud cells, which suppress precipitation or reduce it, are stronger in convective clouds. Results from this study will add technical knowledge on cloud seeding and cloud dissipation for rain enhancement or suppression.

1.6 CONTRIBUTIONS OF THE RESEARCH TO KNOWLEDGE

The outcomes of the study document and contribute to the scientific basis for the management, policies and decision-making on rainwater management. Policies can be technologies of rain enhancement or reduction over West Africa. They will contribute to the improvement of forecasting tools to benefit modellers and meteorological agencies over West Africa for better precipitation prediction results.

The research is expected to:

(i) identify the trends and spatiotemporal variations in the chemical components of aerosols and precipitation over West Africa;

(ii) identify the dominant aerosol and the precipitation time response to aerosol over West Africa; and

(iii) clarify aerosol effects on precipitation intensity, frequency and quality.

1.7 LIMITATIONS OF THE STUDY

Observation data are very important for getting accurate results. Even though forecasts or reanalysis datasets can be used to provide good outcomes. A clear understanding of the effects of aerosol on precipitation intensity, frequency and quality is based on very good datasets first, then a good methodology for very good results. The lack of aerosol observation data is one of the main limitations of this study. Observation precipitation datasets (TRMM) and reanalysis aerosol data (EAC4) were analysed for this study. Due to issues with computational resources WRF-Chem model was not used in this thesis.

1.8 RESEARCH OUTLINE

This thesis is organized into 5 chapters starting with Chapter one, a brief introduction of the research topic and its study area. Chapter two is a literature review of aerosol effects on stratiform, shallow and convective clouds. Chapter three is a description of the materials and methods used in this study. Chapter four presents results and discussion of aerosol effects on precipitation intensity, frequency and quality. Chapter five presents the conclusion of aerosol effects on precipitation investigation and recommendations for future studies for more scientific added values in the field of aerosol and cloud microphysics.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 AEROSOL AND PRECIPITATION CHARACTERISTICS OVER WEST AFRICA

2.1.1 Characteristics of Aerosol in West Africa

Aerosols are fine solid or liquid particles suspended in the atmosphere. In the context of West Africa, aerosols have unique properties and characteristics influenced by various factors such as dust transport, biomass burning, and anthropogenic emissions. Understanding these aerosol characteristics is essential for comprehending their impacts on climate and air quality in the region. West Africa is particularly affected by the transport of Saharan desert dust, which contributes to a significant fraction of aerosols in the atmosphere (Prospero et al., 2002). These dust aerosols are composed of mineral particles originating from the Sahara Desert and are known to have diverse chemical compositions and sizes. They can travel long distances, affecting not only regional but also global climate dynamics and air quality (Kaufman et al., 2005).

In addition to desert dust, biomass burning is another important source of aerosols in West Africa. Biomass burning aerosols result from the combustion of vegetation and agricultural residues, especially during the dry season. These aerosols can significantly impact air quality, visibility, and atmospheric radiative forcing (Adesina et al., 2018). Anthropogenic activities also contribute to aerosol loading in the region. Industrial processes, urban pollution, and vehicle emissions release various aerosol species such as sulphates, nitrates, and black carbon. These anthropogenic aerosols can interact with natural aerosols and modify their properties, further influencing climate and air quality (Ebenso et al., 2019). Houston urbanization notably enhances storm intensity by ∼ 75 % in maximum vertical velocity and precipitation intensity up to 45 %, with the anthropogenic aerosol effect more significant than the urban land effect (Fan *et al.* 2020).

The characterization of aerosol properties in West Africa involves studying their size distribution, composition, optical properties, and vertical profiles. Aerosol measurements and satellite observations, along with modelling studies, are used to understand the spatiotemporal variability of aerosols and their sources in the region (Solmon et al., 2015; Babatunde et al., 2017).

2.1.1.1 Dust

Dust particles from the Sahara Desert have been observed to affect the precipitation patterns over West Africa. Dust particles can act as condensation nuclei and alter the dynamics of the atmosphere, leading to an increase in precipitation. The effects of dust on precipitation are not well understood, but studies have shown that dust can lead to an increase in the amount of precipitation over West Africa, particularly during the wet season. Dust particles from the Sahara Desert act as condensation nuclei, which are particles in the atmosphere that attract water vapour and cause it to condense into droplets. This can lead to an increase in the amount of precipitation in West Africa. This increased precipitation can lead to an increase in the amount of water available for agriculture and other activities. The effects of dust on precipitation can also lead to an increase in the amount of runoff, which can lead to flooding in some areas. This can have a negative impact on local communities, as it can lead to damage to infrastructure and loss of life.

Dust is a major atmospheric aerosol in West Africa and has significant impacts on the region's climate and environment. The seasonal variability of dust transport and deposition is influenced by a complex interplay of regional weather patterns, atmospheric circulation, and land use change. The spatial and seasonal distribution of dust anomalies over West Africa can vary depending on the specific location and time of year. However, in general, the highest concentrations of dust tend to occur during the dry season with peak concentrations occurring in February and March. During this time, the dominant atmospheric circulation pattern, known as the Harmattan, transports dust from the Sahara Desert to West Africa.

2.1.1.2 Black Carbon

Black carbon is a type of air pollutant that is produced from the burning of fossil fuels and biomass burning. It is a major contributor to global warming and can have a significant impact on human health. In West Africa, black carbon is a major concern due to its high levels of pollution in the region. Black carbon in West Africa is primarily produced from the burning of biomass and fossil fuels. Biomass burning includes agricultural waste burning, wood burning, and burning of grasslands. Fossil fuel burning includes emissions from vehicles, factories, and power plants. The burning of biomass and fossil fuels is a major source of air pollution in the region, contributing to high levels of black carbon.

High levels of black carbon in West Africa can have significant impacts on the environment and human health. Black carbon can contribute to global warming and climate change, as well as air pollution and smog. In addition, black carbon can lead to respiratory illnesses and other health problems. It is important to understand the impacts of black carbon in order to mitigate the effects on the environment and human health. The spatial distribution of black carbon in West Africa varies depending on the source of the pollution. For example, the burning of biomass is more common in rural areas, while the burning of fossil fuels is more concentrated in urban areas. In addition, the spatial distribution of black carbon is also affected by wind patterns, which can spread the pollutant over large areas. In order to reduce the levels of black carbon in West Africa, it is important to implement mitigation strategies. These strategies can include the use of cleaner-burning fuels, the implementation of emissions standards, and the promotion of renewable energy sources. In addition, it is important to educate the public about the impacts of black carbon and the importance of reducing emissions.

Black carbon is a type of air pollutant that can have a significant impact on the climate and the environment. The spatial distribution of black carbon anomalies over West Africa can vary depending on a number of factors, including sources of emissions, atmospheric transport patterns, and meteorological conditions. During the dry season, when biomass burning is more common, the spatial distribution of black carbon anomalies tends to be more widespread, with high concentrations of black carbon occurring over much of the region. However, during the wet season, when there is less biomass burning, the spatial distribution of black carbon anomalies can be more localized, with higher concentrations occurring in areas with high levels of human activity, such as urban centres and transportation corridors.

Understanding the spatial distribution of seasonal black carbon anomalies is important for assessing the impacts of air pollution on human health, as well as on the environment and the climate. It can also inform the development of policies and strategies to reduce emissions of black carbon and other air pollutants, and to mitigate their impacts on vulnerable populations and ecosystems.

2.1.1.3 Organic Matter

Organic matter is an important component of soil fertility and soil health in West Africa. The spatial distribution of organic matter in this region is largely determined by natural and anthropogenic factors. Climate and soil type are two of the main factors influencing the spatial distribution of organic matter in West Africa. Anthropogenic factors such as land use and land management practices also influence the spatial distribution of organic matter in West Africa. In addition, deforestation and burning of biomass can also have a significant impact on the spatial distribution of organic matter in the region.

The spatial distribution of seasonal organic matter anomalies over West Africa can vary depending on a number of factors, including land use practices, climate, and soil types. Organic matter is a key component of soils and plays an important role in maintaining soil health and fertility. During the wet season, when there is more vegetation growth and organic matter decomposition, the spatial distribution of organic matter anomalies tends to be more widespread, with higher concentrations occurring in areas with high vegetation cover and organic matter inputs, such as forests, wetlands, and agricultural fields. However, during the dry season, when vegetation is less abundant and organic matter decomposition rates are lower, the spatial distribution of organic matter anomalies can be more localized, with higher concentrations occurring in areas with greater soil moisture retention or organic matter inputs from other sources.

Understanding the spatial distribution of seasonal organic matter anomalies is important for assessing soil health and fertility, and for informing land use practices and agricultural management strategies. It can also help identify areas that are particularly vulnerable to land degradation and soil erosion, and inform the development of soil conservation measures to protect soil health and productivity.

2.1.1.4 Sulphate

Sulphate is a naturally occurring compound found in rocks and minerals, but it can also be produced by human activities. Sulfate concentrations in West Africa are primarily affected by human activities, such as burning fossil fuels, industrial processes, and agricultural practices. These activities release sulphur dioxide, which is then oxidized in the atmosphere to form sulphate aerosols. Sulphate is an important component of the Earth's atmosphere, and its distribution is an important factor in climate change. The region's climate also plays an important role in sulphate distribution, as the dry season leads to higher concentrations of sulphate aerosols due to reduced precipitation. West Africa is a region of the world that has seen a significant increase in sulphate concentrations in recent years. One of the primary sources of atmospheric sulphate is the burning of fossil fuels, such as coal and oil. Other sources include volcanic eruptions and biogenic emissions. Once in the atmosphere, sulphate can be transported over long distances by wind and can contribute to the formation of acid rain. In West Africa, one of the main sources of sulphate is likely to be the burning of fossil fuels for energy production and transportation. However, natural sources such as dust storms and volcanic activity may also contribute to sulphate levels in the atmosphere.

The spatial distribution of sulphate in West Africa has significant impacts on the region's climate, ecosystems, and human health. sulphate aerosols can also act as a fertilizer for plants, leading to increased growth in some areas. However, the aerosols can also cause acid rain, which can lead to soil erosion and damage to ecosystems. The spatial distribution of sulphate in West Africa can also have significant impacts on human health. Inhaling sulphate aerosols can lead to respiratory and cardiovascular problems and can also aggravate existing conditions such as asthma. sulphate aerosols can also lead to eye irritation, headaches, and other symptoms. Long-term exposure to high concentrations of sulfate aerosols can even lead to premature death. There are a number of measures that can be taken to mitigate the impacts of sulfate distribution in West Africa. These include reducing the burning of fossil fuels, improving industrial processes, and implementing agricultural best practices. It is also important to monitor and regulate sulphate concentrations in the region, as well as increase public awareness of the potential impacts of sulphate on human health and the environment.

Sulphate is a type of air pollutant that can have a significant impact on human health and the environment. The spatial distribution of seasonal sulphate anomalies over West Africa can vary depending on a number of factors, including sources of emissions, atmospheric transport patterns, and meteorological conditions. During the dry season, when biomass burning is more common, the spatial distribution of sulphate anomalies tends to be more widespread, with high concentrations occurring over much of the region. Biomass burning releases sulphur dioxide, which can react with other atmospheric pollutants to form sulphate particles. However, during the wet season, when there is less biomass burning, the spatial distribution of sulphate anomalies can be more localized, with higher concentrations occurring in areas with greater industrial and transportation activities.

Understanding the spatial distribution of seasonal sulphate anomalies is important for assessing the impacts of air pollution on human health and the environment, as well as for informing the development of policies and strategies to reduce emissions of sulphate and other air pollutants. It can also help identify areas that are particularly vulnerable to air pollution, and inform the development of public health interventions and other measures to protect vulnerable populations.

2.1.1.5 Sea Salt

Sea salt aerosols are produced when wind-driven waves break up and create sea spray, which is then lifted into the atmosphere. Once in the atmosphere, sea salt aerosols can travel long distances and have important impacts on climate and human health. Sea salt is a major component of the West African coastline. In West Africa, sea salt aerosols can be transported from the Atlantic Ocean by the Harmattan wind, which is a dry and dusty trade wind that blows south from the Sahara Desert. The concentration of sea salt aerosols in the atmosphere is influenced by various factors such as wind speed, sea surface temperature, and proximity to land masses. Sea salt aerosols can also interact with other atmospheric particles, such as sulphur dioxide and nitrogen oxides, to form secondary particles. These particles can have negative effects on human health.

West Africa is an area of diverse geography and climate. It is characterized by long shorelines, and the waters of the Atlantic and Mediterranean Seas. The region is also home to a variety of climates, ranging from tropical to semi-arid. These factors all contribute to the spatial distribution of sea salt in the region. Sea salt is deposited in the region through natural processes such as evaporation, precipitation, and runoff. These deposits are concentrated in areas with higher salinity levels and higher temperatures. Salt deposits are also found in areas with strong onshore winds, which can transport salt from the ocean.

2.1.2 Precipitation Characteristics

Precipitation refers to the deposition of water, in liquid or solid form, from the atmosphere to the Earth's surface. In the context of West Africa, precipitation plays a vital role in the region's climate system, water resources, and socio-economic activities. Understanding the characteristics of precipitation is essential for studying climate variability, droughts, and floods in the region. West Africa experiences distinct precipitation patterns due to its geographical location, monsoonal influence, and topographic features. The precipitation regime is influenced by the West African

Monsoon system, characterized by the movement of the Intertropical Convergence Zone (ITCZ) and associated rain belts (Sultan and Janicot, 2003).

The spatial distribution of precipitation over West Africa varies considerably. Coastal regions, such as the Guinea Coast, receive high annual precipitation due to the influence of the moist maritime air masses (Fontaine et al., 2019). In contrast, the Sahel region experiences a semi-arid climate with lower rainfall amounts and high interannual variability (Hagos et al., 2013). This gradient in precipitation is influenced by factors such as sea surface temperatures, land-sea thermal contrasts, and atmospheric circulation patterns. The variability and characteristics of precipitation in West Africa are also influenced by climate modes and large-scale climate drivers. For example, El Niño-Southern Oscillation (ENSO) events can modulate the West African rainfall patterns, leading to periods of drought or increased precipitation (Fink et al., 2004; Giannini et al., 2003). Other climate drivers, such as the Atlantic Multidecadal Oscillation (AMO) and the Saharan dust outbreaks, can also influence the timing and intensity of rainfall in the region (Evan et al., 2015; Adeyeri et al., 2019). Understanding the spatial distribution of seasonal precipitation anomalies is important for predicting and mitigating the impacts of extreme weather events on agriculture, water resources, and other critical sectors in the region. It can also help identify areas that are particularly vulnerable to climate variability and change, and inform the development of adaptation strategies to build resilience to these changes.

Studies have focused on understanding changes in precipitation patterns over West Africa in the context of climate change. Climate models project a wide range of potential future changes, including shifts in the timing, intensity, and spatial distribution of precipitation (Biasutti et al., 2019; IPCC, 2013). These changes have significant implications for water resources management, agriculture, and the overall socio-economic development of the region.

2.2 LIQUID WATER PATH ROLE ON AEROSOL AND PRECIPITATION INTERACTION

Precipitation efficiency involves not only the measurement of surface precipitation but also vertical air motion within clouds. Aerosols alter warm rain processes by altering cloud microphysics and Liquid Water Path (LWP). It is generally believed that increased aerosol concentrations inhibit the warm rain process through the formation of small cloud droplets and a narrow droplet spectrum; both inhibit collision and coalescence processes (Squires and Twomey, 1966; Warner and Twomey, 1967; Warner, 1968; Radke *et al.*, 1989; Rosenfeld, 1999; Liu *et al.*, 2003). Aerosol pollution suppressed warm-rain formation due to a less efficient collision– coalescence process over central Europe (Barthlott *et al.*, 2022). The driving mechanism for most other aerosol effects on clouds is the first indirect aerosol effect: for a stationary LWP, cloud droplet size decreases with increasing aerosol number concentration (Squires, 1958; Tommy, 1977). For a fixed liquid water path, this results in smaller cloud particle sizes, which suppresses precipitation and prolongs cloud lifetime (Albrecht, 1989). The stagnation of liquid water above freezing causes additional latent heat, which promotes the development of deep convective clouds and increases precipitation (Andreae *et al.*, 2004; Rosenfeld *et al.*, 2008). This exhilarating effect can also increase cloud heights. The effects of aerosols on precipitation, cloud height, volume/liquid water path (LWP) and duration are summarized in a general term: the second indirect aerosol effect (Albrecht, 1989), which is more Much more complicated.

Microphysical variables (Droplet Effective Radius (DER), Liquid Water Path (LWP), COD) available from satellites, LWP plays the most important role in precipitation (Sorooshian *et al.*, 2009; Chen *et al.*, 2011), although these variables are not independent of. Chen *et al.* used matched precipitation data from CloudSat and cloud microphysics from MODIS on A-Train. Chen *et al.* (2011) studied the predictability of warm cloud precipitation. They found that LWP was by far the dominant factor, followed by DER and COD. Therefore, examining the effects of aerosols on precipitation can begin with their effects on these key cloud variables.

Given the dominant effect of LWP on precipitation, it is critical to understand whether and how aerosols modify LWP, which is much more difficult than inferring the effect of aerosols on DER. Contrasting findings reportedly show a positive relationship (Sekiguchi *et al.*, 2003; Storelvmo *et al.*, 2006; L'Ecuyer *et al.*, 2009), negative relationships (Twohy *et al.*, 2005; Matsui *et al.*, 2006; Brenguier *et al.*, 2000), or mixed results (Nakajima *et al.*, 2001; Coakley and Walsh, 2002; Han *et al.*, 2002; Kaufman *et al.*, 2005). Several mechanisms have been postulated. Enhanced aerosol entrainment and droplet evapouration decrease LWP (Ackerman *et al.*, 2004), while inhibition of coalescence suppresses precipitation and thus increases LWP (Lebsock *et al.*, 2008). On the other hand, the laxative effect of drizzle can remove aerosols, leading to an apparently negative relationship that undermines any real causality (Twohy *et al.*, 2005).

2.3 AEROSOL EFFECTS ON PRECIPITATION

Several methods have been used in previous studies to separate aerosol effects on precipitation from other effects. One is to study changes in other factors (such as water vapour) that may cause changes in precipitation. Observed aerosol and precipitation covariance may indicate an aerosol effect on precipitation only if the observed precipitation variability is inconsistent with these other factors. The importance of studying covariance between aerosols, precipitation, and other factors is explicitly explored. In a study of precipitation trends in Israel, Alpert *et al.* (2008) pointed out that failure to adequately account for urban dynamics, such as the heat island effect, could lead to misinterpretation of the data and lead to the erroneous conclusion that the observed decreasing trend in precipitation is due to increased inhibition from upwind areas urban pollution. By comparing the next-month evolution patterns of aerosols, precipitation, and other meteorological variables in the South Asian monsoon preseason, Bollasina and Nigam (2009) reproduced earlier monthly observations and showed that anomalous aerosol formation in May could delay the onset of monsoon rains, Because of the aerosol radiative effect (cooling of the land surface). However, they acknowledge that the pervasive influence of advection precludes reliable analysis of aerosol effects. The following examples illustrate some of the methods that have been used to try to separate the effects of aerosols on precipitation from other effects.

Qian *et al.* (2009) observed that from 1956 to 2005, light rain in eastern China showed a decreasing trend, while heavy rain showed an increasing trend. This is the same time period when pollution in the same part of China has increased dramatically, and the trend of change is not the same, but it is monotonous. As inferred from the global reanalysis products, no correlation was found between the decreasing trend of light rain and water vapour transport. This prompted the authors to rule out the possibility that the light rain trend was caused by wide-ranging changes in meteorological conditions. Tropical regions are particularly susceptible to hydrological-cycle change from either local or remote aerosol emissions (Persad 2023). They then hypothesized that the observed increase in aerosols due to pollution during the same period could be responsible for the observed trend towards a decrease in light rain, as aerosols have a known dampening effect from light to heavy rain. However, they do not discuss whether the change in total water corresponding to the observed light rain trend is within the uncertainty of the water vapour transport data.

Wilcox *et al.* (2010) observed a northward shift of precipitation in the Convergent Tropical Zone (ITCZ) over the tropical Atlantic Ocean during the African Dust Storm. They studied differences in temperature distribution and wind areas in the lower troposphere during African dust storms and low dust conditions. They hypothesize that the northward shift in precipitation is caused by advection of the Saharan Warm Air Layer (SAL), enhanced subtropical deposition, and lower tropospheric warming due to radiative heating from dust. Lau and Kim (2006) compared composite and lagged regressions of aerosol, wind, temperature, and precipitation over the Indian summer monsoon region. They propose an "enhanced heat pump" hypothesis, according to which abnormally high concentrations of absorbing aerosols in the pre-monsoon period are associated with anomalous warming leading to large-scale circulation changes leading to increased Indian monsoon precipitation. Both Lau and Kim (2006) and Wilcox *et al.* (2010) compared the possible contribution of aerosols to observed precipitation changes. Therefore, their hypothesis is reasonable but not unambiguous, although the observed signal is consistent with those numerical simulations, where it is clearer to attribute the changes to specific physical processes.

2.4 MICROPHYSICS

The basis of aerosol effects on cloud and precipitation formation is based on the concept of cloud droplets by CCN activation and the concept of cloud ice by IN nucleation. The former can be represented by a Koehler curve if information such as size distribution and chemical activity coefficients are known. Since such information can be derived from measurements, aerosol properties can be specified according to cloud models. However, the specification of aerosol properties is only suitable for case studies. Not suitable for simulations of durations longer than the lifetime of the aerosol (approximately a few days). More sophisticated simulations should be performed by coupling CRM to detailed aerosol models that can account for particle size, chemical composition, and mixing conditions. Coupling should allow the effects of clouds on aerosols, including aerosol scavenging and aerosol recycling, as well as cloud chemistry, to be simulated simultaneously with the effects of aerosols on cloud microphysical properties. Another area that needs further improvement is the microphysical sensitivity of clouds to aerosol effects. Many bulk water schemes greatly oversimplify the collision efficiency between cloud droplets and precipitation particles, and thus the impact of aerosols on cloud droplet size, and hence the collisional growth process, cannot be fully resolved.

Aerosol particles from hygroscopic materials are good surfaces for condensation of water vapour and are therefore called condensation nuclei. The CCN is part of aerosols and is capable of initiating cloud droplet formation. This ability is closely related to the quality and composition of its water-soluble components. Aerosol can exert a strong influence on the formation of warm rain, mainly through their influence on cloud concentration. As mentioned above, cloud concentration tends to increase with CCN. Due to the competition of water vapour among cloud droplets, higher cloud concentration inevitably leads to smaller cloud droplets. Small cloud droplets are ineffective in collisions, partly due to lower falling velocities and partly due to smaller collision efficiencies. It is difficult for cloud droplets to grow into raindrops only by condensation (usually defined as water droplets with a radius or diameter greater than 100mm), and collision coalescence is considered to be a necessary process for the formation of warm rain. But the collisional coalescence process is inefficient unless some cloud droplets can grow by condensation up to the so-called Hawking limit (about 19 mm radius) (Hocking, 1959). Once a raindrop has started to form, its further growth occurs mainly through cloud droplet collection, and the efficiency of this process is highly dependent on cloud droplet size.

Another effect of increased CCN on warm rain formation is the narrowing of the cloud droplet size spectrum (Fitzgerald and Spyers-Duran, 1973; Martin *et al.*, 1994; Liu and Daum, 2002; Andreae *et al.*, 2004). According to the condensation growth equation, smaller droplets grow faster in size than larger droplets. This means that increasing the cutoff size (representing the smallest cloud droplets) can result in a narrower range of cloud droplet sizes. The difference in cloud droplet size (and thus descent velocity) is important to the collision process because it requires significant relative motion of the two colliding droplets. Therefore, the narrower spectral width will also suppress the formation of warm rain. Note that suppressing collisional coalescence further improves the reduction of the cloud droplet size spectrum.

Note that the warm rain suppression effect may not appear if the increase in CCN is accompanied by a change in the spectral shape of condensation nuclei. An extreme example is the addition of some very large CCNs, often called Giant CCNs (GCCNs), with radii in the micrometre range or larger. Natural GCCNs are large grains of sea salt formed by the collapse or ripple of air bubbles in the ocean (de Leeuw *et al.*, 2011). Due to its inherently large size, GCCN can be directly activated in rain embryos and can easily initiate the warm rain process (Johnson, 1982; O'Dowd *et al.*, 1997; Feingold *et al.*, 1999; Lasher-Trapp *et al.*, 2001; Cheng *et al.*, 2007). Furthermore, since they also compete for water vapour, GCCNs can lower maximum ambient supersaturation, depriving small condensation nuclei of the opportunity to activate into cloud droplets. Also, since there are fewer cloud droplets, each cloud droplet can grow larger and thus be more efficiently converted into rain by collisional coalescence. Thus, GCCN counteracts the first and second indirect effects of Twomey. Large insoluble particles such as mineral dust have similar capabilities, especially when coated with hygroscopic materials. The GCCN effect is used for artificial precipitation. In a process called warm cloud seeding, GCCN-sized salt particles are introduced into clouds to speed up rainfall. However, the effectiveness of GCCN depends on the efficiency of raining without it. In a clean environment (low cloud concentration), cloud droplets can become large enough by condensation to reach the so-called Hawking limit, after which cloud droplets can efficiently grow and transform into raindrops by collisional coalescence. Therefore, GCCN tends to be less important in this context, as suggested by Feingold *et al.* (1999) simulated using a detailed model. They also found that oceanic stratocumulus clouds required higher concentrations of GCCN to produce drizzle at higher CCN concentrations. Although CCN generally increases with condensation nuclei during dust events, its ratio tends to decrease sharply with condensation nuclei, implying that less GCCN is available under severe loading conditions such as dust storms (Liu *et al.*, 2011). Having elucidated the role of dust particles as CCN, it is worth noting that, as recently reported by Ravi *et al.*, dust has very broad impacts on global climate, ecosystems, human health, and agriculture Ravi *et al.* (2011).

The above discussion shows that more condensation nuclei will lead to more cloud droplets and less precipitation. However, there are many examples where increasing CCN does not lead to higher cloud water content or longer cloud lifetime. Ackerman *et al.* (2004) showed that dry air in the upper layers above entrained stratocumulus boundary layer clouds leads to a reduction in cloud water when the upper air humidity is very low. In addition, more and smaller cloud droplets increase downdraft evapouration at the edge of the cloud, resulting in less cloudiness, less cloud cover, and lower cloud depth (Teller and Levin, 2006; Xue and Feingold, 2006).

Cloud top droplet size is determined by many factors such as Atmospheric stability, available water vapour and cloud thickness. During the adiabatic process, cloud droplet size increases linearly with cloud top height, which is further related to potential energy (Rogers and Yau, 1989). It should be noted that an increase in cloud droplet size does not necessarily lead to an increase in precipitation; that is, the first indirect effect is not a necessary cause of, nor does it lead to, an increase in precipitation. Precipitation is controlled by many factors, which are dynamic, thermodynamic and microphysical in nature.

2.5 CCN EFFECT ON PRECIPITATION

Observational studies suggest that increased aerosol concentrations may inhibit the warm rain process by creating a narrow droplet size range that inhibits collision and coalescence processes (Squires and Twomey, 1966; Warner and Tomey, 1967; Warner, 1968; Rosenfeld, 1999). Also, more aerosols reduce precipitation. This is because more aerosols produce smaller cloud droplets, leading to less efficient collisional coalescence and thus less precipitation. Many cloud-resolved modelling studies simulated these processes early in the development of isolated convective systems, finding that it sometimes rained more under polluted conditions.

Several cloud-resolved modelling studies have also investigated the physical processes that may lead to aerosol-induced changes in precipitation. Overall, three mechanisms have been proposed to explain increased precipitation through altered (increasing or decreasing) aerosol concentrations. The first mechanism involves stronger updrafts or downdrafts due to increased latent heat release, as the CCN suppresses the formation of warm rain, thereby retaining more liquid water in clouds, which freezes in the upper layers. This effect may be called the latent heat–dynamic effect. Wang (2005) showed that due to this latent heat effect, precipitation in tropical deep convection increases due to higher CCN concentrations. Khain *et al.* (2005) also found that under conditions of increased precipitation and high CCN concentrations, clouds are associated with stronger updrafts or downdrafts and greater convergence in the boundary layer, making secondary clouds more likely to trigger and prolonging the lifetime of convective systems. van den Heever and Cotton (2007), Lee *et al.* (2008a), and Storer *et al.* (2010) also proved the influences of aerosols on storm development and their effects on enhancing precipitation.

The second mechanism is that the large but small amount of raindrops under high CCN conditions result in greater evaporative cooling. More evaporative cooling can increase the intensity of cold pools near the surface. If enhanced cold pools interact with lower wind shear, convergence may increase, generating more convection and ultimately increasing surface precipitation. This positive feedback mechanism can be called the cool pool effect. This seems to occur in the case of ocean convection, and evaporative cooling in the lower troposphere is more than twice as strong in the polluted scenario as it is in the clean scenario. Note that more evaporative cooling occurs during the evolutionary stages of convective cloud systems. Lee *et al.* (2009a) also showed that high aerosol concentrations lead to greater evaporative cooling, resulting in increased surface precipitation.

Four different microphysical processes influence surface precipitation. The CCN effect on precipitation for low CCN is dominated by suppression of warm rain formation (effect A) and enhancement of rime (effect C). On the other hand, for high CCNs with small changes in snow-raindrop accumulation, snow edge reduction (decreased collection efficiency, effect B) and melting are large enough to dominate cold rain changes. manufacturing. result in suppressed surface precipitation. Overall, the impact of CCN on precipitation is dominated by effects A and B when CCN is high.

However, these four physical mechanisms can influence each other, making it difficult to separate each mechanism separately. For example, strong evaporative cooling (cold pool effect) is seen in the lower troposphere for high CCN-enhanced precipitation (latent thermodynamic effect). Stronger cooling, on the other hand, is likely due to stronger evaporation combined with stronger convective downdrafts (a potential thermodynamic effect). Microphysical effects can affect both latent heat and cooling pools and vice versa. Smaller droplets can enhance the WBF process (that is, snow cover growth at the expense of evaporating droplets), resulting in greater latent heat release. However, a decrease in riming efficiency has the opposite effect on latent heat release. More cloud droplets (due to more CCN) also result in more ice nucleation, resulting in more snow and sleet particles melting, forming more and smaller raindrops, and clouds. It can cause more evaporative cooling under the lower level of clouds. Convection can be increased by either the latent heat effect or the cold pool effect, and increased updrafts lead to higher supersaturation and increased nucleation from ice deposition.

2.6 URBAN POLLUTION

High aerosol concentrations in urban environments affect precipitation variability by providing an important source of cloud condensation nuclei (CCN). The impact of this pollution on precipitation can have large climate impacts, from precipitation affecting the surface and feedback to the surface energy balance to changes in latent heat input to the atmosphere. As the main source of anthropogenic aerosol emissions, urban areas can cause a certain degree of damage to the atmospheric environment, thereby changing the regional climate. There are two main types of disturbances: land cover change and atmospheric emissions. The latter include aerosols and greenhouse gases. The greenhouse effect generally has larger spatial and long-term effects than the aerosol effect. Changes in aerosols and land cover can leave powerful traces but distinguishing the effects of the two is a difficult task.

High aerosol concentrations in urban environments may affect precipitation variability by providing an enhanced source of CCN. Develop hypotheses to explain Urban area impact on convection and precipitation (van den Heever and Cotton, 2007; Shepherd, 2005). It is unclear whether the urban heat island effect or the aerosol effect, or both, contributed to the amplification. Armed with the theory of aerosol regeneration, we can now revisit this phenomenon. Polluted cities are ideal places to induce and amplify busy clouds, especially those near lakes and coasts in summer. In summer, warm, moist air can blow over land from oceans or lakes, with the following conditions favouring cloud recovery: (1) abundant supply of highly hygroscopic anthropogenic aerosols, (2) heat island effect, driving convection, and (3) moist hot air, which can generate a lot of potential energy to maintain strong convection.

This appears to confirm findings of midweek precipitation and convective anomalies, as well as increased lightning in urban areas. TRMM-derived precipitation data using long-term integration Bell *et al.* (2008) found a significant increase in afternoon thunderstorms on aerosol-laden summer weekdays in the southeastern United States, along with increases in ground-measured aerosol concentrations, with winds converging at 1000 hPa and diverging at 300 hPa, with vertical velocities at 500 hPa. These coincidental results are consistent with the idea that aerosols have a significant impact on the dynamics of continental mixing convective clouds (Rosenfeld and Woodley, 2000; Williams *et al.*, 2002).

Increases in lightning density have been found to be concentrated upwind and downwind of metropolitan areas (Orville *et al.*, 2001). Possible reasons are increased convergence associated with the urban heat island effect and changes in microphysical processes associated with anthropogenic pollution. Steiger and Orville (2003) compared a 14-year cloud-to-surface lightning density distribution in Louisiana with the location of PM10 (particulate matter less than 10 mm diameter) sources. Yuan *et al.* (2011) examined lightning data from the TRMM satellite and the flash image sensor on MODIS AOD in 2005. They found unusually high lightning activity in the presence of high aerosol pollution, which they attributed to volcanic activity; they did not find a link to any meteorological anomalies. They also quantified the flash response to AOD: A 60% increase in aerosol exposure resulted in a greater than 150% increase in flash. Aerosols can affect lightning activities by altering the microphysics of clouds. With increasing aerosol loading, cloud ice particle size decreases and cloud ice melting is delayed to cooler temperatures. Although there is seemingly convincing evidence linking aerosols to lightning activity, their true link is much more complicated, especially given the many other drivers associated with urban areas, such as using state-of-the-art surface models and Simulations performed by cloud resolution models (van den Heever and Cotton (2007)).

The discovery of the opposing role of aerosols in regulating rainfall has major scientific and societal implications because it suggests that increased aerosol pollution may make wet regions or seasons wetter and dry regions or seasons drier.

2.7 TOOLS TO IDENTIFY AEROSOL EFFECTS ON PRECIPITATION

The easiest way to remove the influence of raindrops/wash-off on aerosol and cloud pollution from aerosol precipitation analysis is to avoid the relationship between stochastic aerosol and precipitation measurements. Downwind aerosols can be included in analyses based on return trajectory calculations (Hui *et al.*, 2008; Huang *et al.*, 2009b). An equivalent approach would be to include a time delay of the aerosol signal leading to precipitation (Lau and Kim, 2006; Bollasina and Nigam, 2009). Another approach is to exclude aerosol data near cloud scenes or within grid boxes with large cloud parts (Koren *et al.*, 2010a). In the target precipitation area far from the aerosol source, the aerosol variation unrelated to precipitation should be the same as outside and upwind of the precipitation area. On this basis, Huang *et al.* (2009, 2009a) depicted large-scale fluctuations in aerosols over the tropical Atlantic and West African monsoon regions using large-area rainband and no-precipitation averaged aerosols.

To determine the effect of aerosols on precipitation in the Amazon Basin during the biomass-burning season, Jones and Christopher (2010) applied principal component analysis (PCA), a statistical tool commonly used in geosciences. The method includes precipitation and 23 other parameters, including ambient meteorological variables, cloud information (optical depth, high pressure), aerosol optical depth, and location. They interpret the weight of each parameter and its sign relative to the amount of precipitation in each principal component (PC) as a signal that there may be a physical link between the two. Based on this interpretation, they found that atmospheric environmental variables were the dominant factor in precipitation variation, where the first principal component, which explained 25% of the total precipitation variance, had the greatest weight. Following the same argument, they identified the radiative effect of aerosols as the second most important factor in precipitation, represented by the second principal component explaining 15% of the variance in total precipitation. Their results suggest that smog has a dampening effect on precipitation. However, the orthogonality requirement for each PC may obscure the physical phenomena to be revealed.

In studying the effects of aerosols on precipitation in the tropical Atlantic and West African monsoon regions, Huang *et al.* (2009, 2009a, 2009c) used multiple linear regression methods to remove aerosol and precipitation changes associated with water vapour and sea surface temperature (SST), known climate model (e.g., El Niño–Southern Oscillation (ENSO), North American Oscillation (NAO), and Tropical Atlantic Variability (TAV)). The resulting time series of aerosol and precipitation anomalies are considered to be linearly independent of other climate factors. They then compared the spatial distribution and seasonal cycles of anomalous precipitation between large-area averaged months of high and low aerosol anomalies. The comparison shows that during the northern winter, the equatorial and southern African seasons of high biomass burning, precipitation decreases in months with anomalously high aerosols along the southern edge of the rain belt. Spatial patterns and seasonal cycles of precipitation reduction are inconsistent with expected aerosol wet deposition. Numerical simulations including only the radiative effects of soot aerosols reproduced this observation. They concluded that the decrease in precipitation was due to the radiative effects of smoke from biomass burning. Biomass burning aerosol pollution suppresses low-level liquid clouds by local warming and increased evaporation and facilitates the formation of high-level ice clouds by enhancing updrafts and condensation at high altitudes (Liu *et al.*, 2020). Linear regression can only consider concurrent relations.

A strongly recommended approach to isolate the aerosol effect from other effects is to study the aerosol-precipitation relationship under different regimes (Stevens and Feingold, 2009). A regime can be defined in different ways depending on the data and analysis objectives. They include convective properties (cloud work function), environmental conditions of the cloud (static stability) or cloud microphysics, as in the example below.

As is evident from the discussion above, each method of isolating the effect of aerosols on precipitation from other factors has its advantages and disadvantages. Large-scale diagnostics of aerosol effects on precipitation through radiative or CCN changes, or both, are incomplete without consideration of the microphysics (clouds, aerosols, and precipitation), the dynamics of mesoscale clouds, and the large-scale background environment. This requires unprecedented collaboration and coordination among the various subdisciplines in the field of atmospheric science.

2.8 MODEL

In particular, modelling studies are critical to qualitatively and quantitatively understand the relative impact of aerosol pollution on cloud properties and precipitation. The combination of cloud top temperature and effective droplet size estimated using the Advanced Very High-Resolution Radiometer (AVHRR) is used to predict smog (Rosenfeld and Lensky, 1998) and desert dust (Rosenfeld *et al.,* 2001). Analysis of satellite observations shows that, on average, both natural transport and local anthropogenic dust aerosols can significantly reduce cloud water particle size, optical depth, and liquid water paths (Huang *et al.*, 2006a, 2006b, 2010). These results suggest that dust aerosols warm clouds and increase cloud droplet evaporation, further reducing the path of cloud water through the so-called semi-direct effect. This semi-direct effect may play an important role in cloud evolution and exacerbated drought conditions in the semi-arid regions of north-western China (Huang *et al.*, 2006a, 2006b, 2010).

Cloud Resolving Model (CRM) was used to study the influence of aerosols on cloud and precipitation processes, CCN activation must be considered in its microphysical scheme. Studying the influence of CCN and GCCN on clouds requires a two-rectangle or spectral bin microphysics scheme. One of the main differences between the two-moment-mass and spectral bin microphysics schemes is the representation of the cloud particle size spectrum. Two-moment schemes often combine key features of single-moment schemes by calculating the hydrometeor mixing ratio and then adding an additional variable for particle number concentration. The microphysics of warm (ice-free) clouds assumes a bimodal population of water particles. One population is used for small cloud droplets with negligible terminal velocities compared to vertical airspeed, and the other population is used for large raindrops with significant descent velocities. Ice microphysics generally assumes three types of particles: small ice clouds with negligible terminal velocities, snow with terminal velocities on the order of tens of centimetres, and heavy sleet or hail with much faster velocities. Until recently, some CRMs added freezing drops or hailstones as a fourth particle. Rain and snow have low density and high intercept in the Marshal-Palmer distribution (high number set), while hail has high density and low intercept. Only raindrops, snow, sleet and hail have a chance to reach the ground. Sleet represents tropical ocean convection and hail represents mid-latitude storms (McCumber *et al.*, 1991). More than 25 transformations can occur between water vapour, liquid particles, and ice particles, such as B. Vapour deposition and growth of mature ice crystals, aggregation of ice crystals, formation of rain, snow, and hail, aggregation of supercooled cloud droplets leading to rain, snow, and hail growth, droplet shedding of hail, rapid growth of ice crystals in the presence of supercooled water and melting and sublimation of all forms of ice. Certain mathematical functions, such as the Khrgian-Mazin distribution function for cloud droplets and the Marshall-Palmer distribution function for raindrops, snow and sleet, or hail, are considered to represent their size distributions.

It is generally assumed that clouds produce fewer droplets in a clean environment (low CCN concentration). But larger in size due to more condensation and collection growth resulting in a wider size range Contrast with high CCN case (Tao *et al.*, 2007). The result is very similar to those observed and shown by Fletcher (1962), and Squire (1958). Van den Heever *et al.* (2006) and Carrio *et al.* (2007) also found that there are even smaller cloud droplets with a narrow spectrum under dirty conditions. The numerical results obtained from this study exhibit excellent agreement with the observational data, providing evidence that cloud microstructure is heavily influenced by interactions between clouds and aerosols. Twomey works well in simulation. The width of the droplet size distribution may influence the precipitation processes. Smaller Cloud droplets reduce the likelihood of raindrop formation through cloud droplet condensation.

The effect of increasing aerosol concentrations on the cloud lifetime of warm convective clouds was investigated using CRM and large eddy simulations (a special type of cloud model with a resolution of 100 m or less). Teller and Levin (2006) showed that polluted clouds produce less precipitation, leading to increased cloud lifetime under the same meteorological conditions. This result is consistent with a second indirect effect of aerosols on cloud lifetime (Albrecht, 1989; Ackerman *et al.*, 2000). However, a separate modelling study showed that increasing aerosol concentrations from very clean to heavily polluted conditions did not increase cloud longevity, despite suppressed precipitation. In rare cases, long-lived polluted clouds may outlive clean clouds due to the merging of individual clouds. This result contradicts the observation that increased aerosol concentrations lead to increased cloud lifetimes. But the model results are consistent with observations of water inhibition under polluted conditions. ginger *et al.* (2006) proposed that the small cloud lifetime variation is due to the competing effects of precipitation suppression and enhanced evapouration of flat clouds. Differences between the results of Teller and Levin (2006) and Jiang *et al.* (2006) are possibly due to differences in aerosol concentrations (light vs. high pollution) and/or environmental conditions.

Recently, many CRMs have been used to study the role of aerosols in mixed convective clouds. These modelling studies reveal model configurations (2D or 3D), domain sizes, lattice spacings (150-3000 m), microphysics (two-moment volumes, simple or complex spectral ranges), turbulence, radiation, and transverse Boundary conditions (i.e. closed, radiation open or circulating), cases (isolated convection, tropical or mid-latitude thunderstorm lines) and model integration times. A simple indicator, the time-integrated change in precipitation (dP = 100 (Pdirty Pclean)/Pclean) due to the increase in CCN number concentration (dN0 = Ndirty Nclean), was used to study the effect of aerosol concentration on surface precipitation (Table 4). The most notable difference among these model studies is that cumulative precipitation can increase or decrease in response to higher CCN concentrations. Phillips *et al.* (2002), Kane *et al.* (2004, 2005), Khain and Pokrovsky (2004), and Teller and Levin (2006) gradually varied the number concentration of CCN and found that cumulative precipitation decreased substantially with increasing CCN concentration. This is the exact opposite of what Wang (2005), Khain *et al.* (2005), Lee *et al.* (2009a), and Fan *et al.* (2007b) found.

Tao *et al.* (2007) used a two-dimensional CRM with detailed spectral bin microphysics to study the contribution of aerosols to the oceanic tropical mesoscale convective system, summer mid-latitude continental thunderstorm line, and summer short-lived sea breeze convective storms in Florida. In all three case studies, rain suppression in the high CCN operation was evident, but only within the first hour of simulation. In all clean cases, rainwater reaches the ground ahead of time. This result suggests that microphysical processes dominate the initial stages of cloud evolution, during which the transition from condensation to accumulative growth depends very sensitively on cloud droplet size. Clouds in clean environments produce fewer but larger cloud droplets than would be the case under polluted conditions, so there is a greater chance of cloud droplets condensing to form raindrops. This result is in good agreement with many observations and other CRM studies (Khain), and is consistent with Twomey's second indirect effect. At the mature stage of the simulation, the effects of increasing CCN concentrations range from rainfall suppression in the mid-latitude continental case to a small effect in the Florida sea breeze case, to rainfall enhancement in the Pacific oceanic case. These results suggest the need for model simulations over the entire life cycle of convective systems to estimate the impact of aerosols on precipitation processes associated with MCS and thunderstorms. These results also reveal the complexity of aerosol-cloud-precipitation interactions in deep convection.

Khain *et al.* (2008) and Khain (2009) recently performed a series of numerical experiments to determine the determinants of the aerosol effect on precipitation. A scheme has been proposed to classify the impact of aerosols on clouds and cloud systems in different environments. It shows that when the relative humidity is high, the condensation gain (loss) is large and the condensation loss (gain) is small, which may lead to an increase (decrease) in precipitation. Seifert and Beheng (2006), Khain *et al.* (2008), and van den Heever *et al.* (2011) also showed that the influence of aerosols on precipitation and convective structure depends on cloud type. Precipitation decreases accompanied by increases in aerosol concentrations typically occur in relatively dry environments and/or in isolated cumulus and cloud systems that form in areas of high wind shear or stratocumulus. Fan *et al.* (2009) also found that increasing CCN concentration always suppressed convection under strong wind shear conditions but enhanced convection under weak wind shear conditions. On the other hand, clouds that form in humid environments, such as coastal areas, cloud clusters, or tropical thunderstorm fronts, often lead to increased precipitation and increased aerosol concentrations. Such results can also be found in other CRM studies (Wang, 2005; Tao *et al.*, 2007; Fan *et al.*, 2007b) and agree with the LES study by Ackerman *et al.* (2004). Note that Wang (2005), Tao *et al.* (2007), Khain *et al.* (2008), Fan *et al.* (2007a), and Lee (2011) all show that aerosols have a greater effect on precipitation under wetter conditions.

More recently van den Heever *et al.* (2011) used large-scale (10,000 km), long-duration (100 days), high-resolution (1 km) radiative cloud equilibrium (RCE) simulations to assess the effects of increased CCN concentrations on various storm types, occurring in the most diverse under degraded environmental conditions. They found that high concentrations of CCN lead to decreased surface precipitation from shallow clouds but increased precipitation from deep convective clouds, which is related to the mixing response of milder convective storms such as cumulus congestus. They also found that under more polluted conditions, the frequency of systems producing lighter precipitation decreased, while the frequency of systems producing heavy precipitation increased, and concluded that polluted conditions cause systems to occur more frequently, producing more intense precipitation.

In almost all of the above cases, the model simulations used idealized aerosol concentrations. Some CRM domains are too small to resolve observed cloud or precipitation systems (the domain size must be at least twice the size of the simulated features). Furthermore, few of these CRM studies compare model results with observed cloud structure, organization, and radar reflectivity. Note that model simulations also capture storm size and structure under different environmental conditions. For example, leading convective and extensive trailing stratified rain fields are compared with radar reflectivity observed during the mature stages of continental fall (Rutledge *et al.*, 1988). Clean cases (control experiments) usually match observations better. Regarding the amount of radar reflectance, the agreement between simulations and observations is better at lower layers, where only liquid clouds or rain are present. Simulated radar reflectivity tends to be higher than observed in the anvil region where the upper layer and ice-phase particles dominate. This reflects the insufficient description of various ice phase mechanisms in this calculation, especially those related to aerosol effects.

2.9 IMPACT OF AEROSOLS ON PRECIPITATION (MICROPHYSICAL PROCESSES)

In global climate models, the representation of the impact of aerosols on cloud microphysics is generally implemented in a highly parameterized fashion due to the coarse spatial resolution of these models. Such a parameterization usually consists of two major steps: (1) the activation/nucleation of cloud droplets or ice crystals and (2) the "auto-conversion" to convert small cloud droplets or ice crystals (typically from 10 to 100 mm in size) to precipitating hydrometeors, i.e., rain or snow (several hundreds of micrometres to a few millimetres). Note that the latter transition is a parameterization of a series of microphysical processes involving a random collection of small cloud droplets under the influence of updrafts or downdrafts and turbulent mixing at a sub-grid-scale level.

In fact, most global aerosol-climate modelling efforts dealing with the microphysical impact of aerosols have focused on deriving the indirect radiative forcing of aerosols rather than studying the precipitation effect. The former task, in a model without explicitly predicting aerosol number concentration, would be done by using an empirical method to connect aerosol mass with Cloud Droplet Number Concentration (CDNC), auto-conversion rate, and precipitation efficiency to simulate various aerosol effects (Rotstayn, 2000; Kiehl *et al.*, 2000; Menon *et al.*, 2002; Ming *et al.*, 2005; Penner *et al.*, 2006; Jones *et al.*, 2007). The aerosol–CDNC relationships used in various aerosol climate models appear to be qualitatively consistent with each other and with satellite estimates. However, the modelled results for the aerosol albedo effect, the optical response of clouds to changes in aerosol level, or CDNC, can vary significantly and even deviate from satellite-based estimates. Moreover, simulations of aerosol effects on cloud cover, altitude, lifetime, and outgoing longwave radiation, including dynamic feedback, differ even more when performing more complex tasks such as (Quaas *et al.*, 2009). To date, there is still controversy over whether indirect forcing from aerosols should be treated as forcing or response and estimating such effects is one of the major uncertainties in climate modelling. For details of indirect coercion studies in Haywood and Boucher (2000), Ramaswamy *et al.* (2001) and Lohmann and Feichter (2005).

In global models, several physics-based parameterizations have been developed to simulate the activation of liquid or ice cloud particles (Abdul-Razzak and Ghan, 2000, Nenes and Seinfeld, 2003, Karcher and Roman, 2003, Liu and Penner, 2005, Barahona and Nenes, 2007). These schemes are also useful for modern aerosol climate models with improved microphysical representations of aerosols and clouds. Early-generation models have also gone beyond pure aerosol activation to include a more physics-based description of microphysical cloud processes. For example, Rasch and Kristjánsson (1998) and Kristjánsson (2002) described the automatic conversion of cloud water to rain, ice to snow, and cloud water accumulation from rain and snow. This implementation allows the model to simulate the size and concentration of cloud droplets and, most interestingly, the specific effects of aerosols on the onset and amount of precipitation.

A major step forward is the recent development of a microphysical two-moment scheme of cloud droplets and ice crystals for global climate models (Roman *et al.*, 1999, 2007. Minget *et al.*, 2007. Morrison and Guettelmann, 2008. Wang and Penner, 2010). Evaluation of these relatively comprehensive models is just beginning (Gettelman *et al.*, 2008; Roman, 2008; Wang and Penner, 2010). This type of scheme requires the model to predict both the mass and number concentration of a particular water meteor. Cloud particle types are classified by size, phase, physical state, and often density. Based on the type of Probability Distribution Function (PDF) chosen for the size distribution of a particular water meteor, all microphysical transformations and mass-kinetic properties where the predicted number of moments equals the number of undefined parameters in the PDF. A size distribution is derived that defines different prediction moments. Efforts to introduce a two-moment scheme for convective clouds in GCM are just beginning. Ming *et al.* (2007) introduced his CDNC prediction scheme into the convective parameterization of Geophysical Fluid Dynamics Laboratory (GFDL) GCMs. Lohmann (2008) tested his two-moment scheme for convective clouds in the

ECHAM general circulation model. Song and Zhang (2011) used a one-row climate model to test his two-moment scheme with four water meteors in convective clouds. Clearly, such a task remains very difficult due to the sublattice nature of convection in current climate models.

Attempts to use two-moment cloud microphysics schemes in GCM are still in their early stages, and current schemes are still less comprehensive than corresponding schemes developed long ago for cloud-resolving models (Wang and Chang, 1993). Nonetheless, by taking such an approach, modelling the effect of aerosols on precipitation becomes much more physical than previous generation models, in which only the mass-mixing ratio of water meteors was predicted. In particular, in combination with the size-dependent aerosol module, the two-moment cloud microphysics scheme provides a link between the predicted number concentration of CCN by the aerosol module and the predicted CDNC by the cloud microphysics module. In addition to the two-moment scheme, sub-grid-scale variability was also introduced to further improve the microscopic physical features modelled in Morrison and Gettelman (2008). There, cloud water variability is represented by the PDF obtained from observations and extended to all relevant microscopic-physical transformations.

Studies have demonstrated that with the two-moment scheme, models tend to produce global total precipitation closer to observations than the previous generation of schemes (Lohmann *et al.*, 2007; Gettelman *et al.*, 2008). On the other hand, in representing the formation of raindrops, a random process involving the collection of smaller cloud droplets, models with the two-moment scheme still need to include a parameterization of auto-conversion and subsequent accretion growth of precipitation particles. This parameterization thus remains a major tuning job for simulating the effect of aerosols on precipitation. A recent sensitivity study demonstrated that by allowing raindrops to form directly from the activation of GCCN (a hypothesized path), the modelled hydrological cycle would become faster, compared to the case without such a path; this was manifested by faster rainfall and lower atmospheric water vapour content, although the total precipitation amount did not change much (Posselt and Lohmann, 2008). Early attempts to bring the two-moment cloud microphysical scheme into the convection parameterization of GCMs have also identified the impact of aerosols on modelled precipitation features. Lohmann (2008) found that using a two-moment scheme and including prescribed aerosol emissions can improve the modelled geographical distribution of precipitation change from past to present climate compared to observations. discovered. Song and Zhang (2011) found that the two-moment scheme changed the precipitation distribution between the convective and stratified parts of the modelled cloud and that in practice it was obtained using a simpler microphysics scheme. We found that the ratios were closer to the observations than the results. Both studies confirm the suppression of convective precipitation by increasing aerosol concentration.

Despite progress in introducing physics-based aerosol and cloud schemes into his GCM, validation of modelled precipitation changes due to microphysics aerosol effects remains a challenge. This problem inherits the problems in determining the CDNC's pre-industrial climatology reference state, and the results are urgent for estimating the anthropogenic enhancement of cloud radiative forcing in the present era. (Rotstayn and Penner, 2001. Wang and Penner, 2009). For example, models often introduce a lower bound to prevent low CDNC values. This results in a spatially uniform distribution of CDNCs and a significant underestimation of aerosol effects on cloud albedo (Hoose *et al.*, 2009). In addition, more advanced schemes of aerosol and cloud microphysics also introduce new parameters. This may contribute to the difficulty in investigating whether the microphysical effects of aerosol-cloud precipitation can explain some known variations in precipitation.

2.10 AEROSOL EFFECTS ON PRECIPITATION QUALITY

Previous studies have shown two schools of thought on chemical aerosol effects on precipitation. The first one is the aerosol effect on rainfall quality. Some studies argued that excess nitrogen in precipitation has altered plant-soil nutrient relations and induced directional biological shifts in ecosystems (Fenn *et al.*, 1998; Baron *et al.*, 2000; Wolfe *et al.*, 2003; Neff *et al.*, 2008). As said earlier, West African food security relies on rain-fed agriculture however harmful rainwater quality on crops will be disastrous for this region. Matichuk *et al.* (2006) and Sorooshian *et al.* (2011) argued that reductions in sulfur dioxide (SO_2) emissions in the Southwest of the United States of America over the last several years have resulted in reduced particulate sulfate levels, which influences precipitation pH. Teixeira *et al.*, (2008) proved that sulfate is the main dominant source of acidity in precipitation in other regions such as Brazil.

The second school of thought is the aerosol effect on rainfall amount. Due to the high energy received in regions close to the equator, Potential Evapotranspiration (PET) is very high in those areas. Water loss from evapotranspiration is only replaced by precipitation. Several studies have shown the negative effect of high aerosol concentration on precipitation. For example, Huang et al (2009) showed that suppression of precipitation during months of high aerosol concentration occurs in both convective and stratiform rain. This suggests the suppression of deep convection due to the aerosol. Sorooshian *et al.* (2013) found that both dust (coarse mode aerosol) and smoke (fine mode aerosol) contribute to precipitation suppression. Some observational studies suggest that aerosol pollution may decrease orographic precipitation by as much as 30% annually (Levin and Cotton, 2009).

The dust effect on precipitation over West Africa was investigated by Lau *et al.* (2009), they found that dust emission over West Africa affects both monsoon development and its precipitation, aerosols from that emission interact with shortwave and longwave radiation and lead in changes to clouds physical and radiative properties. Dust has a cooling effect on the Earth surface, that effect can weaken the vertical movement of air mass, and have a negative effect on clouds. Konare *et al.* (2008), and Toure *et al.* (2012) used a regional climate model (RegCM) to show precipitation reduction during high dust period, whereas Akinyoola *et al.* (2019) used RegCM4 to show increased precipitation amount in the Guinea Coast over West Africa.

Wake *et al.* (1992); Legrand and Mayewski (1997); Schwikowski *et al.* (1999); Preunkert *et al.* (2003); Olivier *et al.* (2006); Dias *et al.* (2012) all showed that in addition to natural aerosol, which is dust, West Africa is impacted by anthropogenic particulate matter. Other work has shown that the close relationship between SO_2^{4-} and NO_3^- in rain is mainly linked to anthropogenic inputs.

2.10.1 pH in Rainwater

Rainwater is a naturally occurring form of water that has a Potential Hydrogen (pH) level that can vary greatly. The pH level of rainwater is affected by a variety of factors such as atmospheric components in the air. Understanding the pH of rainwater is important for understanding the environment and for making sure that the water is safe for use. The pH of rainwater is also affected by the presence of pollutants in the air and in the soil, such as nitrogen and sulphur compounds. Additionally, the pH of rainwater can be affected by the presence of acid rain, which is caused by the burning of fossil fuels. The pH of rainwater can be measured using a pH meter, which is a device that measures the acidity or alkalinity of a solution. The pH meter measures the hydrogen ion concentration of the solution, and the results are displayed on the meter's digital display. The pH of rainwater can also be measured with pH test strips, which are strips of paper that change colour when exposed to a solution of a certain pH level.

The pH of rainwater is important because it affects the environment and the safety of the water. Rainwater with a high pH can cause damage to plants and animals, and it can also be harmful to humans if consumed. In addition, a high pH can cause the corrosion of metals and other materials. It is important to monitor the pH of rainwater in order to ensure that it is safe for use and that it is not causing any damage to the environment. The pH of rainwater can be regulated by controlling the amount of pollutants in the air and in the soil, as well as by controlling the amount of acid rain. It is important to regulate the pH of rainwater in order to ensure that it is safe for use and that it is not causing any damage to the environment.

2.10.2 Sulphate in Rainwater

Sulphate of rainwater is a type of chemical compound composed of sulphur and oxygen atoms. It is typically found in the atmosphere, soil, and water. Sulphate of rainwater is also known as sulphuric acid and is a major component of acid rain. It is formed when sulphur dioxide and oxygen react in the atmosphere and can have a damaging effect on plants, animals, and aquatic life. Sulphate of rainwater can have a damaging effect on the environment. It can damage plants and aquatic life, and can also corrode metal structures, such as bridges and buildings. In addition, it can also affect human health, as it can irritate the eyes, nose, and throat. Acid rain can also have a negative impact on soil, as it can reduce soil fertility, and can also increase the acidity of the soil, which can lead to the leaching of essential nutrients from the soil. This can have a detrimental effect on crops and other vegetation.

One of the best ways to prevent the formation of sulphate in rainwater is to reduce the amount of sulphur dioxide released into the atmosphere. This can be done by reducing the use of fossil fuels, such as coal and oil, and by increasing the use of renewable energy sources, such as solar and wind power. In addition, governments can also implement regulations to limit the amount of sulphur dioxide that is released into the atmosphere. This can include regulations on the burning of fossil fuels, and the use of scrubbers and other technologies to reduce the amount of sulphur dioxide released into the atmosphere.

2.10.3 Potassium in Rainwater

Rainwater is a significant source of potassium for many ecosystems. Potassium is an essential mineral for plant growth, and it is found in rainwater in the form of dissolved salts. Rainwater also helps to regulate the acidity of the soil, which is important for healthy plant growth. Rainwater is a natural source of potassium that is easily absorbed by plants. Plants use potassium to help regulate their metabolism, and it is also necessary for the development of new cells and the maintenance of existing cells. Without enough potassium, plants cannot properly absorb other essential nutrients, and they may become stunted or die. The presence of potassium in rainwater can help to improve the fertility of soils, allowing for better crop yields. Potassium helps to regulate the acidity of the soil, which can help to reduce the risk of plant diseases. Additionally, potassium helps to improve the water retention of soils, which can help plants to survive periods of drought. Rainwater is also a major source of potassium for many plants and animals. Animals need potassium to help regulate their metabolism, and they can obtain this mineral from rainwater. Additionally, animals can also obtain potassium from the food they eat, as many plants contain high levels of potassium.

Although potassium is beneficial for many plants and animals, too much potassium in rainwater can be harmful. Excess potassium can cause a build-up of salts in the soil, which can lead to soil degradation and reduce crop yields. Additionally, too much potassium in rainwater can lead to the leaching of other essential minerals, such as calcium, magnesium, and iron. Excess potassium in rainwater can also lead to the contamination of drinking water sources. Potassium can react with other minerals, such as chlorine, and create a toxic compound that can be harmful to humans and animals. Therefore, it is important to monitor the potassium levels in rainwater to ensure it is not too high. The amount of potassium in rainwater can be measured using a variety of methods. One of the most common methods is to measure the electrical conductivity of the water, which can indicate the amount of potassium present. Additionally, a laboratory test can be used to measure the amount of potassium in rainwater. It is important to monitor the amount of potassium in rainwater to ensure that it is not too high. Therefore, it is important to take steps to reduce the amount of potassium in rainwater. There are a number of steps that can be taken to reduce the amount of potassium in rainwater. One of the most effective methods is to reduce the amount of fertilizer and other chemicals that are used on crops. Additionally, steps can be taken to reduce the amount of runoff from fields, which can help to reduce the amount of potassium in rainwater. It is also important to monitor the amount of potassium in rainwater to ensure that it is not too high.

2.10.4 Sodium in Rainwater

Rainwater is a complex mixture of compounds, including sodium. It is formed by the condensation of water vapour in the atmosphere, which is then precipitated on the Earth's surface. Sodium is an important element in the formation of rainwater, as it is highly soluble in water and can be easily transported from the atmosphere to the Earth's surface. Rainwater is an important resource for many ecosystems, and it is essential for the maintenance of the water cycle. Sodium is an important component of rainwater, as it helps to regulate the pH of the water and can also act as a buffer, preventing drastic changes in pH. Sodium also helps to regulate the salinity of the water, which is important for the health of aquatic life. Sodium plays an important role in the formation of rainwater. It is highly soluble in water and can be easily transported from the atmosphere to the Earth's surface. Sodium is also an important nutrient for many organisms, as it helps to maintain fluid balance and is essential for cell function. It is also an important component of the food chain, as it is taken up by plants and then passed on to animals. Sodium is found in many food sources, including fruits, vegetables, and meat, and is essential for human health.

High levels of sodium in the water can lead to an increase in salinity, which can be harmful to aquatic life. High levels of sodium can also lead to an increase in the pH of the water, which can be detrimental to plants and animals. In addition, high levels of sodium can lead to an increase in the concentration of other pollutants, such as heavy metals and organic compounds. It is also important to monitor sodium levels in order to prevent contamination of drinking water sources. It is important to be aware of the potential impacts of sodium on the environment and to take steps to reduce the amount of sodium in rainwater. High levels of sodium in rainwater can have negative impacts on both human health and the environment, such as contributing to soil salinization and causing health problems in people with high blood pressure. Therefore, ongoing monitoring and management of sodium levels in rainwater are crucial to mitigate these potential impacts.

2.10.5 Nitrate in Rainwater

Nitrate of rainwater is a form of nitrogen found in water. It is produced naturally by the breakdown of organic matter, such as plants, animals, and soil. Nitrates are essential for healthy plant growth, as they act as a fertilizer and help plants absorb other nutrients. Nitrates can also be found in some fertilizers and can be added to water to provide additional nutrients for plants. Nitrate of rainwater is also a pollutant, as it can cause eutrophication in water bodies. Eutrophication is an increase in the concentration of nutrients which can lead to algal blooms and other negative impacts on water quality.

Nitrates can also be harmful to humans when consumed in large amounts, as they can cause health problems such as methemoglobinemia.

Nitrate of rainwater is beneficial to plants, as it provides essential nutrients for growth. It can also be used to supplement soils that are lacking in nitrogen. Nitrates are also important for maintaining healthy aquatic ecosystems, as they provide food for algae and other organisms that are important for the food chain and nutrient cycling. Nitrates can also be used to reduce the effects of acid rain. Nitrates can neutralize the acidity of rainwater, making it less harmful to the environment. This can help reduce the damage caused by acid rain to plants, animals, and other organisms. Nitrate of rainwater can be used as a fertilizer for plants. It can also be used to supplement soils that are lacking in nitrogen. Nitrates can also be used to reduce the effects of acid rain, as they can neutralize the acidity of rainwater and make it less harmful to the environment.

Nitrate of rainwater can be harmful when consumed in large amounts. It can cause health problems such as methemoglobinemia, which is a condition that affects the oxygen-carrying capacity of the blood. Nitrates can also be a pollutant, as they can leach into groundwater and contaminate drinking water supplies. This can be a serious health hazard and can lead to long-term health problems for humans and animals.

Nitrate of rainwater can be measured in a variety of ways. A common method is to measure the concentration of nitrates in water samples. This can be done using a nitrate test kit, which is a simple and inexpensive way to measure nitrate levels in water. Other methods for measuring nitrate levels include spectrophotometry and ion chromatography. The amount of nitrate of rainwater in a water sample can also be estimated by measuring the amount of nitrogen in the sample. This can be done using the Kjeldahl method, which is a chemical method for measuring the amount of nitrogen in a sample.

Nitrate pollution can be prevented by reducing the use of fertilizers and other agricultural products that contain nitrates. Other measures that can be taken to reduce nitrate pollution include reducing runoff from agricultural fields and improving sewage and septic systems. In addition, it is important to monitor nitrate levels in drinking water and other sources of water. This can help to identify areas where levels are too high, and to take action to reduce the risk of nitrate pollution. Nitrate can be removed from rainwater using a variety of methods. One of the most common methods is to use a nitrate filter, which is designed to remove nitrate from water. This can be used to treat drinking water, as well as water used for irrigation. In addition, nitrate can also be removed from rainwater using biological processes, such as denitrification. This involves using bacteria to convert nitrate into nitrogen gas, which is then released into the atmosphere.

2.10.6 Ammonium in Rainwater

Rainwater is a vital element of the water cycle, and it is an important source of water for many people and ecosystems. One of the most important components of rainwater is ammonium, a compound of nitrogen and hydrogen. Ammonium is an important nutrient for plants and animals, and it is also a major contributor to the acidity of rainwater. Ammonium in rainwater can come from natural sources, such as decaying organic matter, or from human activities, such as burning fossil fuels or fertilizers. Ammonium is also released into the atmosphere from livestock and other agricultural activities. The amount of ammonium in rainwater can vary widely depending on the sources of the ammonium and the location of the rain. In some areas, ammonium levels can be very high, while in other areas they may be very low. Ammonium in rainwater can have a variety of effects, both positive and negative. On the positive side, ammonium can act as a fertilizer for plants, helping them to grow and thrive. On the negative side, it can also cause acid rain, which can damage plants and animals. Ammonium can also lead to eutrophication, which is an increase in the nutrients in a body of water. This can lead to an imbalance in the ecosystem, resulting in algal blooms and other problems.

Measuring the amount of ammonium in rainwater is an important part of understanding the effects of ammonium on the environment. There are a variety of methods for measuring ammonium, including chemical tests, spectroscopy, and chromatography. Measuring ammonium in rainwater can help scientists and policymakers to better understand the effects of ammonium on the environment, and to develop strategies for mitigating the negative effects of ammonium in rainwater. There are a variety of strategies for mitigating the negative effects of ammonium in rainwater. These include reducing emissions of ammonium from human activities, using better agricultural practices, and increasing the use of natural fertilizers. In addition, scientists are also investigating ways to use ammonium to fertilize crops without causing eutrophication or other negative effects. These strategies can help to reduce the negative impacts of ammonium on the environment. Ammonium is a form of nitrogen that can be found in the atmosphere and can be deposited in rainwater. The presence of ammonium in rainwater can have both positive and negative effects on the environment. On the positive side, ammonium can provide nutrients to plants and can help to fertilize the soil. On the negative side, excessive amounts of ammonium in rainwater can lead to acidification of soils and water bodies, which can have negative effects on aquatic ecosystems and can damage crops. It is important to monitor the levels of ammonium and other pollutants in rainwater in order to better understand the impacts of these pollutants on the environment and to take appropriate measures to reduce their levels if necessary.

Even though measurements and model simulations show the strong pollution interaction with cloud microphysics, the magnitude or direction of the effect on precipitation and its variations with meteorological conditions have not been clearly identified. Chemical relationships between aerosols and precipitation over West Africa have been studied in a few locations. None of these studies above investigated the chemical interaction between aerosols and precipitation over West Africa.

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 STUDY AREA

The main focus of this study is the chemical reactions between aerosols and clouds over West Africa (Figure 3.1). West Africa is geographically delimited between latitudes 2°N and 24°N and longitudes 18°W to 15°E (). West Africa has two climate sub-regions, such as Guinea Coast (2°N- 10°N, 18°W - 15°E) and the Sahel region (10°N - 20°N, 18°W - 15°E). There are many reasons for focusing this study on the two subregions of West Africa. First, the food security of this region is based on rain-fed agriculture. Second, the rainy season in the Sahel is very short, it lasts mostly between 3 and 4 months per year. Third, the Sahel is the closest region to the Sahara, which makes it one of the most polluted areas in the world. Fourth, West Africa has two opposite subregions, a wet one called Guinea Coast and a dry one called Sahel, this humidity difference may come from the aerosols' interactions with clouds. The summer monsoon in the Sahel region mainly occurs from June to September, that is, June-July-August-September (JJAS) (heavy rainy season). Although influenced by other factors, the Inter Tropical Discontinuity (ITD) is the main contributor to the West African summer monsoon precipitation. On the other hand, according to Diallo et al. (2014), the summer monsoon in the Guinea region exhibits two distinct periods. The first period occurs from April to June, while the second period takes place from October to November. The aerosol effect on precipitation is very strong in West Africa because the aerosol concentration in West Africa is one of the highest in the world. Due to its proximity to one of the world's largest and highly active aerosol emission regions, the West African Monsoon (WAM) system serves as an excellent natural laboratory for investigating the impacts of chemical aerosols on precipitation. If there is any significant chemical large-scale aerosol effect on precipitation at all, it should be more readily detected in this region.

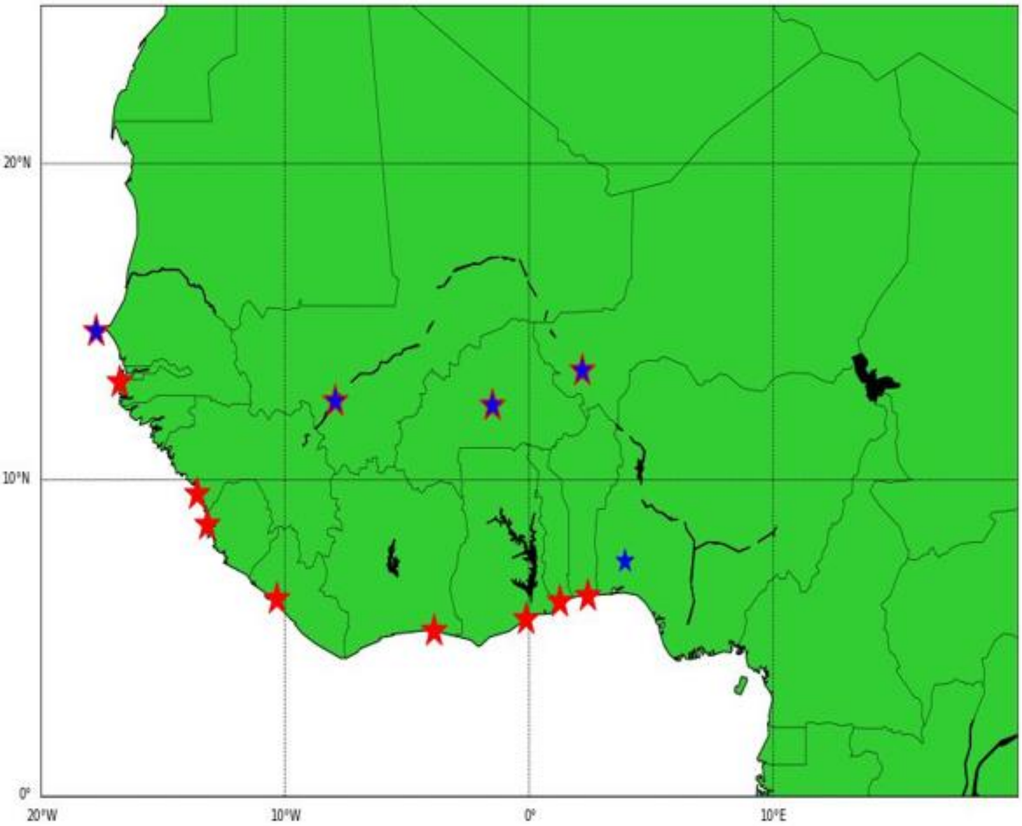

Figure 3.1: Study area (West Africa). Red stars are synoptic stations where climatic data were mined and the blue ones where rainwater were collected for this study.

3.2 METHODS AND DATA COLLECTION

***Table 3.1**: synoptic weather stations of used data acquired from national meteorological agencies across West Africa*

Station	Country	Coordinates (Lat/Lon/Alt)	Source
Abidjan	Cote d'Ivoire	5.25/-3.93/7	SODEXAM
Accra	Ghana	5.6/-0.16/68	GMET
Bamako*	Mali	12.53/-7.95/380	ANMM
Banjul	Gambie	13.2/-16.8/36	MoFWR
Conakry	Guinea	9.56/-13.63/26	DNMG
Cotonou	Benin	6.35/2.38/5	ANMB
Dakar*	Senegal	14.73/-17.5/27	ANACIM
Roberts Field	Liberia	6.25/-10.35/10	MAL
Lome	Togo	6.16/1.25/20	ANAMET
Niamey*	Niger	13.48/2.16/223	DMNN
Ouagadougou*	Burkina Faso	12.35/-1.51/316	ANAM-BF
Lungi	Sierra Leone	8.61/-13.2/25	SLMet
Ibadan*	Nigeria	7.49/3.9/228	-

3.2.1 Data Description

The precipitation data used in this study were obtained from multiple sources, including:

1. TRMM 3B42RT: Retrieved from the NASA website, this dataset has a spatial resolution of 0.25 x 0.25 and a temporal resolution of 3 hours. The time range covered is from 2003 to 2019.
2. CRU: Retrieved from the CEDA website, the CRU dataset has a spatial resolution of 0.5 x 0.5 and a temporal resolution of monthly data. The time range covered is from 1991 to 2019.
3. IN-SITU data: Acquired from national meteorological agencies across West Africa, these data cover the period from 1991 to 2020, the source of the data is presented in Table 3.2.
4. ERA5: Retrieved from the ECMWF website, the ERA5 dataset has a spatial resolution of 0.25 x 0.25 and a temporal resolution of daily data. The time range covered is from 2003 to 2019.

The aerosol data utilized in this study include:

1. EAC4 (CAMS Global Reanalysis): Retrieved from the COPERNICUS/ECMWF website, this dataset has a spatial resolution of 0.75 x 0.75 and a temporal resolution of 3 hours. The time range covered is from 2003 to 2019.
2. CAMS global atmospheric composition forecasts: Also obtained from the COPERNICUS/ECMWF website, this dataset has a spatial resolution of 0.4 x 0.4 and a temporal resolution of 3 hours. The time range covered is from 2003 to 2019.

For more detailed information, please refer to Table 3.1 and 3.2.

3.2.1.1 ERA INTERIM

Era Interim data are global reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a horizontal resolution of approximately 25 km x 25 km on 60 levels in the vertical up to 0.1 hPa (T255 spectral). they are available from 1 January 1979 to 31 August 2022.

3.2.1.2 Tropical Rainfall Measuring Mission (TRMM) 3B43 (monthly), 3B42 (daily) and 3B42RT (3-hourly)

NASA and Japan's National Space Development Agency worked together in a joint space mission to monitor and study tropical and subtropical precipitation and the associated release of energy. Five (5) instruments were used in this mission, such as (1) Precipitation Radar (PR); (2) TRMM Microwave Imager (TMI); (3) Visible Infrared Scanner (VIRS); Clouds and Earth's Radiant Energy System (CERES); and Lightning Imaging Sensor (LIS). TMI and PR are used for precipitation. For climate research, TRMM Multi-satellite Precipitation Analysis (TMPA) 3B43 monthly and 3B42 daily and sub-daily (3hr) precipitation averages are mostly used. Both products are available in 0.25° spatial resolution, covering 50° North to 50° South from 1998 to date.

Tropical Rainfall Measurement Mission (TRMM) is from the research-quality 3-hourly TRMM Multi-Satellite Precipitation Analysis TMPA (3B42). It is provided by the NASA GES DISC, as a value-added product, the result is in mm/h. For a qualitative investigation of aerosol effects on rain frequency over West Africa, precipitation is divided into three categories light ($r < 2.5$ mm/h), moderate (2.5 mm/h $\leq r <$ 10 mm/h) and heavy rain (10 mm/h $\leq r <$ 50 mm/h). Rain events of 12 stations over West Africa were divided into two groups. The first one is precipitation when aerosol concentration is lower than the 10^{th} percentile and the second is rainfall when is higher than the 90^{th} percentile. Each group is divided into the number of percentile aerosol events to get the rainfall frequency percentage.

3.2.1.3 ECMWF Atmospheric Composition Reanalysis 4 (EAC4)

ECMWF Atmospheric Composition Reanalysis 4 (EAC4) is from ECMWF's global reanalysis of atmosphere composition generation. It focuses on long-lived greenhouse gases, such as carbon dioxide (CO2) and methane (CH4).

The dataset is part of ECMWF's reanalysis of atmospheric composition, which focuses on long-lived greenhouse gases: carbon dioxide (CO2) and methane (CH4). Emissions and natural fluxes from the surface are critical for the evolution of long-lived greenhouse gases in the atmosphere. In this dataset, CO2 fluxes from terrestrial vegetation are modeled to simulate variations over a wide range from diurnal to interannual. CH4 chemical losses are represented by climate loss rates and surface emissions are from a range of datasets.

The reanalysis combines model data with observations from around the world into a globally complete and consistent dataset using atmospheric models based on the laws of physics and chemistry. This principle, called data assimilation, is based on the method used by the Center for Numerical Weather Prediction and the Center for Air Quality Forecasting, where every few hours (12 hours for ECMWF) previous forecasts are optimally combined with new available observations Produce a new best estimate of the state of the atmosphere, called an analysis, from which updated, improved forecasts are created. Reanalysis works in the same way to provide data sets that go back more than a decade. Reanalysis is not limited to issuing forecasts in a timely manner, allows more time to collect observations, and goes back in time to incorporate improved versions of the original observations, all of which benefit the quality of the reanalysis product.

The assimilation system is able to estimate the bias between observations and separate high-quality data from bad data. Atmospheric models allow for estimates in locations with little data coverage or for air pollutants that cannot be directly observed. Each grid point on a global scale provides estimates for each regular problem time over long periods of time, and always in the same format, making reanalysis a very convenient and popular dataset.

Observing systems have changed dramatically over time, and while an assimilated system can fill in data gaps, an initially much sparser network will lead to less accurate estimates. Therefore, EAC4 is only available since 2003. The analysis program assimilates data over a 12-hour window using the 4D var assimilation method, which takes into account the precise timing of observations and model development within the assimilation window.

3.2.1.4 CAMS global atmospheric composition forecasts

CAMS issues a global forecast of atmospheric composition twice daily. Projections include more than 50 chemicals (such as ozone, nitrogen dioxide, and carbon dioxide) and seven different types of aerosols (desert dust, sea salt, organics, black carbon, sulphate, nitrate, and ammonium aerosols). In addition, several meteorological variables are available. The initial conditions for each forecast are obtained by combining previous forecasts with current satellite observations through a process called data assimilation. This best estimate of the state of the atmosphere at the first forecast time step called the analysis, provides a globally complete and consistent dataset, allowing for the detection of air pollutants in locations with poor observational data coverage or for which direct observations are not possible. The location estimates are available.

The forecast itself uses atmospheric models based on the laws of physics and chemistry to determine the evolution of concentrations of all species over the next five days. In addition to the required initial state, inventory-based or observation-based emission estimates are also used as boundary conditions for the land surface. The Global Forecast System CAMS is updated approximately annually, which results in technical and scientific changes. The horizontal or vertical resolution can be changed, new species can be added, and generally, the accuracy of predictions can be improved. See the documentation for details on these system changes. Users looking for a more consistent long-term data set should instead use the CAMS Global Reanalysis, available through ADS, covering the period from 2003 onwards.

3.2.1.5 The CRU TS (Climate Research Unit Gridded Time Series)

The CRU TS (Climate Research Unit Gridded Time Series) dataset provides a high-resolution monthly grid of Land-based (excluding Antarctica) observations dating back to 1901, including ten observations and derived data variables. Table 3.2 presents their acronyms and other relevant information. The individual station rows are anomalysed using observations from 1961-1990, then gridded as 0.5° regular grid using Angular Distance Weighting (ADW) (Harris *et al.* 2020).

3.2.1.6 ERA5 data

ERA5 provides hourly estimates of a large number of atmospheric, agricultural and oceanic climate variables. The data cover the Earth in a 30-kilometer grid and break down the atmosphere into 137 levels from the surface to an altitude of 80 kilometers. ERA5 contains information on the uncertainty of all variables at reduced spatial and temporal resolution.

Quality Assured Monthly Updates for ERA5 (1959-present) are released in real-time over 3 months. Preliminary daily updates of the dataset are provided to users in real-time for 5 days.

Preliminary ERA5 datasets from 1950 to 1978 are also available in the Climate Data Store (CDS) (1959-1978 replaced by Quality Assurance datasets).

ERA5 uses advanced modeling and data assimilation systems to combine large numbers of historical observations into global estimates.

ERA5 replaces the ERA-Interim Reanalysis, which was discontinued on 31 August 2019. You can learn about the main features of ERA5 and important changes related to ERA-Interim.

3.2.1.7 In-situ data

Thirty (30) years from 1990 to 2020 variables such as precipitation (rain gauge), wind speed, relative humidity, and temperature (minimum, mean and maximum) of synoptic stations were mined for this study (Table 3.1): **country** (synoptic stations)

Senegal (Dakar /Yoff, Matam, Kolda and Diourbel);

Togo (Lome, Dapaong, Sokode and Atakpame);

The Gambia (Banjul / Yundum, Fatoto, and Kerewan);

Niger (Niamey / Aero, Agadez, Tahoua and Zinder);

Mali (Bamako / Senou, Kayes, Sikasso, Mopti and Kidal);

Guinea Bissau (Bissau Aeroport, Bafata and Bolama);

Guinea Konakry (Conakry / Gbessia, Boke, Nzerekore and Kanka);

Ghana (Accra, Kumasi, Tamale and Wa);

Cote d'Ivoire (Abidjan, Man, Bouake and Korhogo);

Burkina Faso (Ouagadougou, Bobo-Dioulasso, Po and Dori);

Benin (Cotonou, Parakou, Kandi and Save)

Table 3.2: *data description*

Acronyms	Resolution	Source	Period	Variables
TRMM 3B42RT	0.25 x0.25	NASA	2003 - 2019	Precipitaion
EAC4 (CAMS Global Reanalysis)	0.75 x 0.75	COPERNICUS / ECMWF	2003 - 2019	Aerosols
CRU	0.5 X 0.5	CEDA	1991 - 2019	Precipitaion
IN-SITU	-	NMS	1991 - 2020	Precipitaion
ERA5	0.25 x 0.25	ECMWF	2003 - 2019	Precipitaion
CAMS global atmospheric composition forecasts	0.4 X 0.4	COPERNICUS / ECMWF	2003 - 2019	Aerosols

3.2.2 Data Quality Control and Validation

Both satellite and ground-based data are used in this study. Gridded data are processed by agencies, they do quality control also before making them available. This study needed just to take gridded data from reliable sources.

3.2.2.1 Plausible value check for ground-based data

This study verified if the data values are within acceptable range limits. For example, the limits of variance of data can be as follow:

1. Air temperature: -10°C to 50°C;
2. dew point temperature: -10°C to 35°C;
3. ground temperature: -10°C to 60°C;
4. soil temperature: -10°C to 50°C;
5. relative humidity: 0 to 100%;
6. atmospheric pressure level: 500 to 1100 hPa;
7. wind direction: 0 to 360 degrees;
8. wind speed: 0 to 75 m/s for 2- to 10-minute average;
9. solar radiation (irradiance): 0 to 1600 W/m^2;
10. precipitation amount (one-minute intervalley): 0 to 40 mm.

Data outside the range limit above will be flagged as erroneous.

3.2.2.2 Time consistency check for ground-based data

This study verified the rate of change of instantaneous data to detect unrealistic jumps in values. Table 3.3 may provide information on the potential upper limits of variability.

Table 3.3*: data threshold*

Parameter	**Limit for suspect**	**Limit for erroneous**
Air temperature	3°C	-
Dew point temperature	2°C or 3°C	4°C
Ground temperature	5°C	10°C
Soil temperature 5 cm	0.5°C	1°C
Soil temperature 10 cm	0.5°C	1°C
Soil temperature 20 cm	0.5°C	1°C
Soil temperature 50 cm	0.3°C	0.5°C
Soil temperature 100 cm	0.1°C	0.2°C
Relative humidity	10%	15%
Atmospheric pressure	0.5 hPa	2 hPa
Wind speed (2-minute average)	10 m/s	20 m/s
Solar radiation (irradiance)	800 W/m^2	1000 W/m^2

Possible limits of a minimum variability can be as follow:

- ✓ Air temperature: 0.1°C over the past 60 minutes;
- ✓ Dew point temperature: 0.1°C over the past 60 minutes;
- ✓ Ground temperature: 0.1°C over the past 60 minutes;
- ✓ Soil temperature may be very stable, so there is no minimum required variability;
- ✓ Relative humidity: 1% over the past 60 minutes;
- ✓ Atmospheric pressure: 0.1 hPa over the past 60 minutes;
- ✓ Wind direction: 10 degrees over the past 60 minutes;
- ✓ Wind speed: 0.5 m/s over the past 60 minutes;

If the data values fail the time consistency checks, they should be flagged as doubtful.

To achieve the first specific objective, which is "to identify chemical components of aerosols and precipitation over West Africa", this study will use 30 years of aerosol data, from 1990 to 2019, from the National Aeronautics and Space Administration (NASA) and ERA INTERIM, the European Centre for Medium-Range Weather Forecasts (ECMWF) and national meteorological agencies. Aerosol data were used to display the spatial aerosol distribution to identify aerosols' chemical components in the West African atmosphere. Then we collected rainwater from some West African countries (Burkina Faso, Mali, Niger, Nigeria and Senegal), and analyse them to identify precipitation's chemical components. Precipitation samples were collected in plastic cylinders. Cylinders were placed on the roof around 5 meters from the ground. Samples were stored in a cool place. Then samples were transported for laboratory analysis. Precipitation samples were analyzed to quantify free acidity (pH), conductance, and concentrations of ammonium (NH_4^+), nitrate (NO_3^-), potassium (K^+), sodium (Na^+), and sulfate (SO_2^{4-}) ions.

3.2.3 Methods

3.2.3.1 Mann-kendal Test

To achieve the second specific objective, we have used Mann-kendal Test to verify the trend in our time series data. The importance of the Mann-kendal Test is to get useful information from the correlations between precipitation and aerosol variables. Then we have done the comparison between aerosol and precipitation anomalies. To quantify the magnitude of aerosol effect on precipitation we have used Spearman correlation (coefficient of correlation and significance test) to quantify the magnitude of aerosols on precipitation over West Africa. Yearly and seasonal spatiotemporal variations in the chemical components of aerosols and precipitation of period 2011 - 2019 was displayed using python.

3.2.3.2 Correlation Coefficient

The correlation coefficient is used as a numerical measure of the statistical link between variables. When computing a correlation coefficient, a variable from a given set of observations is compared to a sample component from another random variable with a known distribution.

Python is the tool used to perform correlations between aerosol and precipitation variables. The correlation coefficient represents the relationship between the six given variables dust mass density, black carbon mass density, organic matter mass density, sulphate mass density, sea salt mass density and precipitation. Correlation values from 0.00 to 0.19 are considered as very weak, from 0.20 to 0.39 as weak, from 0.40 to 0.59 as moderate, 0.60 to 0.79 as strong and from 0.80 to 1.00 as very strong according Sperman's correlation interpretation. Correlation values range from -1 to +1, with ±1 indicating the largest possible correlation and 0 the lowest possible correlation.

$$\boldsymbol{\rho}_{\boldsymbol{rx},\boldsymbol{ry}} = \frac{\boldsymbol{cov}(\boldsymbol{r}_{\mathrm{m}},\boldsymbol{r}_{\mathrm{n}})}{\boldsymbol{\sigma}_{\mathrm{rm}}\boldsymbol{\sigma}_{\mathrm{rn}}} \qquad \textbf{3.1}$$

Where,

$\boldsymbol{cov}(\boldsymbol{r}_{\mathrm{m}}, \boldsymbol{r}_{\mathrm{n}})$ is the covariance ranked data r_m and r_n.

$\boldsymbol{\sigma}_{\mathrm{rm}}$ and $\boldsymbol{\sigma}_{\mathrm{rn}}$ are the standard deviations of r_m and r_n.

The presence of dust in the atmosphere over West Africa can have a significant impact on the amount of precipitation the region receives. Dust can also act as a Cloud Condensation Nuclei (CCN) for condensation, increasing the amount of precipitation in certain areas. This is especially true in the Sahel region, where dust is abundant and higher concentrations of dust particles can cause more intense rainfall. In addition, dust particles can absorb and store water vapour, leading to more frequent and intense rains in the area. Dust pollution is a major problem in West Africa. Dust particles are released into the atmosphere from a variety of sources, including wind erosion of soil, mining activities. Dust pollution is a major problem in West Africa, and steps must be taken to mitigate its effects. Dust particles can be reduced by improving land management practices, such as reducing wind erosion of soil and planting vegetation to hold soil in place. In addition, mining activities and burning of biomass should be minimized to reduce the amount of dust particles released into the atmosphere. In addition, dust particles can be collected and removed from the atmosphere using specialized filters and other devices. This can help reduce the amount of dust particles in the atmosphere.

The correlation between aerosols and rainfall in West Africa is an important topic of study, as aerosols can have a significant impact on regional climate and precipitation patterns. The correlation between dust and rainfall in West Africa is an important topic of research due to the potential impact of dust on the region's agricultural productivity, water availability, and public health. To test the significance of this correlation, statistical analysis can be performed using observational data and models. One commonly used statistical method for testing the correlation between variables is the Pearson correlation coefficient. This measures the strength and direction of the linear relationship between two variables, in this case aerosol concentrations and rainfall anomalies, and ranges from -1 to +1. A value of -1 indicates a perfect negative correlation, a value of +1 indicates a perfect positive correlation, and a value of 0 indicates no correlation. To test the significance of the correlation between aerosols and rainfall, hypothesis testing can be used. This test measures the strength and direction of the linear relationship between two variables and can be used to determine if the correlation is significant at a given level of confidence (usually 95% or 99%). To determine the significance of the correlation between dust and rainfall in West Africa, a statistical test such as Pearson's correlation coefficient could be used. The null hypothesis would be that there is no correlation between aerosols and rainfall, while the alternative hypothesis would be that there is a significant correlation. The statistical significance of the correlation can then be determined using a t-test, with a p-value of less than 0.05 indicating statistical significance.

3.2.3.3 Spatial Anomaly Analysis

Yearly and seasonal anomalies are used in this study to detect aerosol and rainfall variabilities. The anomaly analysis used refers to the study period from 2011 to 2019. The anomaly is a tool that can measure the magnitude of deviations from the mean aerosol and precipitation values.

$$A = y - \bar{y} \qquad 3.2$$

Where A is anomaly, y aerosol or precipitation a time t in the period 2011 to 2019 and $\bar{y}$ the mean aerosol or precipitation in the study period.

3.2.3.4 10th and 90th precipitation frequency percentile

To investigate the quantitative effects of aerosols on rain frequency over West Africa, the precipitation data was categorized into three groups: light ($r < 2.5$ mm/h), moderate (2.5 mm/h $\leq r <$ 10 mm/h), and heavy rain (10 mm/h $\leq r <$ 50 mm/h). Rain events from 12 stations located across West Africa were classified into two groups, based on aerosol concentration percentile. The first group contained precipitation data with the 10th percentile aerosol concentration. 10th percentile precipitation is the amount of rainfall that is exceeded by 90% of the observed aerosol values. While the second group contained data with the 90th percentile aerosol concentration. 90th percentile precipitation is the amount of rainfall that is exceeded by only 10% of the observed aerosol values. Each group was then further divided based on the percentile of aerosol events to obtain the rainfall frequency percentage.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 AEROSOLS AND PRECIPITATION TREND

4.1.1 Aerosols Trend

The Mann-kendall Trend Test also known as the Mann-kendall Tau test is used to determine if there is a significant long-term linear trend in aerosol data over the study period. It is used in this study to determine if aerosol data are increasing or decreasing over time. The technique is also useful for detecting changes in aerosol composition, such as changes in the types of aerosols present in the atmosphere. Table 4.1 shows the results of the Mann-kendall Trend Test applied to aerosol data. It shows no trend in the long-term aerosols. The technique is also useful for monitoring air quality and detecting changes in the atmosphere. The Mann-kendall Trend Test can also be used to detect if there is a seasonal pattern in the data. However, the Mann-kendall Trend Test is limited in that it can only detect linear trends. It cannot detect non-linear trends or seasonal patterns. The standardised test statistic z for fine dust, medium dust, coarse dust, black carbon, sulphate, fine sea salt and medium sea Salt are -0.146, -0.183, -0.226, -0.996, -0.61, -0.61 and -0.46 respectively. These mean means the decreasing trend is not significant. The standardised test statistic z for organic matter and Coarse Sea Salt are 0.601 and 1.36 respectively. These mean means the increasing trend is not significant.

4.1.2 Precipitation Trend

Results from Table 4.1 show no trend in precipitation of the period 2003 – 2019. Meaning that precipitation of the study period is not increasing or decreasing over time. The standardised test statistic z is 0.565 which means the increasing trend is not significant.

Table 4.1: *Mann-kendall Trend Test of precipitation and aerosol data*

Variable	Trend	h	p	z	Tau	s	Var_s	slope	Intercept
Precipitation	no trend	False	0.572	0.565	0.037	214	141882	0.041	37.7
Fine Dust	no trend	False	0.884	-0.146	-0.010	-56	141882	-5.8e-09	3.0e-05
Medium Dust	no trend	False	0.855	-0.183	-0.012	-70	141882	-1.4e-08	6.9e-05
Coarse Dust	no trend	False	0.821	-0.226	-0.015	-86	141882	-4.5e-08	0.0
Black Carbon	no trend	False	0.319	-0.996	-0.065	-376	141882	-1.2e-10	1.2e-07
Organic Matter	no trend	False	0.601	0.523	0.034	198.0	141882	9.7e-10	2.3e-06
Sulphate	no trend	False	0.543	-0.61	-0.04	-230	141882	-1.3e-10	2.6e-07
Fine Sea Salt	no trend	False	0.543	-0.61	-0.04	-230	141882	-1.4e-10	2.6e-07
Medium Sea Salt	no trend	False	0.646	-0.46	-0.03	-174	141882	-7.2e-09	2.0e-05
Coarse Sea Salt	no trend	False	0.173	1.36	0.09	514	141882	2.0e-09	1.4e-06

4.2 SPATIOTEMPORAL DISTRIBUTION OF AEROSOL AND PRECIPITATION

4.2.1 Precipitation

Figure 4.1 shows a plot of monthly precipitation distribution over West Africa in the period of 2011–2019. Monthly precipitation is displayed by taking the monthly mean of the study period. It shows that the dry months of the study period are from December to March and the wet months are from April to November. The Guinea region receives more precipitation than the Sahel region. Countries like Guinea Bissau, Guinea Conakry, Sierra Leone and Liberia receive more precipitation between 120 to 220 mm/month from August to November. While South Nigeria receives between 90 to 220 mm/month from March to July and from September to November. Cote d'Ivoire, Togo, and Benin receive between 60 to 150 mm/month from March to July and November and December. Sahelian countries such as Mali, Niger, Senegal, The Gambia and Burkina Faso receive between 10 to 120 mm/month from June to October. Precipitation can have an impact on the region's society, as it affects the availability of resources and can lead to social and political instability.

Precipitation levels vary significantly from season to season and location to location, resulting in a complex spatial distribution of precipitation over West Africa. Precipitation in West Africa is largely influenced by the Inter Tropical Discontinuity (ITD), which is an area of low pressure in the atmosphere that shifts north and south of the equator depending on the season. This shift affects the amount of rainfall in the region, resulting in wetter conditions in the Guinea zone and drier conditions in the Sahel. West Africa is a region of vast climatic diversity. Precipitation distribution is highly variable, ranging from higher heavy rains in the coastal Guinea areas to mostly light and moderate in the Sahel and Savanna. The region is characterized by a strong monsoonal climate, with the wet season typically lasting from May to September (Sylla *et al.*, 2012). The amount of precipitation also varies considerably from year to year, with some years being much wetter than others. The amount of precipitation in West Africa also varies greatly from region to region. Coastal Guinea areas tend to receive more rainfall than inland areas, while the Sahel region is particularly prone to drought. The amount of rainfall in the region affects the availability of water for drinking, irrigation, and other uses. It also affects the growth of vegetation, which in turn affects the availability of food and other resources. Precipitation also has an impact on the region's economy, as it affects the availability of resources such as water, food, and fuel. It can also affect the tourism industry, as areas with higher precipitation levels are more likely to attract visitors.

4.2.2 Dust

Figures 4.2 to 4.4 show a plot of yearly ultrafine (0.03 – 0.55 μm), fine and coarse (0.55 - 9 μm, 9 – 20 μm) dust distribution, respectively over West Africa in the period of 2011–2019. The yearly mean of the same period of Dust Mass Density (0.03 – 0.55 μm (ultrafine mode), 0.55 - 9 μm, 9 – 20 μm (fine and coarse mode)). They show that the atmosphere over the Sahara region has high concentration of dust particles, which are typically classified into three aerosol sizes: coarse, fine, and ultrafine. This high dust concentration is mainly due to the arid and semi-arid climate of the region, which leads to dry and windy conditions that promote the lifting of dust particles from the surface. As the dust-laden air moves away from the Sahara towards the Sahel region, which lies at the southern edge of the Sahara, the dust concentration gradually decreases. However, the Sahel region is still significantly polluted due to the very high dust concentration over the Sahara. They show that the high dust concentration over the Sahara decreases over Guinea, as Guinea is not located south of the Sahara. Guinea is located on the western coast of Africa, far away from the Sahara region. Therefore, it is unlikely to be affected significantly by the dust concentration originating from the Sahara. Previous researchers found that the aerosol chemical components in dust are: Carbon (C), Hydrogen (H), Nitrogen (N), Sulphur (S),

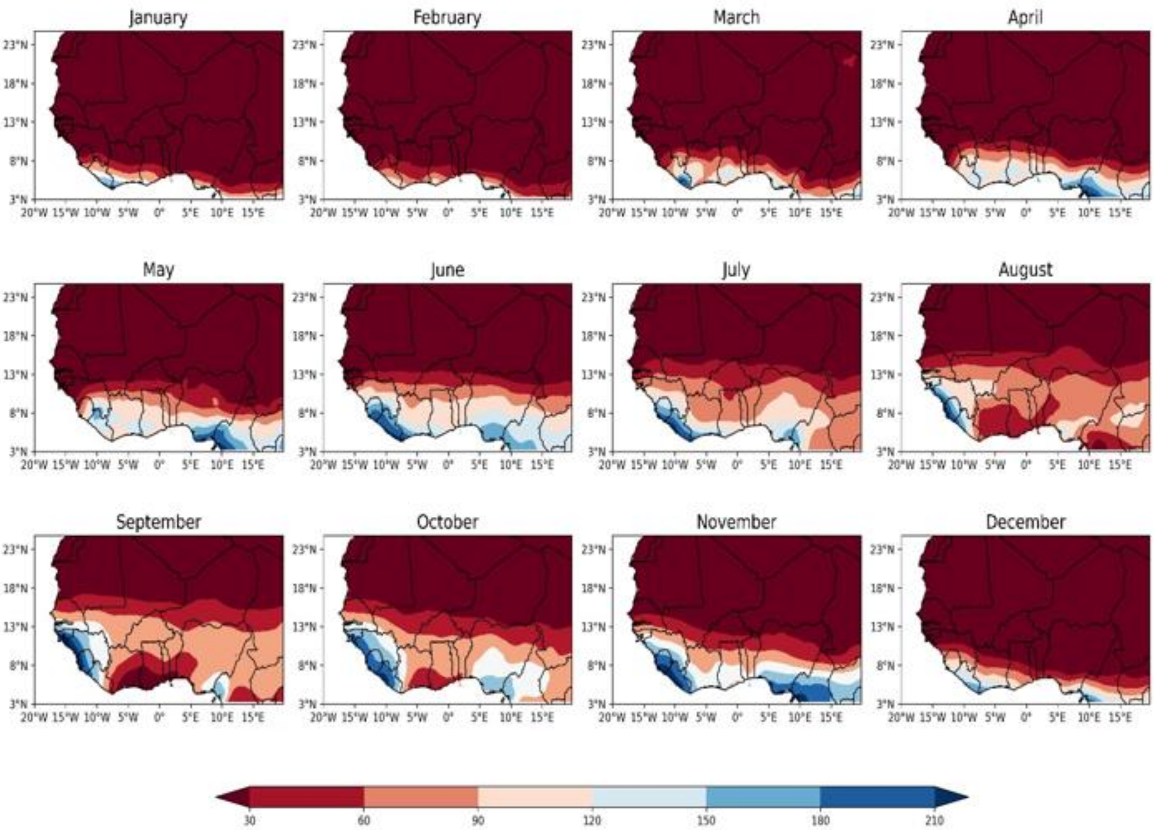

Figure 4.1: Yearly mean CRU spatial precipitation distribution

Sodium Chloride (NaCl), Sulphate (SO_4^{2-}), Silicon Dioxide (SiO_2), Aluminium Oxide (Al_2O_3), Ferric Oxide (Fe_2O_3), Calcium Oxide (CaO), Magnesium Oxide (MgO), Potassium Oxide (K_2O), Manganese Oxide (Mn_3O_4), Carbon Dioxide (CO_2) (Calvo *et al.*, 2013; Quinn *et al.*, 2009).

Climate change is likely to have an impact on the amount of dust in the atmosphere over West Africa. Warmer temperatures can lead to an increase in the amount of dust in the atmosphere, which can lead to an increase in the amount of precipitation. In addition, climate change can also lead to an increase in the amount of convection in the atmosphere, which can lead to an increase in the amount of precipitation over West Africa. This increased precipitation can have a positive impact on local communities, as it can lead to an increase in the amount of water available for agriculture and other activities (Shields *et al.*, 2023).

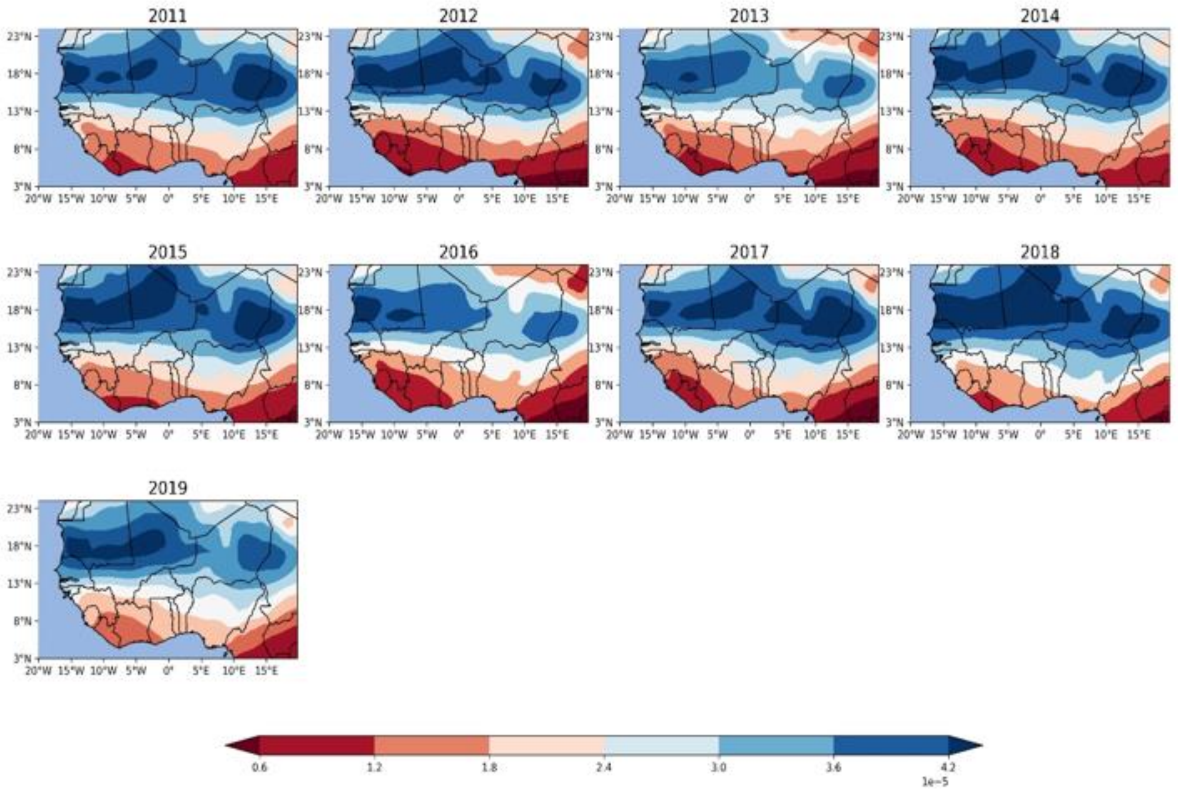

Figure 4.2: Yearly mean spatial dust mass density (0.03-0.55 μm) distribution

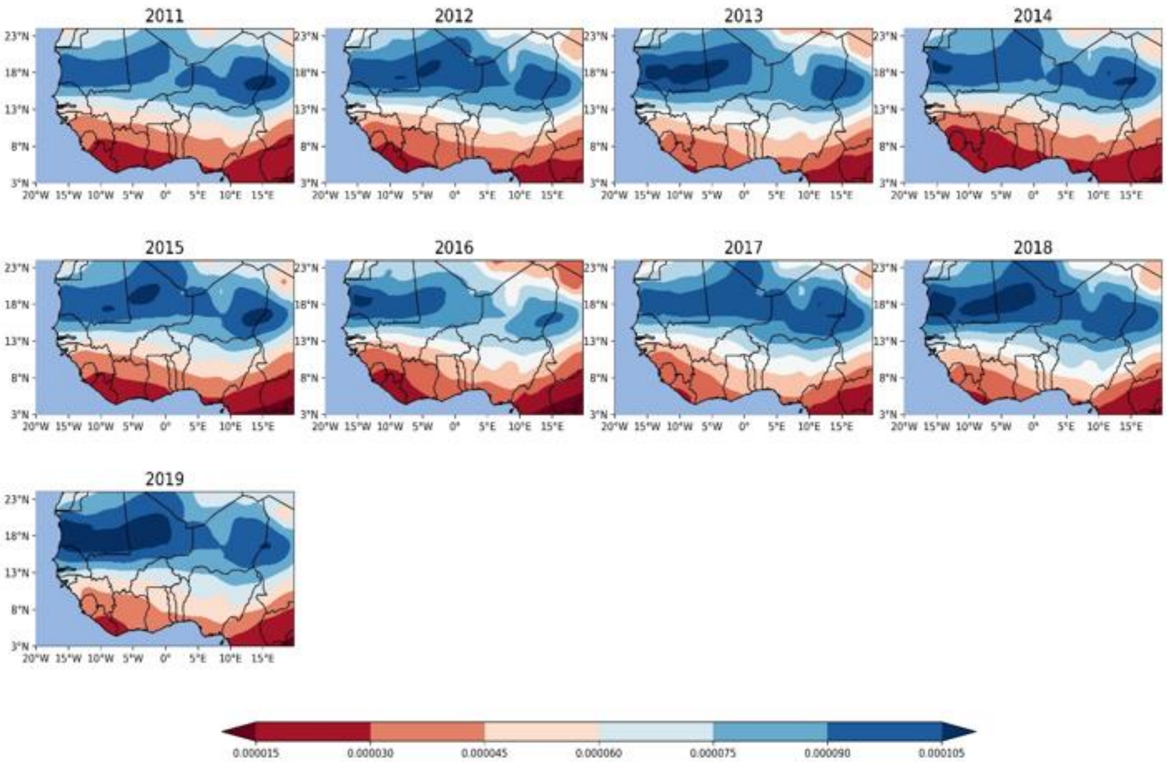

Figure 4.3: Yearly mean spatial dust mass density (0.55-9 μm) distribution

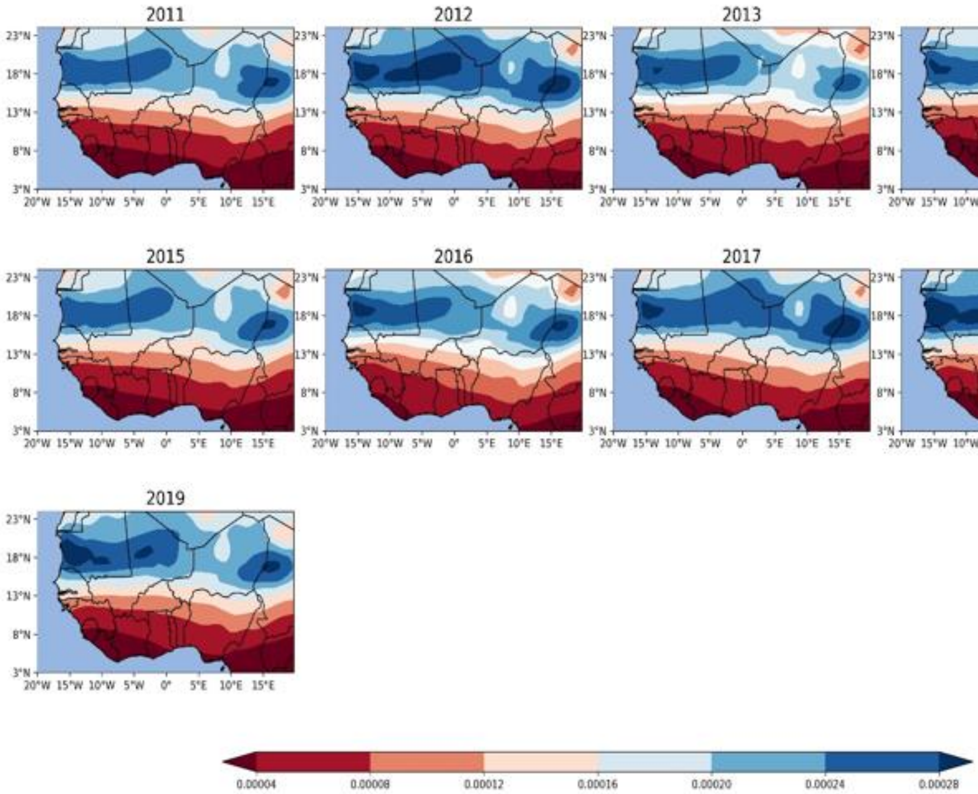

Figure 4.4: Yearly mean spatial dust mass density (9-20 µm) distribution

4.2.3 Black carbon

Figure 4.5 shows the yearly mean of Black Carbon Mass Density during the study period. It shows high black carbon concentration over the coastal Guinea countries (Guinea Bissau, Guinea Conakry, Sierra Leone, Liberia, Cote d'Ivoire, Togo, Benin and Nigeria) due to significant biomass burning in Central Africa, shipping and industrial activities. black carbon concentration over the Sahel region (Mali, Niger, Senegal, The Gambia and Burkina Faso) is low. However, the exact concentration and distribution of black carbon in the atmosphere over Guinea would depend on various factors, including the prevailing winds, topography, and the sources of black carbon emissions in the region. Chemical component in black carbon is Carbon (C).

4.2.4 Organic matter

Figure 4.6 shows the yearly mean of organic matter Mass Density of the study period. It shows high organic matter concentration over the coastal Guinea (Guinea Bissau, Guinea Conakry, Sierra Leone, Liberia, Cote d'Ivoire, Togo, Benin and Nigeria) due to significant biomass burning in Central Africa. Biomass burning in Central Africa can release large amounts of organic matter into the atmosphere, which can then be transported by winds and deposited over other areas. In this case, it appears that the organic matter has been transported over the coastal Guinea region, resulting in a high concentration of organic matter there. Organic matter concentration over the Sahel region (Mali, Niger, Senegal, The Gambia and Burkina Faso) is low, this can be explained by the large distance between organic matter source and the Sahel rerion. The spatial distribution of organic matter in West Africa has important implications for soil fertility and soil health. Areas with higher levels of organic matter tend to have higher levels of soil fertility, while areas with lower levels tend to have lower levels of soil fertility. In addition, organic matter plays an important role in soil health, as it helps to improve soil

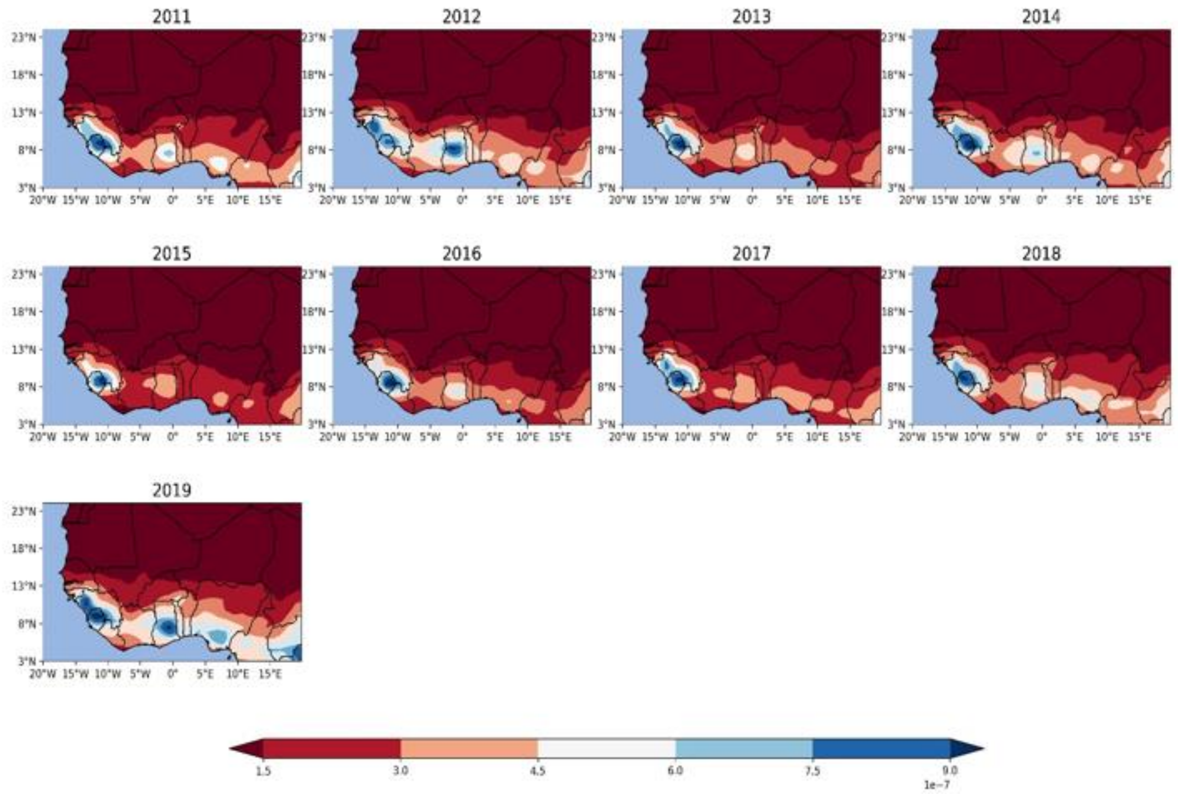

Figure 4.5: Yearly mean spatial black carbon mass density distribution

structure and water-holding capacity, as well as providing a source of nutrients for plants. Chemical components in organic matter are: Carbon (C), Hydrogen (H) and Nitrogen (N).

4.2.5 Sulphate

Figure 4.7 shows the yearly mean of sulphate Mass Density during the study period. The high sulphate concentration observed over parts of coastal Guinea in countries like Nigeria, the Sahel in countries like Burkina Faso, Niger and Senegal. This high sulphate concentration could be attributed to various factors, such as anthropogenic activities and natural sources. One potential source of sulphate is industrial activity, particularly the burning of fossil fuels in power plants and other industrial processes. However, in many parts of West Africa, industrial activity is relatively limited, so other sources of sulphate may be more significant. Another potential source of sulphate is the burning of biomass, which can release sulphur-containing compounds into the atmosphere. This could be particularly relevant in areas where agricultural practices involve burning crop residues or where forest fires are common. Finally, the transport of air masses from other regions could also contribute to the observed sulphate concentrations. For example, sulphate particles could be transported from areas with high industrial activity or from regions affected by volcanic activity. Chemical component in sulphate is Sulphate (SO_4^{2-}).

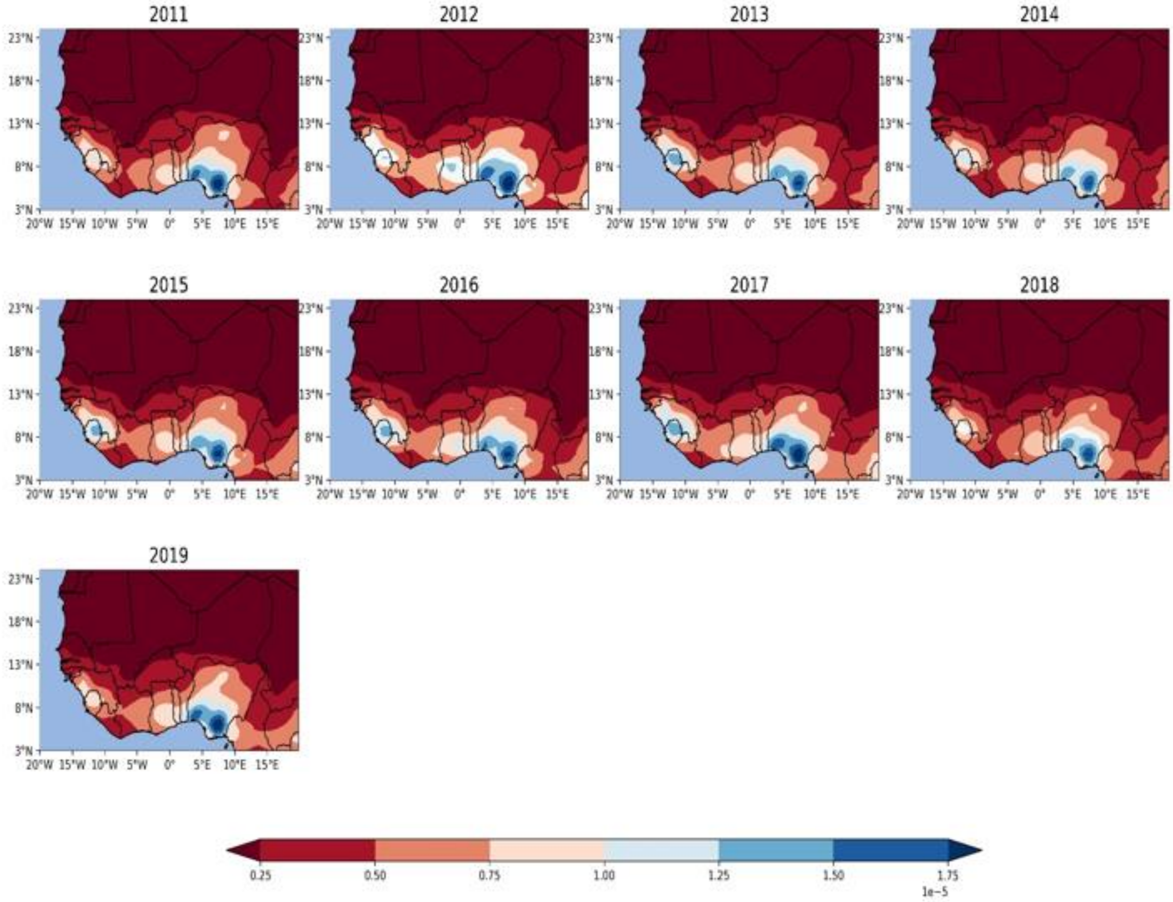

Figure 4.6: Yearly mean spatial organic matter mass density distribution

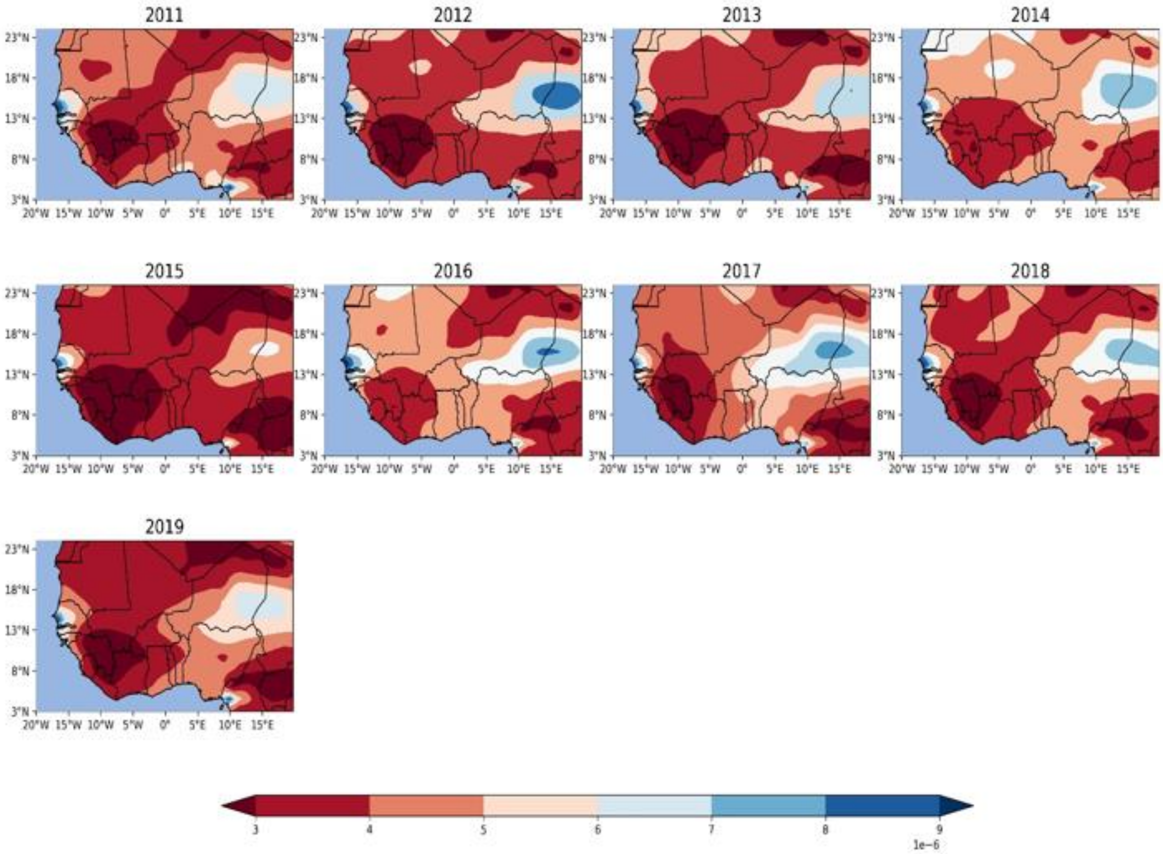

Figure 4.7: Yearly mean spatial sulphate mass density distribution

4.2.6 Sea salt

Figures 4.8 – 4.10 show the yearly mean of Sea Salt Mass Density (0.03 – 0.5 μm, 0.5 - 5 μm, 5 – 20 μm) of the study period. The high sea salt concentration observed over the coast of West Africa is likely due to several factors. Firstly, the West African coastline is exposed to the Atlantic Ocean, which is a significant source of sea salt aerosols. The waves and wind in the ocean can cause sea salt to be released into the atmosphere, which can then be transported over land by wind patterns. Secondly, the arid and semi-arid climate of the region can also contribute to high levels of sea salt in the air. Dust and sand particles can become suspended in the air and create an abrasive environment, leading to the generation of more sea salt particles through a process known as sea salt cycling. Due to the difference of sea salt size residence time in the West African atmosphere, fine sea salt concentration is far higher than the coarse sea salt concentration. Finally, human activities such as agriculture and mining can also contribute to sea salt concentrations through the disturbance of soil and sediment, which can release salt into the atmosphere. Chemical component in sea salt is Sodium Chloride (NaCl).

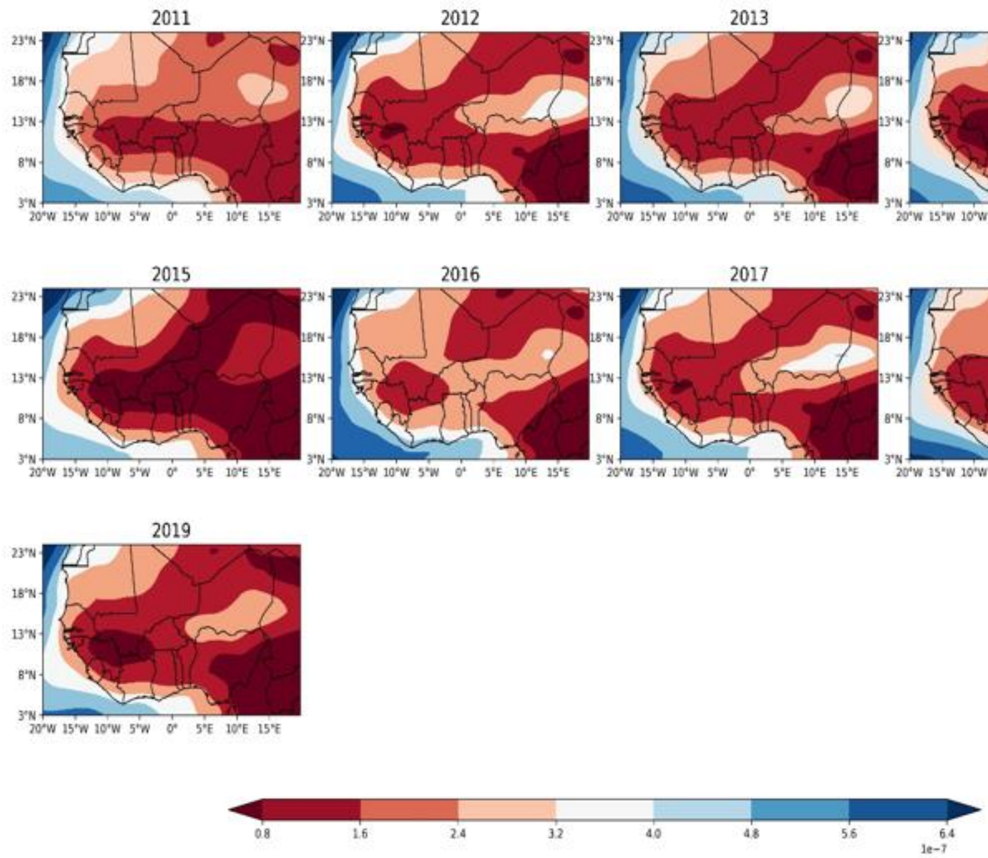

Figure 4.8: Yearly mean spatial sea salt mass density (0.03-0.5 μm) distribution

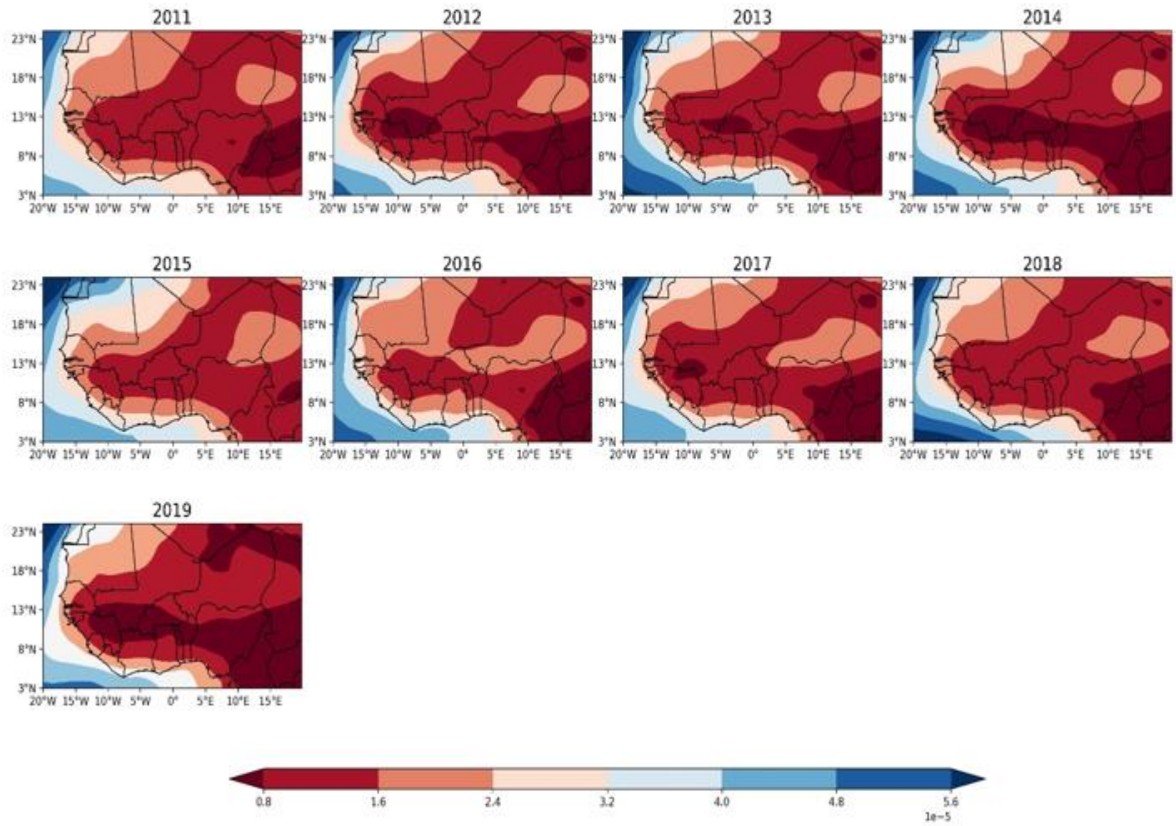

Figure 4.9: Yearly mean spatial sea salt mass density (0.5-5 μm) distribution

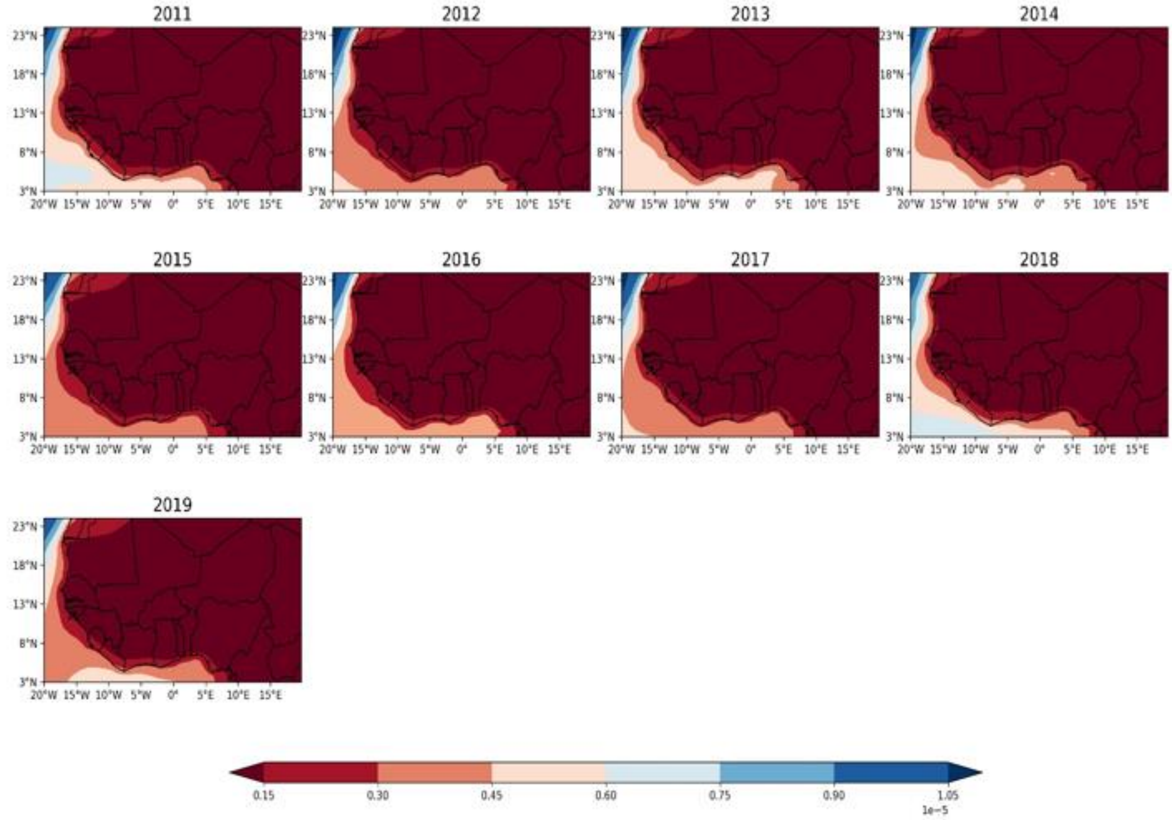

Figure 4.10: Yearly mean spatial sea salt mass density (5-20 μm) distribution

4.3 AEROSOL AND PRECIPITATION ANOMALIES

4.3.1 Yearly anomaly

The spatial distribution of precipitation anomalies over West Africa can vary significantly from year to year. Generally, the region experiences a gradient of decreasing rainfall amounts from the humid coastal areas in the south to the semi-arid Sahel region in the north. During wet years from 2011 to 2016, the spatial distribution of precipitation anomalies tends to be more uniform, with above-normal rainfall amounts occurring over much of the region. However, during dry years from 2017 to 2019 some areas (part of the Sahel (2017) and part of the Guinea coast (2019)) experienced slight drought conditions while others receive closer to normal rainfall amounts. Many parts of West Africa experienced a severe drought, with rainfall amounts well below normal levels. This led to crop failures and food shortages in many areas.

For example, during the wet years from 2011 to 2016, much of West Africa experienced above-normal rainfall amounts, with the exception of some areas in the southwestern part of West Africa which experienced below-normal precipitation. Understanding the spatial distribution of precipitation anomalies is important for identifying areas that are particularly vulnerable to drought or flooding in many parts of the region and caused significant damage to crops and infrastructure, as well as for developing targeted strategies to mitigate the impacts of extreme weather events on agriculture, water resources, and other critical sectors in the region. Overall, the precipitation anomaly over West Africa is a complex phenomenon that is influenced by a wide range of factors. Understanding and predicting these anomalies is important for farmers, policymakers, and others who rely on the region's agricultural output and natural resources.

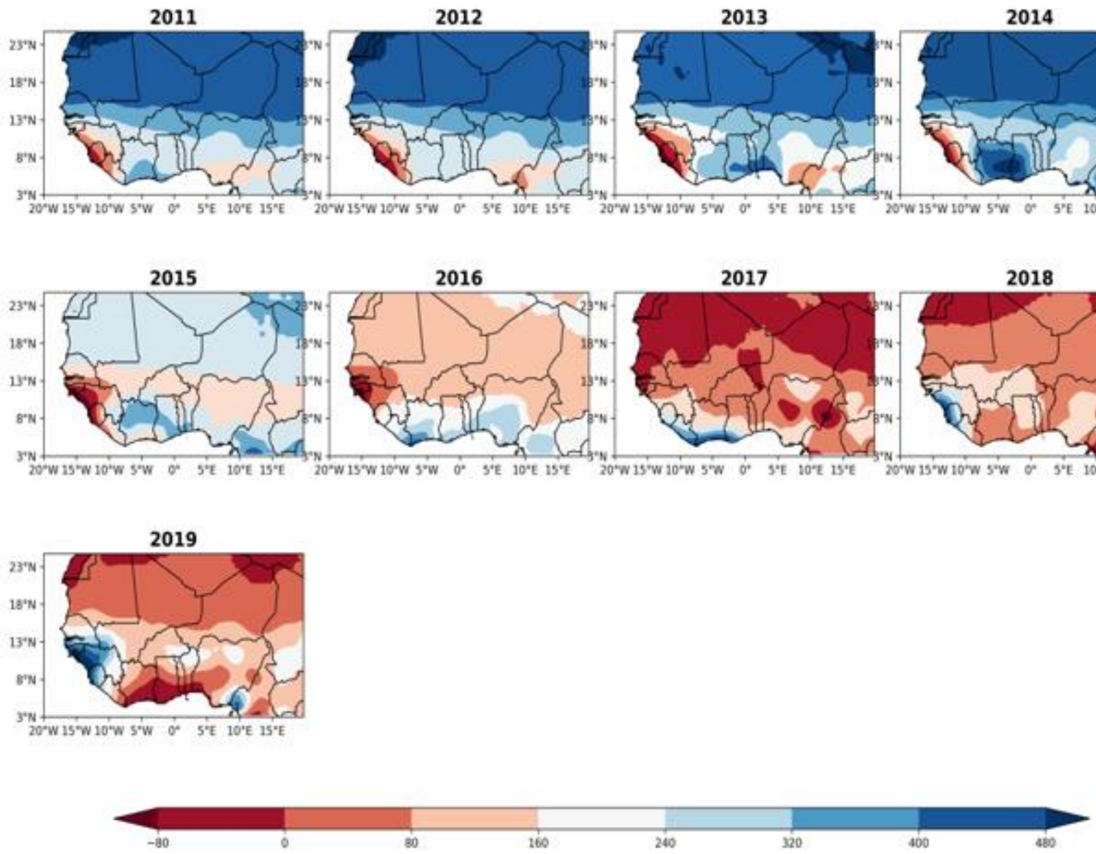

Figure 4.11: Yearly mean CRU spatial precipitation anomaly distribution

4.3.2 Seasonal anomaly

4.3.2.1 Precipitation

Aerosol properties show large regional, seasonal and interannual variations. Seasonal precipitation and aerosol mass density anomalies are displayed by taking the seasonal mean of the period of 2011 - 2019 and subtracting it from the seasonal mean of each season known as December - January - February (DJF), March - April - May (MAM), June - July - August (JJA), and September - October - November (SON). This study displayed the spatial seasonal precipitation distribution of the period 2011 to 2019. Figure 4.12 shows a map of spatial precipitation anomalies across a region over the study period. The colour dark brown has been chosen to represent negative anomalies. Negative anomalies are mostly observed during the seasons of DJF and JJA over West Africa with positive precipitation anomaly in countries like Guinea Bissau, Guinea Conakry, Sierra Leone, Liberia and part of South Nigeria. This means that during these seasons, the precipitation received in West Africa is below average. Positive anomalies are mostly observed during the seasons of MAM and SON over West Africa with negative precipitation anomaly in countries like Guinea Bissau, Guinea Conakry, Sierra Leone, Liberia and part of South Nigeria.

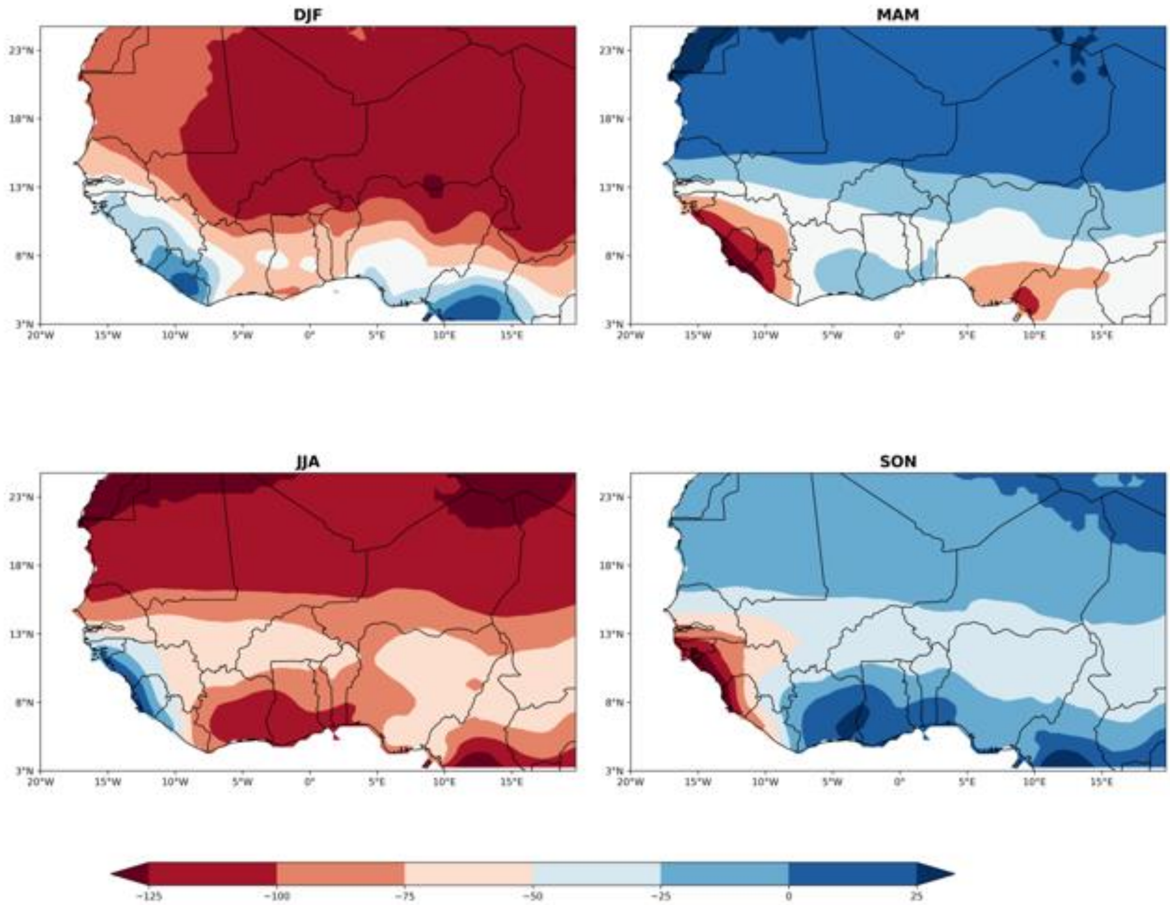

Figure 4.12: Seasonal mean CRU spatial precipitation anomaly distribution

4.3.2.2 Dust

In the study area, Figures 4.13 and 4.14 show that the aerosol mass density anomaly was significantly positive during the SON season and slightly positive during MAM, and it was negative during the DJF (except the coarse mode in Figure 4.15) and JJA seasons, indicating that the aerosol mass density anomaly increased in the Sahel region in the MAM and SON season with different magnitude. The aerosol mass density anomaly was significantly higher during the MAM and SON seasons. The MAM and SON seasons have significantly higher rainfall.

The study area has a seasonal variation in the aerosol mass density anomaly, which is positively correlated with the amount of rainfall received in the region. Aerosol mass density anomaly was significantly positive during the SON season and slightly positive during MAM. This means that during these seasons, there was an increase in the number of aerosol particles in the air, which could have resulted from various sources such as dust storms, wildfires, or anthropogenic activities. In contrast, the aerosol mass density anomaly was negative during the DJF and JJA seasons, indicating that the amount of aerosol particles in the air decreased during these seasons. Results suggest that the aerosol mass density anomaly was significantly higher during the MAM and SON seasons, which also have significantly higher rainfall. This suggests that there may be a relationship between aerosol particles and rainfall in the study area, which is an interesting topic for further investigation. Results suggest that the study area has a seasonal variation in the aerosol mass density anomaly, which is positively correlated with the amount of rainfall received in the region. This information can be useful for understanding the impact of aerosol particles on the climate and for predicting future changes in the region.

The spatial distribution of dust anomalies can vary across West Africa depending on regional climate patterns and land use changes. For example, in the Sahel region, dust transport is strongly influenced by the Intertropical Convergence Zone (ITCZ) and the African easterly jet. In contrast, in the coastal regions of West Africa, dust concentrations are generally lower due to the influence of oceanic moisture. Overall, the spatial and seasonal variability of dust anomalies in West Africa is complex and influenced by a range of factors (Evans *et al.*, 2020).

4.3.2.3 Black carbon

Figure 4.16 show that during the DJF and JJA seasons, the black carbon mass density anomaly was significantly positive with some places with negative black carbon mass density anomaly (Sierra Leone and Liberia). This means that the observed black carbon mass densities during these seasons were higher than the long-term averages, which also have significantly lower rainfall. On the other hand, during the MAM and SON seasons, the black carbon mass density anomaly was slightly negative except part countries like Ghana, Sierra Leone and Liberia where black carbon mass density anomaly was positive. This indicates that the observed black carbon mass density during these seasons was slightly lower than the long-term average.

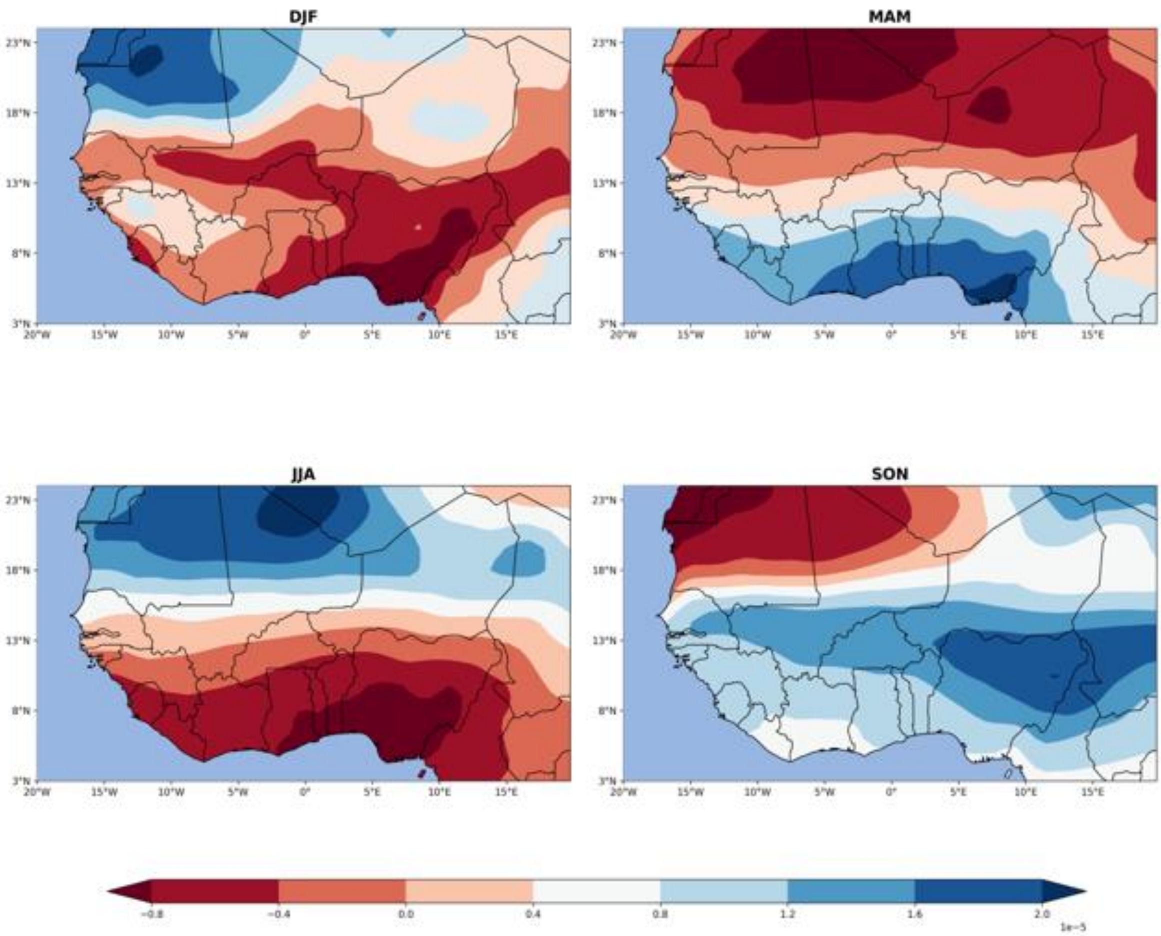

Figure 4.13: Seasonal mean dust mass density anomaly (0.03-0.55μm) distribution

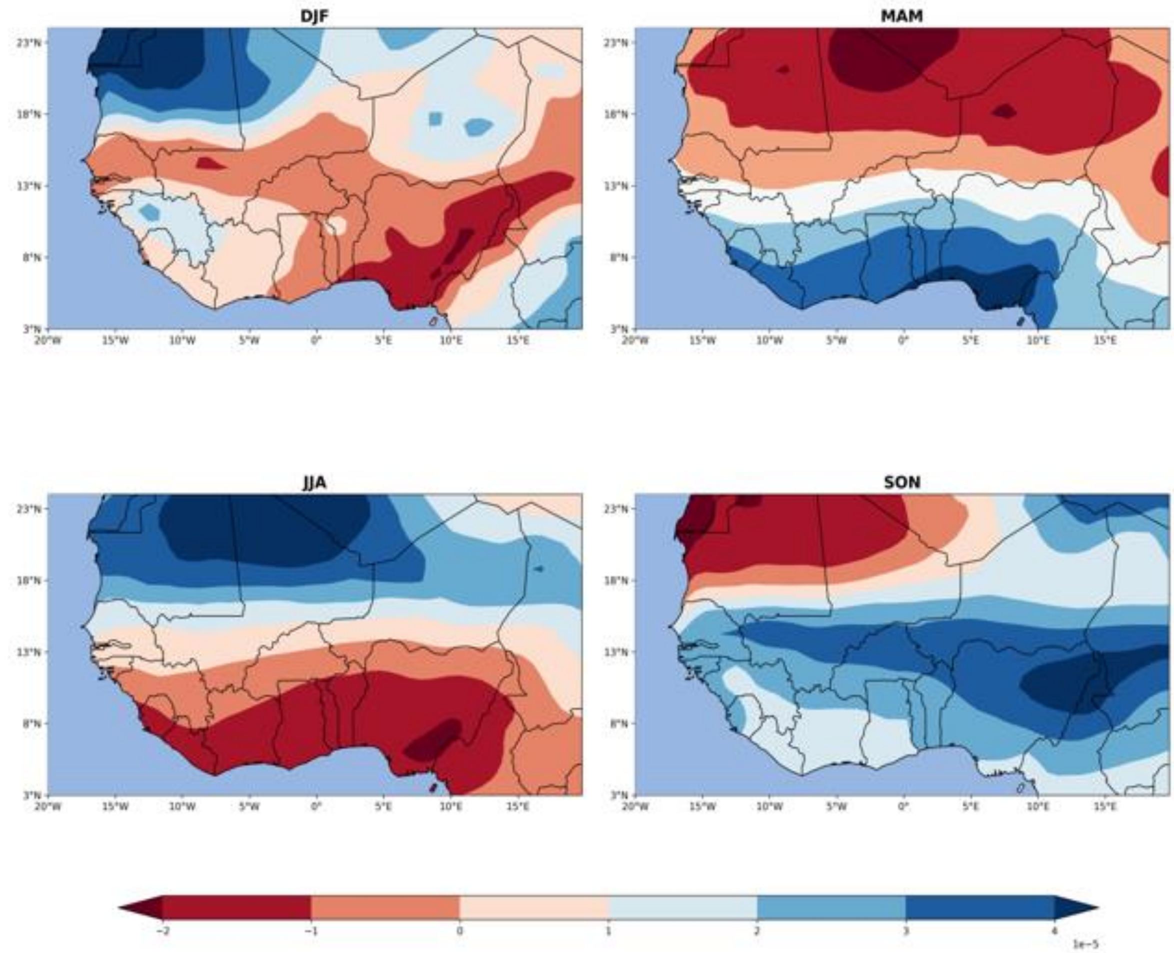

Figure 4.14: Seasonal mean dust mass density anomaly (0.55-9μm) distribution

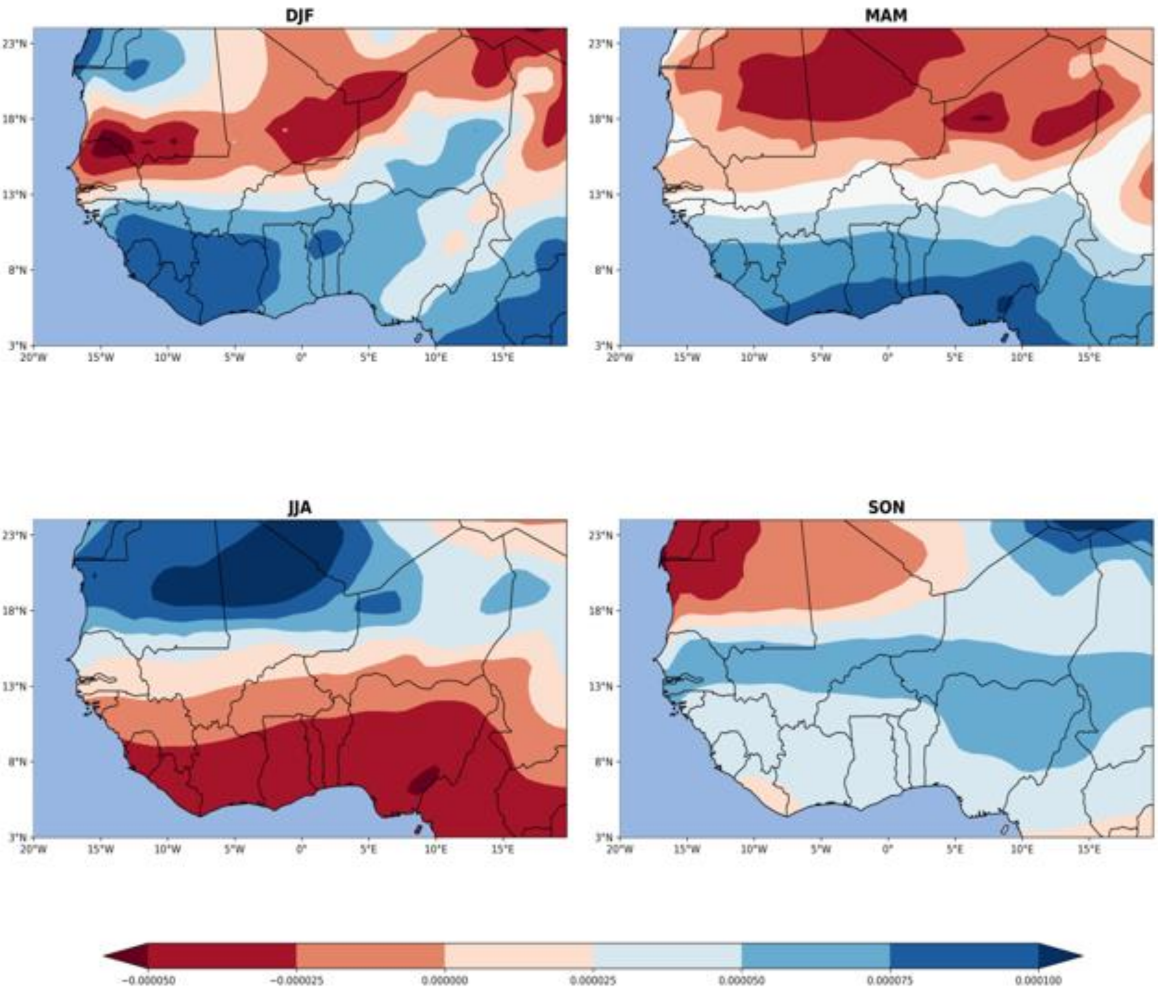

Figure 4.15: Seasonal mean dust mass density anomaly (9-20μm) distribution

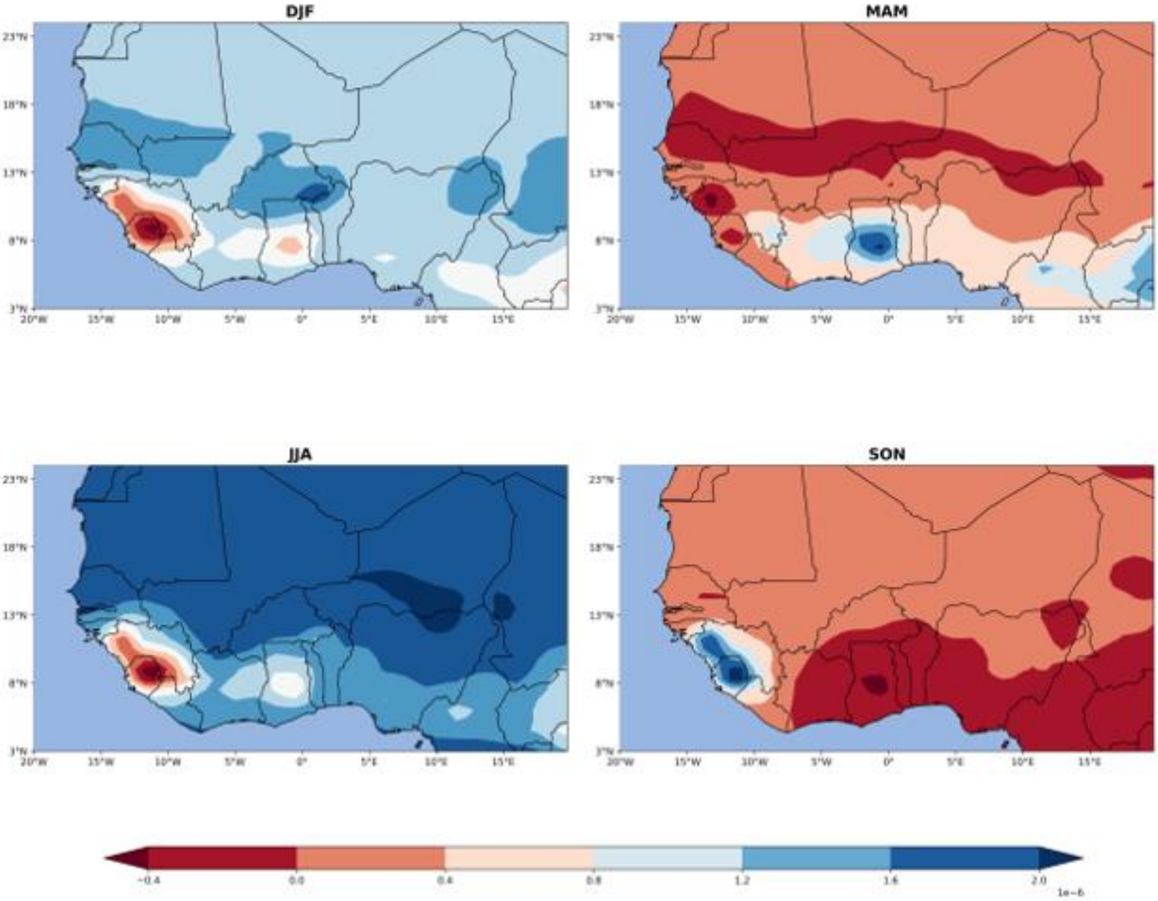

Figure 4.16: Seasonal mean black carbon mass density anomaly distribution

4.3.2.4 Organic matter

Figure 4.17 show that during the DJF and JJA seasons, there is a significantly positive anomaly in organic matter mass density with some places with negative black carbon mass density anomaly (Sierra Leone and Liberia). This suggests that there is more organic matter present during these seasons, which matches with rain reduction during the two seasons. Conversely, during the MAM and SON seasons, there is a significantly negative anomaly in organic matter mass density except part countries like Ghana, Sierra Leone and Liberia where black carbon mass density anomaly was positive. This suggests that there is less organic matter present during these seasons. Results suggest that the MAM and SON seasons have significantly higher rainfall than the other two seasons. This may suggest that the West African atmospheric organic matter variation affects the amount of seasonal rainfall. During the dry season, organic matter concentrations can be higher in the Sahel region, where soils are generally sandier and have lower organic matter content, but where the retention of soil moisture can lead to increased organic matter accumulation.

4.3.2.5 Sulphate

Figure 4.18 shows that during the DJF and JJA seasons, there is a significantly negative anomaly in sulphate mass density except part of countries like Senegal and Niger where sulphate mass density anomaly was positive. This suggests that there is less sulphate present during these seasons than the seasonal mean. Conversely, during the MAM and SON seasons, there is a significantly positive anomaly in sulphate mass density except part of countries like Senegal and Niger where sulphate mass density anomaly was negative. This suggests that there is more sulphate present during these seasons than the seasonal mean. Results suggest that the MAM and SON seasons have significantly higher rainfall than the other two seasons. This may suggest that the amount of sulphate present in the atmosphere has an impact on the amount of seasonal rainfall. More rainfall could lead to more rainout of sulphate from the atmosphere, resulting in a lower mass density of sulphate during these seasons. Conversely, during the DJF and JJA seasons, when there is less rainfall, there may be less washout of sulphate from the atmosphere, leading to a higher mass density of sulphate.

4.3.2.6 Sea salt

Sea salt is a type of aerosol that is formed when ocean waves generate small particles of salt that are then carried into the atmosphere. The spatial distribution of seasonal sea salt anomalies over West Africa can vary depending on a number of factors, including ocean currents, wind patterns, and meteorological conditions. During the dry season, when atmospheric conditions are generally more stable and winds are weaker, the spatial distribution of sea salt anomalies tends to be more localized, with higher concentrations occurring in areas that are closer to the coast and more exposed to oceanic aerosols. However, during the wet season, when there is more atmospheric mixing and stronger winds, the spatial distribution of sea salt anomalies can be more widespread, with high concentrations occurring over much of the region. During DJF, MAM, and JJA seasons, the sea salt mass density anomaly was significantly negative, which could imply that there was a decrease in the amount of sea salt particles in the air during these seasons. This decrease in sea salt particles could be due to changes in wind patterns or other meteorological factors. In contrast, during SON, the sea salt mass density anomaly was significantly positive, suggesting an increase in the amount of sea salt particles in the air during this season. This increase could be due to changes in ocean currents, wind patterns, or other factors. Results suggest that during JJA, the sea salt mass density anomaly was significantly positive in the coastal West Africa region. This increase in sea salt particles could be due to factors such as increased ocean currents or wind patterns that bring more sea salt particles into the air.

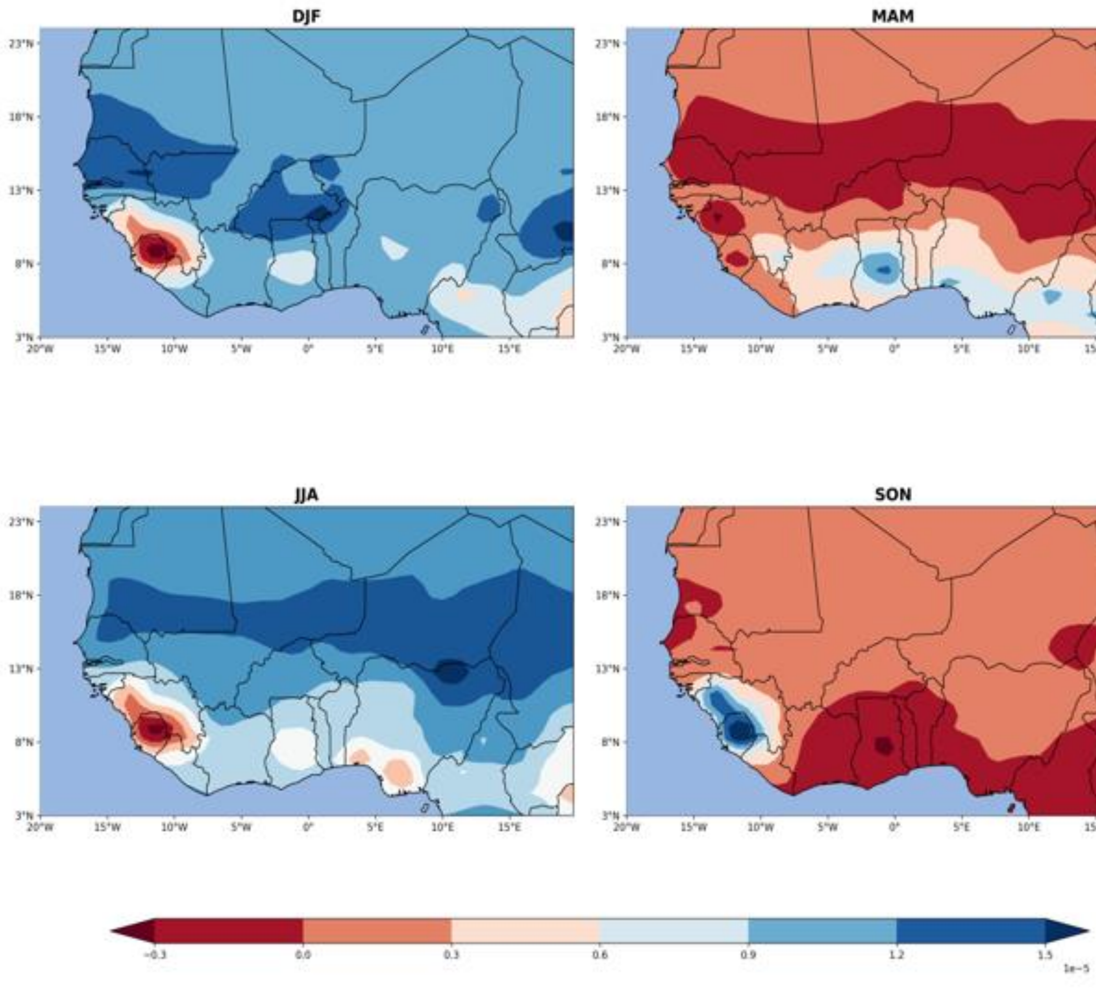

Figure 4.17: Seasonal mean organic matter mass density anomaly distribution

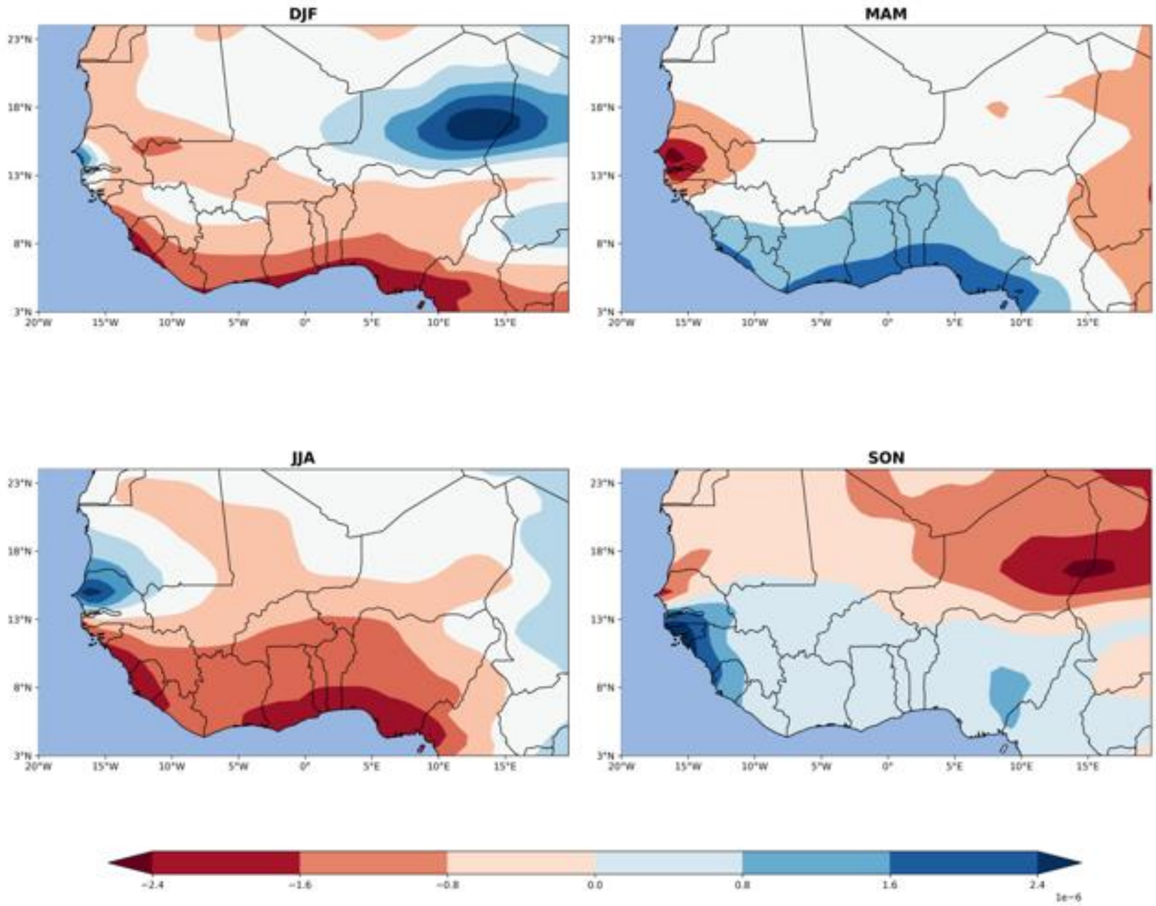

Figure 4.18: Seasonal mean sulphate mass density anomaly distribution

The MAM and SON seasons were found to have significantly higher rainfall. The relationship between rainfall and sea salt mass density anomaly is complex and depends on various factors, such as wind patterns, ocean currents, and temperature. However, it is possible that the increase in sea salt particles during SON, when there is higher rainfall, could be related to the role of sea salt particles as cloud condensation nuclei, which could influence the amount and timing of rainfall in the region.

For example, studies have shown that during the dry season, sea salt concentrations in West Africa are generally highest along the coast and in areas that are directly downwind from the ocean. During the wet season, sea salt concentrations can be elevated over much of the region, with higher concentrations occurring in areas with greater atmospheric mixing and in locations that are closer to sources of sea salt aerosols. Understanding the spatial distribution of seasonal sea salt anomalies is important for studying the impacts of aerosols on climate and the environment, as well as for informing the development of atmospheric modelling and forecasting systems. It can also help identify areas that are particularly vulnerable to the effects of sea salt aerosols, such as coastal regions and areas that are heavily impacted by air pollution.

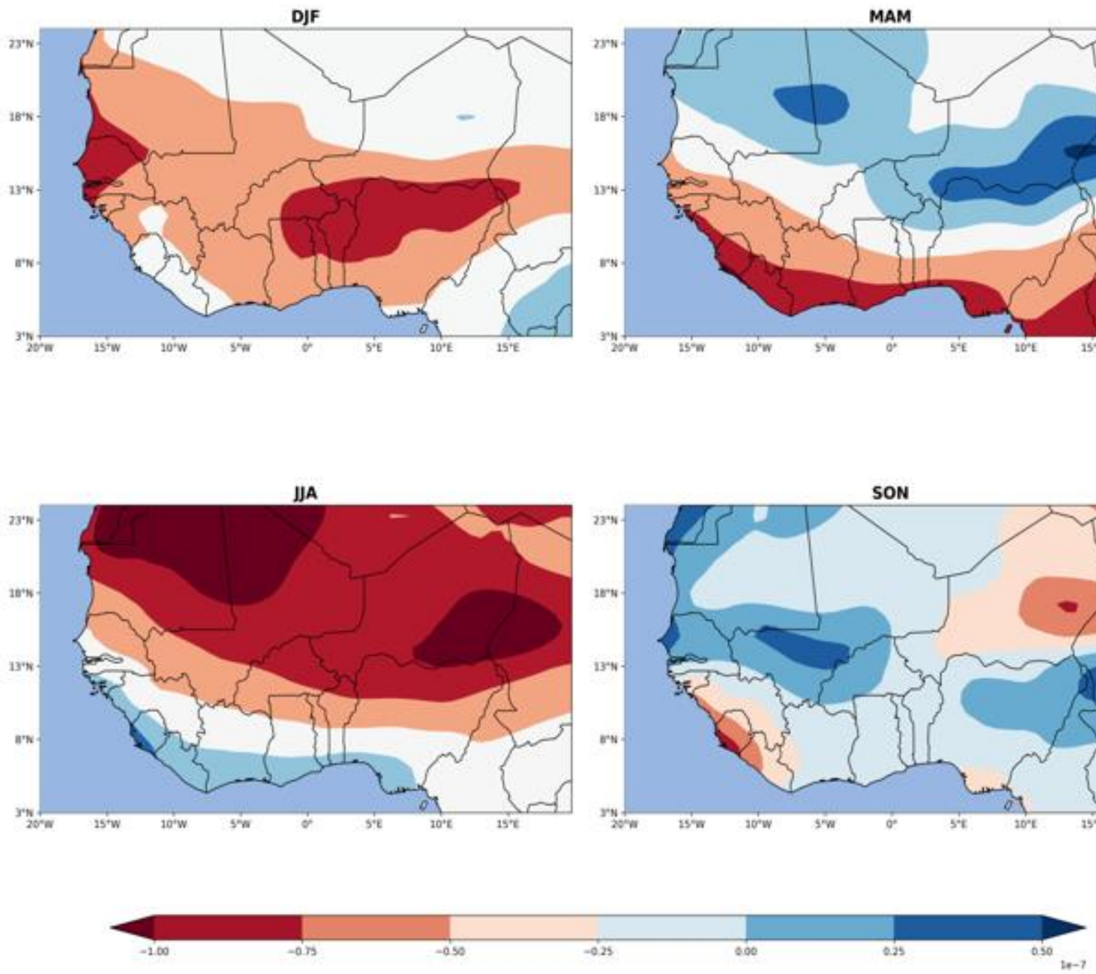

Figure 4.19: Seasonal mean sea salt mass density anomaly (0.03-0.5μm) distribution

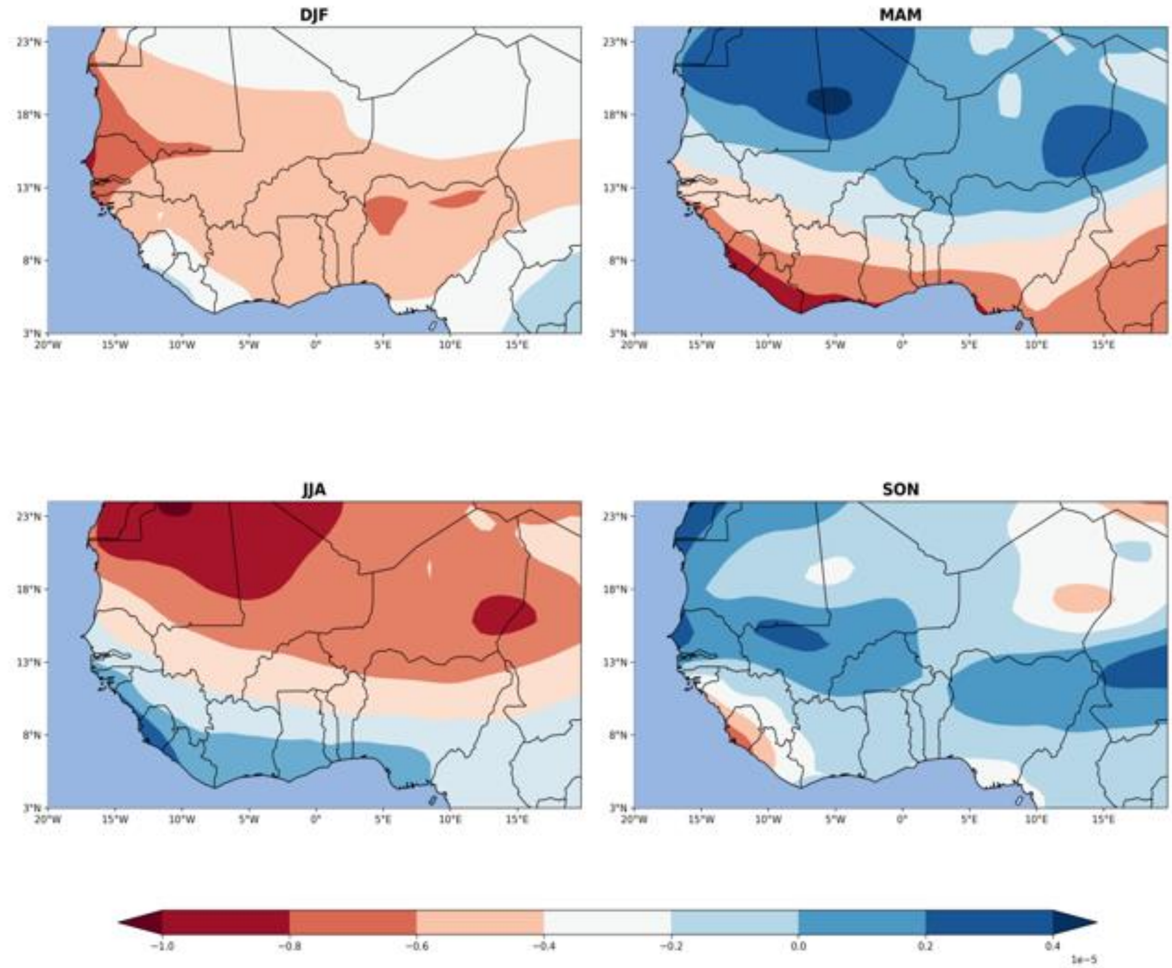

Figure 4.20: Seasonal mean sea salt mass density anomaly (0.5-5μm) distribution

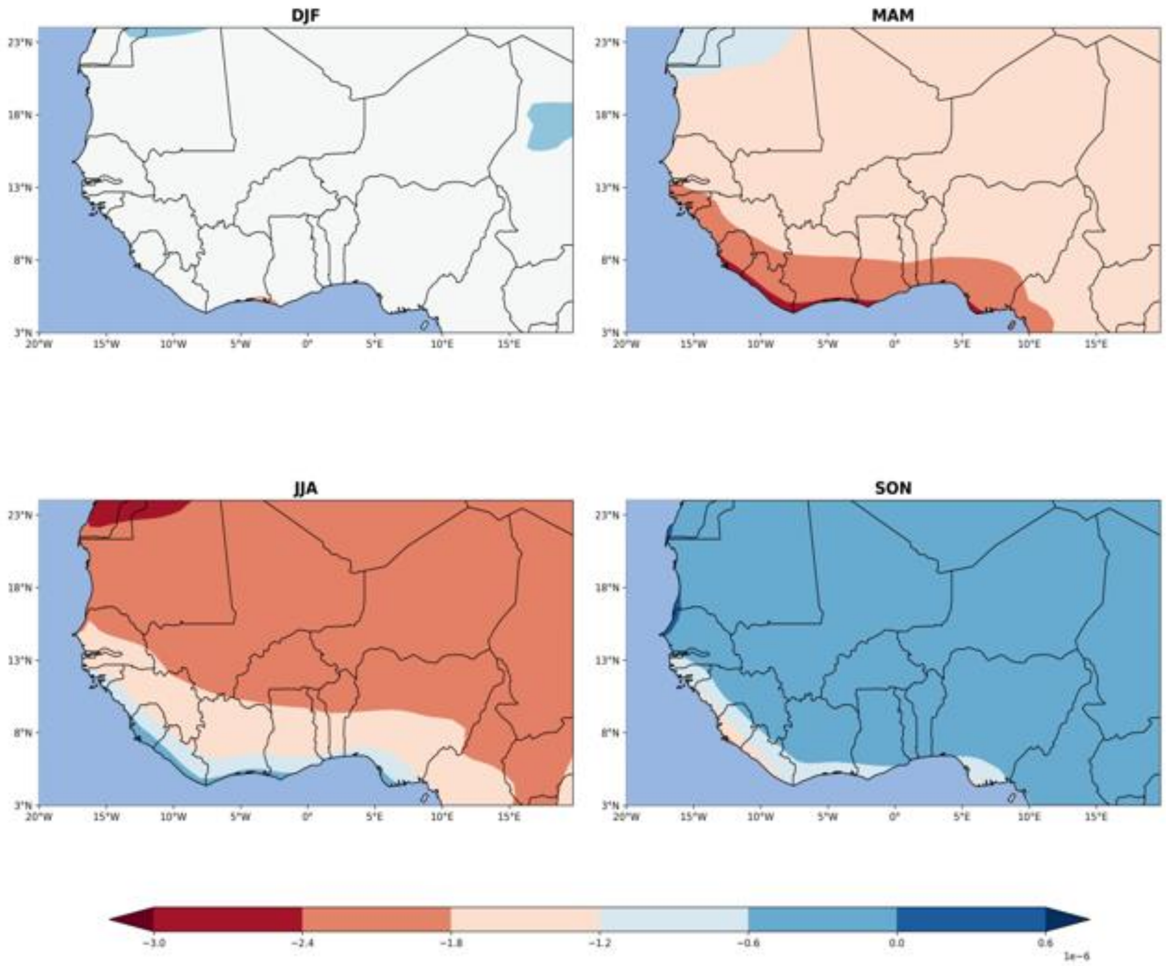

Figure 4.21: Seasonal mean sea salt mass density anomaly (5-20μm) distribution

4.3.2.7 Hovmoller precipitation anomaly diagrams

A Hovmoller diagram is a graphical representation of a time series of data in a latitude-time (or longitude-time) format. For precipitation anomaly over West Africa, a Hovmoller diagram can show how the precipitation varies over time and location. In a Hovmoller precipitation anomaly diagram over West Africa, time would be shown on the vertical axis, while longitude (or latitude) would be shown on the horizontal axis. The precipitation anomaly values would be indicated by colour, with positive anomalies represented by blue colour and negative anomalies represented by red colour.

From the analysis of the Hovmoller diagram for precipitation anomalies in West Africa, it appears that there has been a reduction in precipitation over the five-year of the study period (2015 - 2019), with 2019 being the worst year (Figure 4.22). This trend could have significant implications for agriculture, water resources, and other aspects of life in the region. To further understand the implications of this trend, it may be useful to investigate the potential causes of the reduction in precipitation, such as changes in atmospheric aerosol concentration. It may also be worthwhile to explore strategies for adapting to changing precipitation patterns, such as improving water management practices, crop selection, or implementing drought-resistant farming techniques.

Figure 4.23 shows a Hovmoller precipitation anomaly diagram over West Africa might show the time series of precipitation anomalies at different longitudes or latitudes of the year 2019. The diagram would show how the precipitation anomalies change over time at each location, allowing for the identification of any trends or patterns in the data. Such a diagram could be useful for studying the variability of precipitation over West Africa, which can have significant impacts on agriculture, water resources, and human livelihoods. By visualizing the spatial and temporal patterns of precipitation anomalies, researchers and policymakers can better understand the drivers of precipitation variability in the region and develop strategies to mitigate the impacts of extreme weather events.

4.4 CORRELATION BETWEEN AEROSOLS AND RAINFALL AND ITS SIGNIFICANCY TEST

Correlation coefficient analyses of the study period were obtained for aerosol mass density and rainfall with their corresponding linear regression plot shown in Figures 4.26–4.28.

4.4.1 Dust Mass Density and Precipitation

Results suggests that there is a relationship between ultrafine dust and precipitation over West Africa, but the nature of this relationship varies depending on the region. In the Sahel region, there is a weak positive correlation between ultrafine dust and precipitation, which means that when there is but not significant, which means that when there is no statistic link between aerosols and precipitation. In contrast, in the Guinea zone, there is a strong negative correlation between ultrafine dust and precipitation, which means that when there is more ultrafine dust in the air, there tends to be less precipitation (Figures 4.26 to 4.28).

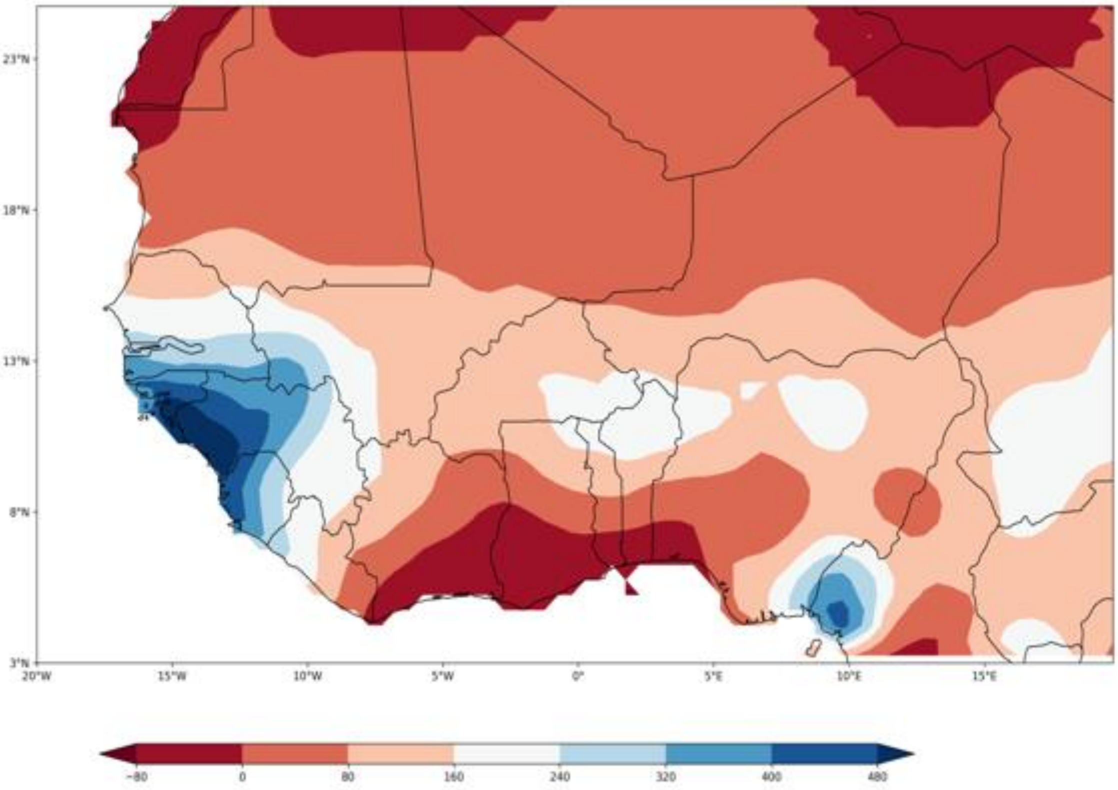

Figure 4.22: CRU spatial precipitation distribution of the year 2019

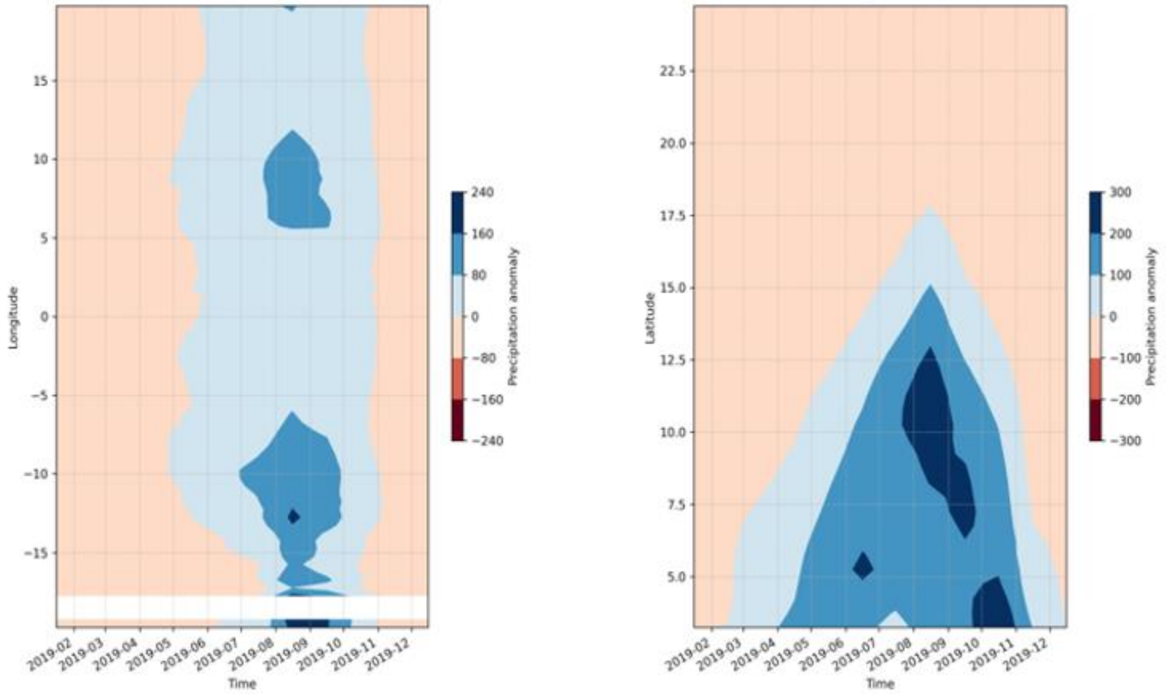

Figure 4.23: Hovmoller diagrams of monthly CRU precipitation anomaly 2019

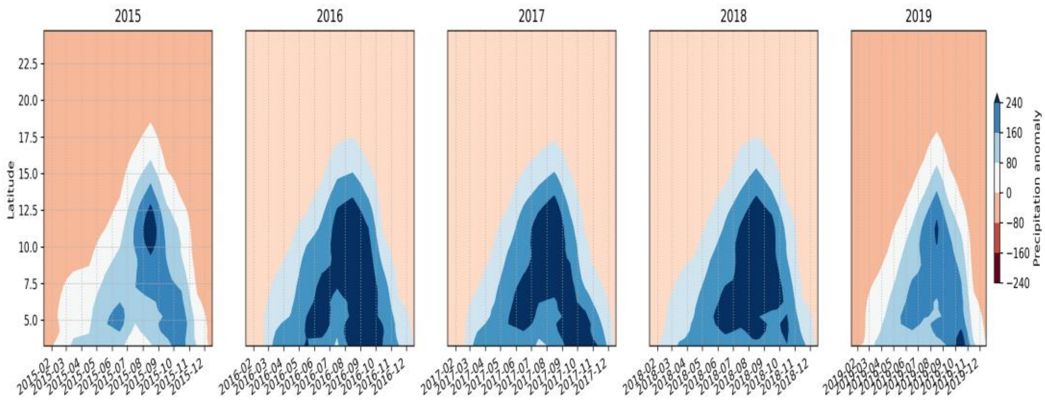

Figure 4.24: Hovmoller diagrams of monthly CRU precipitation anomaly from 2015 to 2019

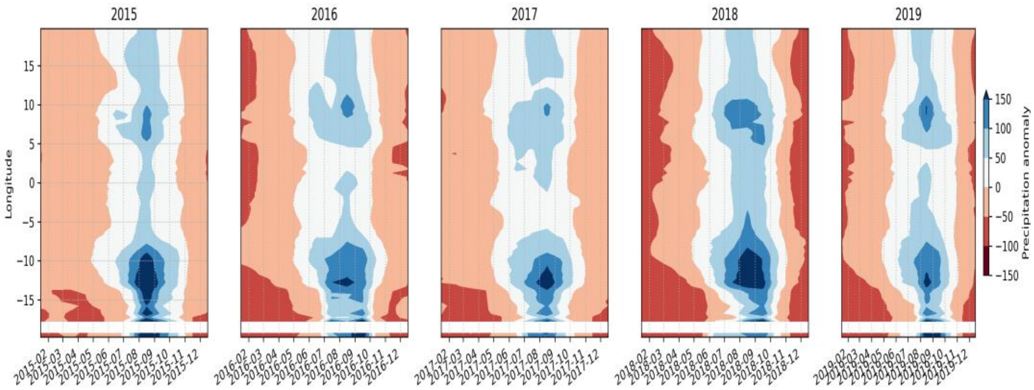

Figure 4.25: Hovmoller diagrams of monthly CRU precipitation anomaly from 2015 to 2019

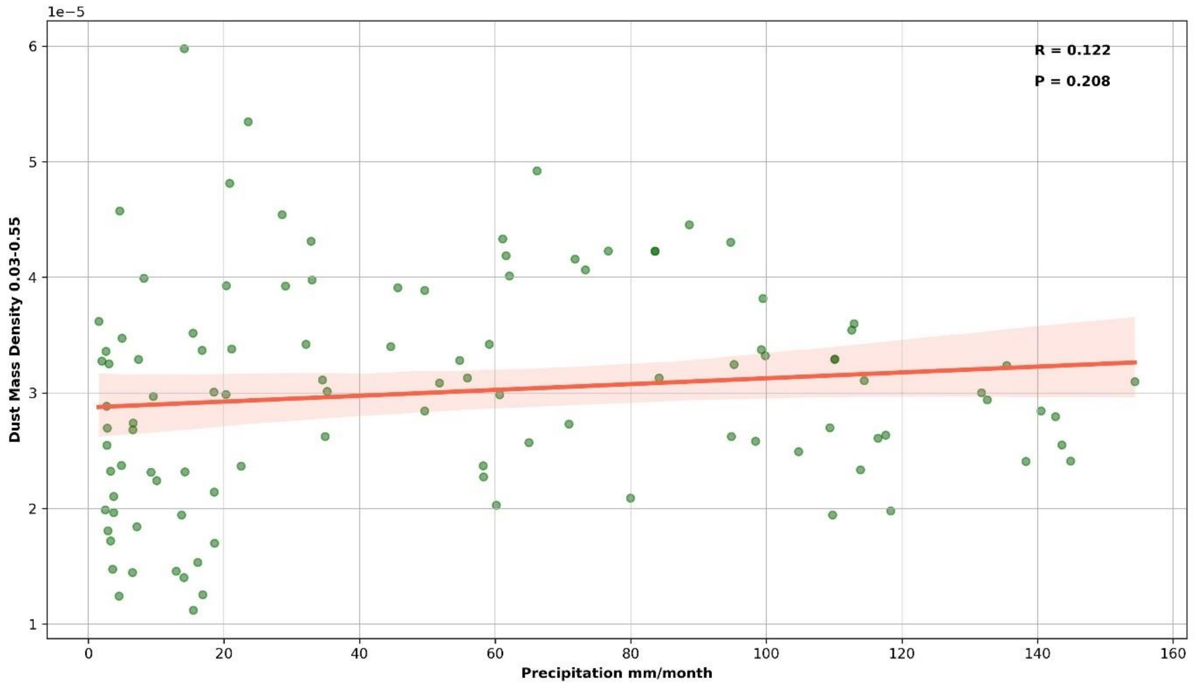

Figure 4.26: Precipitation and dust mass density 0.03 – 0.55 µm linear regression over West Africa

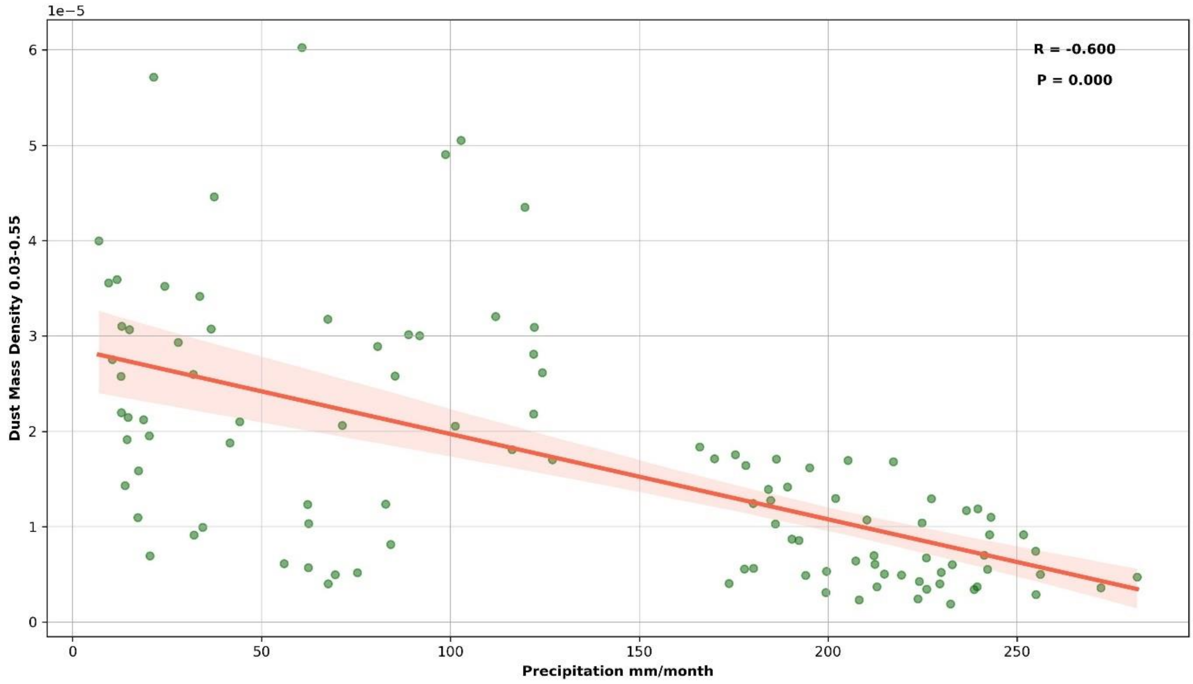

Figure 4.27: Precipitation and dust mass density 0.03 – 0.55 µm linear regression over the Guinea zone

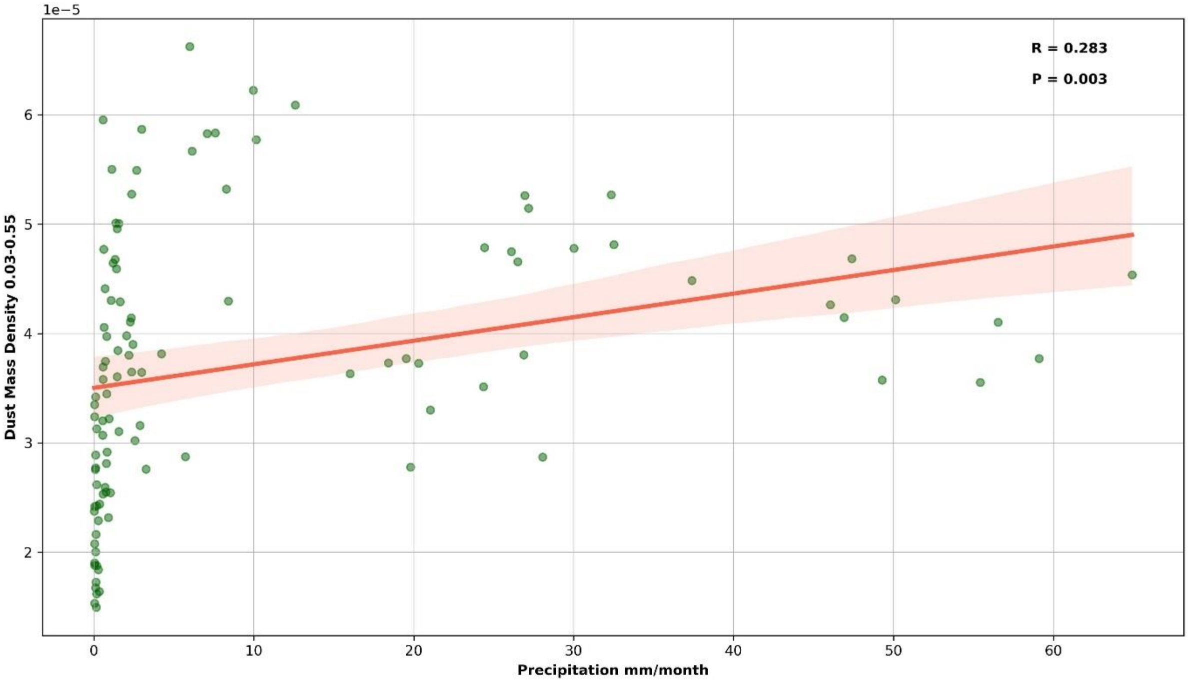

Figure 4.28: Precipitation and dust mass density 0.03 – 0.55 μm linear regression over the Sahel zone

Results suggest that there is a relationship between fine dust and precipitation over West Africa, but again, the nature of this relationship varies depending on the region. In the Sahel region, there is a weak positive correlation between fine dust and precipitation, which means that when there is more fine dust in the air, there tends to be slightly more precipitation. In the Guinea zone, there is a moderate negative correlation between fine dust and precipitation, which means that when there is more fine dust in the air, there tends to be less precipitation.

Results suggest that there is a relationship between coarse dust and precipitation over West Africa, and once again, the nature of this relationship varies depending on the region. In the Sahel region, there is a moderate positive correlation between coarse dust and precipitation, which means that when there is more coarse dust in the air, there tends to be more precipitation. This may be because coarse dust particles can act as cloud condensation nuclei, which can enhance cloud formation and lead to more precipitation. In contrast, in the Guinea zone, there is a very weak negative correlation between coarse dust and precipitation, which means that when there is more coarse dust in the air, there tends to be slightly less precipitation.

4.4.2 Sulphate Mass Density and Precipitation

The correlation between sulphate and rainfall in West Africa has also been investigated in this study. However, the relationship between sulphate and rainfall is complex and can depend on several factors, such as the sources of sulphate emissions and the local atmospheric circulation patterns. This study found that there is a relationship between sulphate and precipitation in West Africa. In the Sahel region, there is a moderate positive correlation between sulphate and precipitation, which means that when there is more sulphate in the air, there tends to be slightly more precipitation. This may be because sulphate aerosols can act as cloud condensation nuclei and enhance cloud formation, leading to more precipitation. In contrast, in the Guinea zone, there is a moderate negative correlation between sulphate and precipitation, which means that when there is more sulphate in the air, there tends to be less precipitation. In West Africa, there is a strong negative correlation between sulphate and precipitation, which means that when there is more sulphate in the air, there tends to be less precipitation.

However, the relationship between sulphate and rainfall in West Africa is an important area of research, as it can inform efforts to mitigate the impact of anthropogenic emissions on regional climate patterns.

4.4.3 Black carbon mass density

The correlation between black carbon and rainfall in West Africa has also been a topic of research. However, the relationship between black carbon and rainfall is complex and has not been fully established. Results suggest that there is a very strong negative correlation between black carbon and precipitation over West Africa, with an even stronger negative correlation over the Guinea zone and a strong negative correlation over the Sahel. This indicates that when there is more black carbon in the air, there tends to be significantly less precipitation in all regions. This relationship may be due to the fact that black carbon can interact with other aerosols in the atmosphere, which can further reduce cloud formation and precipitation.

4.4.4 Organic matter mass density

The correlation between organic matter and rainfall in West Africa has also been investigated in this study, as organic matter can influence soil fertility and moisture retention, which can in turn impact agricultural productivity in the region. This study found suggests that there is a very strong negative correlation between organic matter and precipitation over West Africa, with an even stronger negative correlation over the Guinea zone and a moderate negative correlation over the Sahel. This indicates that when there is more organic matter in the air, there tends to be significantly less precipitation in all regions. Additionally, organic matter can interact with other aerosols in the atmosphere, which can further reduce cloud formation and precipitation.

4.4.5 Sea salt mass density

The correlation between sea salt and rainfall in West Africa has also been studied, as sea salt aerosols can impact regional climate through their interaction with clouds. However, the relationship between sea salt and rainfall is complex and can depend on several factors, such as the sources and transport pathways of sea salt aerosols and the local atmospheric circulation patterns. Results suggest that there is a relationship between ultrafine sea salt and precipitation over West Africa. In the Guinea zone, there is a moderate positive correlation between ultrafine sea salt and precipitation, which means that when there is more ultrafine sea salt in the air, there tends to be slightly more precipitation. This may be because sea salt aerosols can act as cloud condensation nuclei and enhance cloud formation, leading to more precipitation. In contrast, in the Sahel region, there is a moderate negative correlation between ultrafine sea salt and precipitation, which means that when there is more ultrafine sea salt in the air, there tends to be slightly less precipitation. Overall, in West Africa, there is a strong negative correlation between ultrafine sea salt and precipitation, which means that when there is more ultrafine sea salt in the air, there tends to be less precipitation.

Results suggest that there is a relationship between fine sea salt and precipitation over West Africa, with different correlations depending on the region. In the Guinea zone, there is a strong positive correlation between fine sea salt and precipitation, which means that when there is more fine sea salt in the air, there tends to be more precipitation. This may be because sea salt aerosols can act as cloud condensation nuclei and enhance cloud formation, leading to more precipitation. In contrast, in the Sahel region, there is a moderate negative correlation between fine sea salt and precipitation, which means that when there is more fine sea salt in the air, there tends to be slightly less precipitation. Overall, in West Africa, there is a moderate negative correlation between fine sea salt and precipitation, which means that when there is more fine sea salt in the air, there tends to be slightly less precipitation.

Results suggest that there is a relationship between coarse sea salt and precipitation over West Africa, with different correlations depending on the region. In the Guinea zone, there is a strong positive correlation between coarse sea salt and precipitation, which means that when there is more coarse sea salt in the air, there tends to be more precipitation. This may be because sea salt aerosols can act as cloud condensation nuclei and enhance cloud formation, leading to more precipitation. In contrast, in the Sahel region, there is a moderate negative correlation between coarse sea salt and precipitation, which means that when there is more coarse sea salt in the air, there tends to be slightly less precipitation. In West Africa, there is a weak positive correlation between coarse sea salt and precipitation, which means that when there is more coarse sea salt in the air, there tends to be slightly more precipitation. However, this relationship is not as strong as the relationships observed for fine sea salt and ultrafine sea salt.

4.5 DOMINANT AEROSOL OVER WEST AFRICA

The maximum aerosol (dust, black carbon, organic matter, sulphate and sea salt) mixing ratio of 12 stations over West Africa is shown in Figure 4.29. It shows that dust pollution is the dominant aerosol over all stations used in this study. Organic matter is the second most significant aerosol in this region, which contributes to atmospheric pollution. During the monsoon season, the winds blow from East Africa to the Atlantic Ocean and move high dust concentrations from the source to Dakar and the West parts of West Africa. Among all stations Dakar is the most dust polluted over the Sahel region during its rainy season from July to September while Lungi (Sierra Leone) has the lowest dust pollution over the Guinea region during its rainy season from June to November, this is the reason why they are taken as polluted (P-case) and clean cases (C-case).

4.6 AEROSOL EFFECTS ON RAIN FREQUENCY

4.6.1 Dust Effects on Rain Frequency

Figure 4.30 illustrates rain event numbers in the C-case in blue colour and P-case in brown colour of Abidjan (Cote d'Ivoire), Lungi (Sierra Leone), Ouagadougou (Burkina Faso), Dakar (Senegal), Bamako (Mali) and Niamey (Niger) stations. A comparison between the C-case (10^{th} percentile) and P-case (90^{th} percentile) shows that aerosol concentration variations affect precipitation frequency over all selected stations. Rain events percentages of 10% and 90% percentile have been summarized in Table 1 to 5 for dust, black carbon, organic matter, sulphate and sea salt, respectively. For all rain types, the C-case has more rain events for dust and sulphate. For black carbon, and organic matter the C-case has more rain events except Niamey. But the magnitude of rain frequency of the pollution cases is different for stations. The rain event percentages under low and high dust concentrations for each city are presented for both the C-case and the P-case. The figures suggest that, in general, dust pollution is associated with a reduction in rain event percentages compared to the C-case. The reductions in rain event percentages under the P-case compared to the C-case. The estimates given in Table 4.2 suggest that dust pollution is associated with a reduction in rain frequency in the stations of Abidjan, Lungi, Ouagadougou, Dakar, Bamako, and Niamey are respectively -3.6%, -4.17%, -2.07%, -11.51%, -2.43% and -2.66%. These results suggest that the reduction in rain event percentages due to dust pollution is more significant over Dakar during its rainy season, with a reduction of 11.51%. It's worth noting that the specific effects of dust pollution on precipitation patterns can vary depending on a range of factors, such as the location, season, and type of dust emission source.

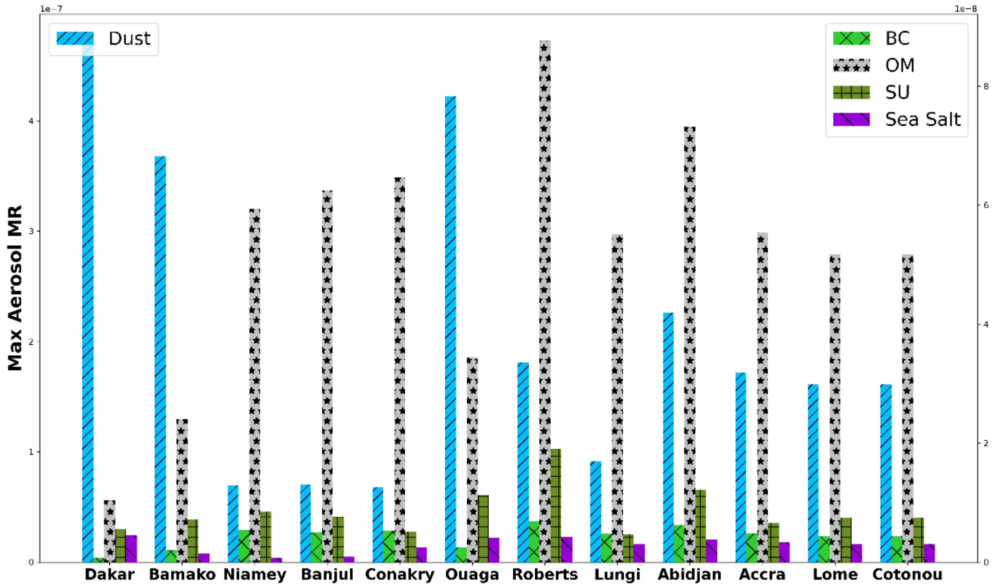

Figure 4.29: Maximum aerosol mixing ratio. BC means Black Carbon, OM means Organic Matter and SU means Sulphate

However, the results presented here suggest that, overall, dust pollution is associated with a reduction in rain frequency in the cities included in the study. This can be explained by the summer wind direction (monsoon) which transports dust from the Sahel to American continent. High aerosol concentration enhances rain droplet formation and increases rain events during the rainy season. In the P-case, 90% of aerosol concentration is taken, which increases cloud droplets with a decrease in the size (precipitation suppression) (Twomey, 1977).

Dust can have significant effects on precipitation patterns over West Africa. The region is particularly susceptible to these effects due to its proximity to the Sahara Desert, which is a major source of airborne dust particles. Dust can also act as a seed for cloud formation, which can lead to increased rainfall in some cases. However, this effect is highly dependent on the size and composition of the dust particles, as well as the prevailing atmospheric conditions. The effects of dust on precipitation in West Africa are complex and multifaceted, and can vary greatly depending on a range of factors including the timing, location, and intensity of dust events, as well as the prevailing atmospheric conditions and other environmental factors.

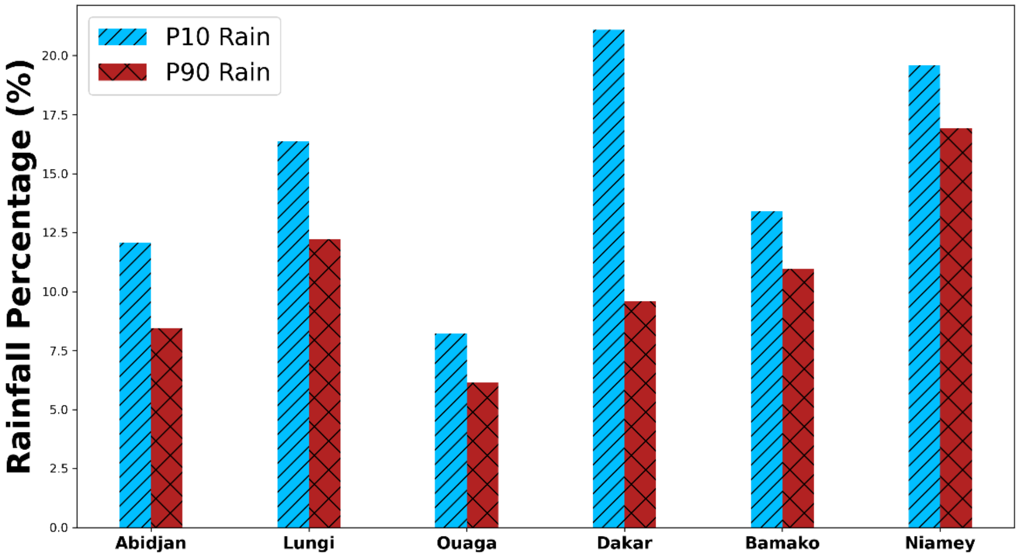

Figure 4.30: precipitation frequency under dust C-case in blue color (rainfall that is exceeded by 90% of the observed aerosol values) and P-case in brown (rainfall that is exceeded by only 10% of the observed aerosol values)

4.6.2 Black Carbon Effects on Rain Frequency

Black carbon pollution has been found to have a negative effect on precipitation frequency in the region in question, as indicated by the percentage reductions in rain frequency compared to the C-case. The reductions in rain frequency in stations (Abidjan, Lungi, Ouagadougou, Dakar, Bamako and Niamey) are as follows: 2.09%, 1.17%, 1.22%, 12.62%, 1.92% and 0.62% compared with the C-case. These results suggest that black carbon pollution is associated with a decrease in precipitation frequency of varying degrees in this region.

4.6.3 Organic matter effects on rain frequency

Organic matter, such as dust and vegetation, can also have an impact on precipitation over West Africa. Dust particles can act as cloud condensation nuclei, promoting the formation of clouds and precipitation. In the Sahel region of West Africa, where rainfall is highly variable, organic matter plays a significant role in determining precipitation patterns. Studies have shown that dust particles from the Sahara Desert can be transported over long distances and contribute to the formation of rainfall in the region. At the same time, changes in vegetation cover due to land use and climate change can also affect the amount and timing of precipitation. The estimates given suggest that organic matter pollution is also associated with a reduction in rain frequency in most of the cities included in the study, namely Abidjan, Lungi, Ouagadougou, Dakar, and Bamako. The rain event percentages under low and high organic matter concentrations for each city are presented for both the C-case and the P-case. The reductions in rain event percentages under the P-case compared to the C-case are as follows: 2.84%, 2.07%, 0.76, 11.57%, 0.44% and 11.24%. It's worth noting that in the case of Ouagadougou and Bamako, negligible reduction in rain frequency was observed under the P-case compared to the C-case. However, in the case of Niamey and Dakar, the reductions in rain frequency due to

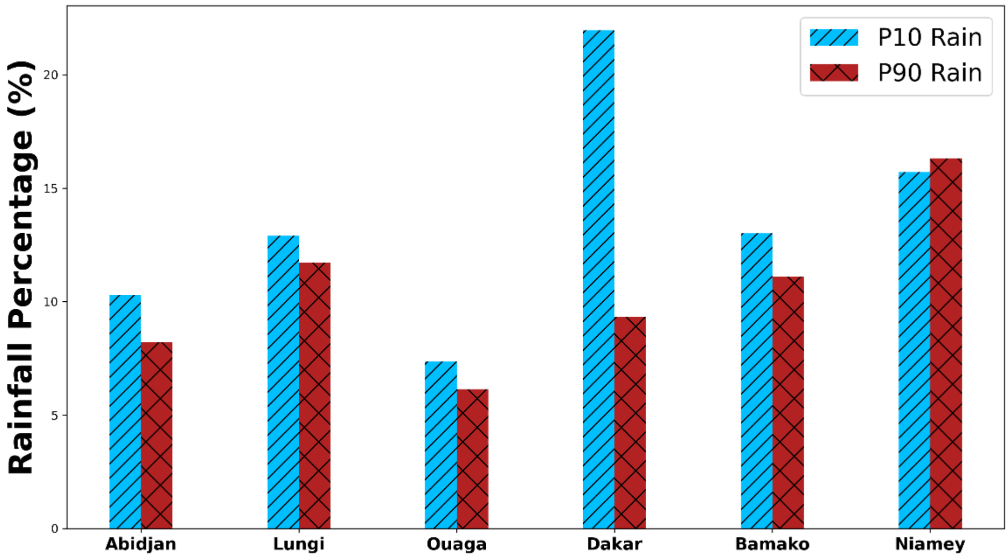

Figure 4.31: precipitation frequency under black carbon C-case and P-case

organic matter pollution were significant as those observed under organic matter pollution, with a reduction of 11.24% compared to 11.57% under organic matter pollution. Results suggest that organic matter pollution is also associated with a reduction in rain frequency in some of the cities included in the study, but the specific effects can vary depending on the location and other factors.

One example of the impact of organic matter on precipitation in West Africa is the phenomenon of the "Saharan air layer." This layer of warm, dry air and dust can inhibit the formation of clouds and precipitation, leading to drought conditions in some areas. Overall, the effects of organic matter on precipitation in West Africa are complex and can vary depending on local meteorological conditions and the amount and distribution of organic matter in the atmosphere. Further research is needed to fully understand these effects and their implications for the region's climate and ecosystems.

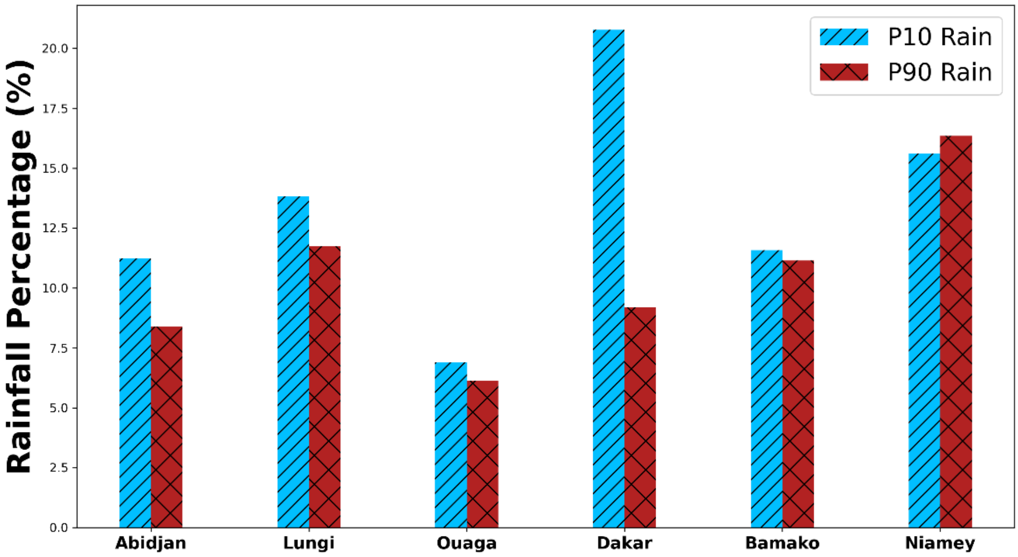

Figure 4.32: precipitation frequency under organic matter C-case and P-case

4.6.4 Sulphate effects on rain frequency

Sulphate is another type of air pollutant that can have an impact on precipitation over West Africa. Sulphate is primarily produced by the burning of fossil fuels and biomass, and it can contribute to the formation of acid rain, which can damage crops, forests, and waterways. Sulphate particles can also affect precipitation patterns in West Africa by altering the microphysical properties of clouds. Sulphate particles can act as cloud condensation nuclei, promoting the formation of smaller cloud droplets and reducing the amount of rainfall that reaches the ground. The estimates given in the statement suggest that sulphate pollution is also associated with a reduction in rain frequency in the cities of Abidjan, Lungi, Ouagadougou, Dakar, Bamako, and Niamey. The rain event percentages under low and high sulphate concentrations for each city are presented for both the C-case and the P-case. The reductions in rain event percentages under the P-case compared to the C-case are as follows: 2.44%, 1.05%, 0.67%, 7.39%, 2.6% and 0.63%. These results suggest that sulphate pollution is associated with a reduction in rain event percentages compared to the C-case in all cities except for Ouagadougou, where the reduction is not significant. The reduction in precipitation frequency due to sulphate pollution can be explained by the suppression of the conversion of cloud droplets to rain droplets, which is a process that is necessary for precipitation to occur. Results presented suggest that sulphate pollution is associated with a reduction in rain frequency in most of the cities included in the study. However, it's worth noting that the specific effects of sulphate pollution on precipitation patterns can vary depending on a range of factors, such as the location, season, and type of sulphate emission source.

The impact of sulphate on precipitation in West Africa is complex and can vary depending on several factors, including the amount and distribution of sulphate in the atmosphere, local meteorological conditions, and the presence of other pollutants and organic matter. However, it is clear that reducing sulphate emissions is essential for mitigating the negative impacts on precipitation and protecting the health and wellbeing of people in the region.

4.6.5 Sea salt effects on rain frequency

Sea salt is a natural component of the atmosphere and can also have an impact on precipitation patterns over West Africa. Sea salt particles can act as cloud condensation nuclei, promoting the formation of clouds and precipitation. However, the impact of sea salt on precipitation over West Africa is complex and can vary depending on several factors. For example, studies have shown that sea salt particles can compete with other particles, such as dust and organic matter, for available water vapour in the atmosphere. This competition can lead to changes in cloud properties and precipitation patterns, depending on the relative amounts of different types of particles present in the atmosphere. Results suggest that sea salt pollution is associated with an increase in rain frequency in most of the cities included in the study. The rain event percentages under low and high sea salt concentrations for each city are presented for both the C-case and the P-case. The increases in rain event percentages under the P-case compared to the C-case are as follows: 2.75%, 3.91%, -1.45%, 4.48%, -0.16% and 4.11%. These results suggest that sea salt pollution is associated with an increase in rain event percentages compared to the C-case in most cities, except for Ouagadougou and Bamako, where the increase is not significant. The increase in precipitation frequency due to sea salt pollution can be explained by the fact that sea salt particles can act as cloud condensation nuclei (CCN), which are necessary for cloud formation. When sea salt particles are present in the atmosphere, they can lead to the formation of more clouds, which in turn can lead to more rain events. results presented suggest that sea salt pollution is associated with an increase in rain frequency in most of the cities included in the study, although the specific effects can vary depending on the location and other factors.

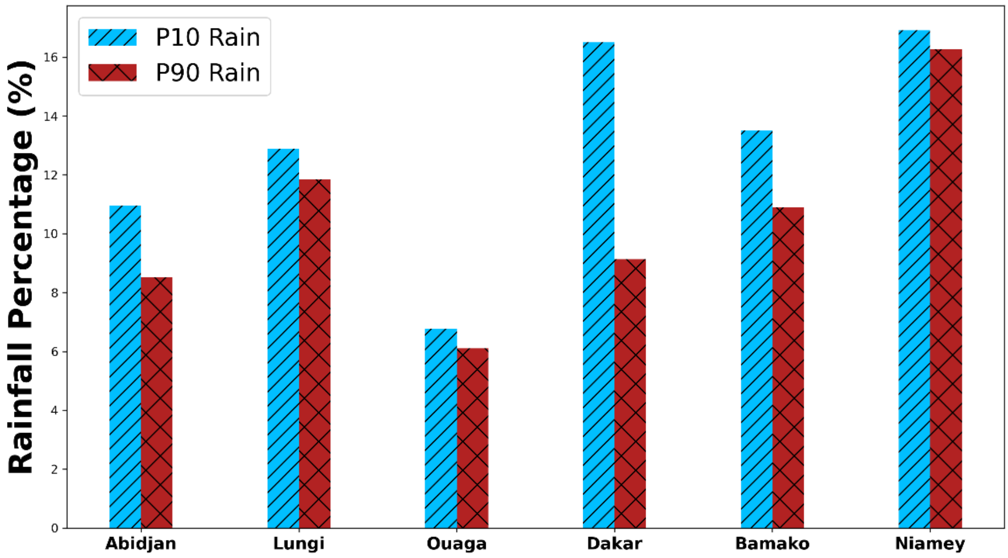

Figure 4.33: precipitation frequency under sulphate C-case and P-case

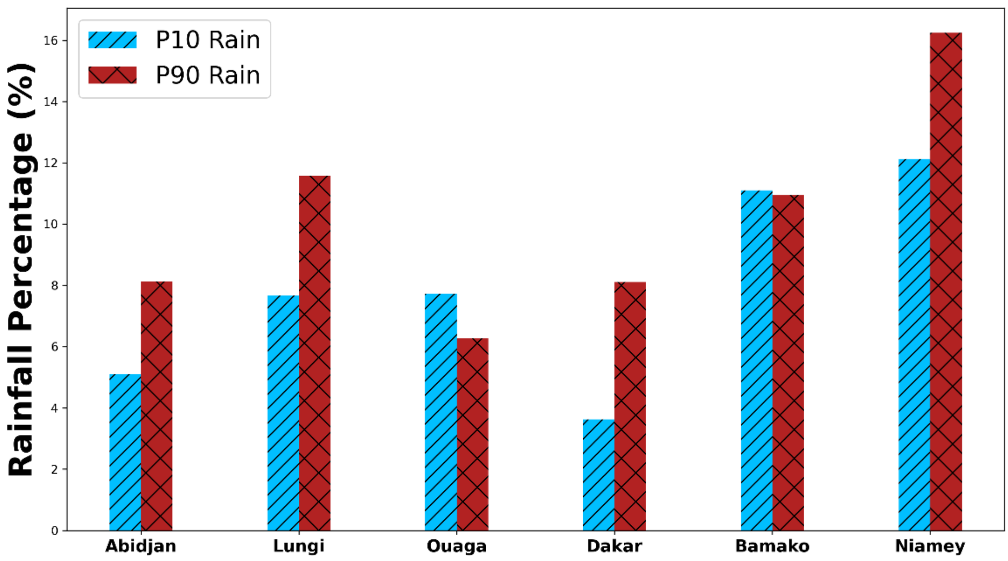

Figure 4.34: precipitation frequency under sea salt C-case and P-case

This study found that an excess of aerosols in the West African atmosphere increases cloud droplets and leads to a decrease in the radii. This size reduction in droplets hinders their ability to reach the threshold necessary for precipitation formation and ultimately results in a reduction or suppression of precipitation in the region. This, in turn, leads to a decrease in the frequency of precipitation events. These results are consistent with a study by Koren *et al.* (2005) investigated the aerosol effect on cloud properties over the Atlantic Ocean and found that increased aerosol concentrations led to an increase in cloud droplet number concentration while decreasing their size, consequently suppressing precipitation. Another relevant study by Rosenfeld *et al.* (2008) examined the impact of aerosols on precipitation in the Amazon rainforest. The researchers observed that an abundance of aerosols caused a reduction in raindrop size, preventing them from growing large enough to initiate rainfall, resulting in a significant decrease in precipitation over the region. Furthermore, a study by Adebiyi *et al.* (2015) specifically focused on West Africa and investigated the influence of aerosols on cloud properties and precipitation. The researchers found that the abundance of mineral dust aerosols in the region altered cloud microphysical properties, leading to reduced cloud droplet size and a decrease in rainfall.

However, sea salt pollution had a positive effect on precipitation frequency, increasing rain events during the rainy season. Sea salt acts as giant cloud condensation nuclei (CCN), leading to an increase in cloud droplets and enhancing precipitation. Additionally, it implies that sea salt pollution has a positive effect on precipitation frequency, increasing the occurrence of rain events during the rainy season. Sea salt particles, when present in the atmosphere, can act as effective CCN due to their hygroscopic properties. These particles have the ability to attract water vapour, forming cloud droplets around them. Consequently, an increase in sea salt aerosols can lead to an increase in the number of cloud droplets and affect precipitation patterns. These results are consistent with a study by Rosenfeld *et al.* (2016) investigated the impact of sea salt aerosols on cloud properties and precipitation. The researchers found that the presence of sea salt particles enhanced cloud droplet concentrations and increased the liquid water path. This increase in cloud droplets and liquid water path facilitated the formation of larger and more efficient raindrops, ultimately enhancing precipitation. Another study by Wang *et al.* (2017) focused on the effect of sea salt aerosols on rainfall during the East Asian monsoon season. The researchers observed that sea salt particles acted as CCN and contributed to the formation of more numerous and smaller cloud droplets. This, in turn, increased the collision and coalescence process, leading to enhanced rainfall. Furthermore, a study by Fan *et al.* (2018) investigated the influence of sea salt aerosols on precipitation over the North Atlantic. The researchers found that sea salt particles acted as efficient CCN, enhancing cloud droplet concentrations and promoting the development of precipitation. They concluded that sea salt pollution could potentially increase rainfall frequency and intensity in the region.

Given the importance of precipitation in West Africa, it is important to manage it effectively. This can be done through a variety of methods, such as the use of weather forecasting and climate models to predict precipitation. Other methods include the use of water harvesting and storage systems, as well as the use of drought-tolerant crops and irrigation systems. It is also important to manage the region's water resources effectively. This can be done through the use of water conservation measures, such as the use of efficient irrigation systems and the use of rainwater harvesting. It is also important to manage the region's land resources effectively, as this can help to reduce the impact of drought and improve the availability of resources. Climate change is expected to have a significant impact on precipitation in West Africa. In particular, the wet season is expected to become shorter and more intense, while the dry season is expected to become longer and drier. This could have a significant impact on the region, particularly in terms of agricultural productivity and water availability. The changing precipitation patterns in West Africa are likely to have a significant impact on the region's agricultural sector. In particular, the shorter and more intense wet season is likely to lead to increased flooding and soil erosion, while the longer and drier dry season is likely to lead to increased drought and water scarcity. These changes could have a significant impact on the region's food security, as well as its economic development.

4.7 AEROSOL EFFECTS ON RAIN CLASSES’ FREQUENCY

4.7.1 Dust Effects on Light Rain Frequency

Rainfall rate comprised between 0.1 mm/h to less than 2.5 mm/h is considered light rain. Light precipitation frequency in the C-case and P-case does not vary significantly. However, dust pollution has different effects on light rain in different stations. In Abidjan and Dakar, dust pollution increases light rain by about 0.89% and 1.4%, respectively. In contrast, dust pollution decreases light rain significantly in Lungi by about -3.29%, in Ouagadougou by about -6.59%, Bamako by about -8.9%, and Niamey by about -2.45%.

Dust is a common aerosol in West Africa that can have significant impacts on precipitation patterns. While dust is typically associated with dry and dusty conditions, it can also affect light precipitation events in the region. Light precipitation events are typically associated with low-level atmospheric moisture, and the presence of dust in the atmosphere can alter the microphysical properties of clouds and affect the formation and distribution of precipitation. Dust particles can act as cloud condensation nuclei, which can lead to the formation of smaller cloud droplets and a decrease in precipitation efficiency. The effects of dust on light precipitation in West Africa are complex and dependent on a number of factors, including the type and concentration of dust particles, the atmospheric moisture content, and the regional meteorological conditions. Further research is needed to better understand these effects and their potential impacts on water resources and agriculture in the region.

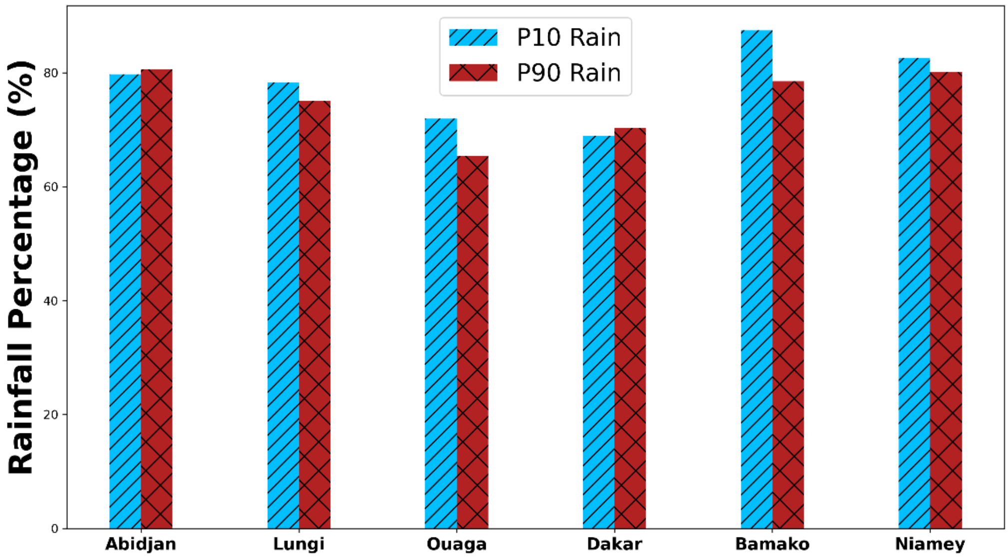

Figure 4.35: light precipitation frequency under dust C-case and P-case

4.7.2 Black carbon effects on light rain frequency

Black carbon pollution has different effects on light rain in various stations. In Abidjan, Dakar and Niamey black carbon pollution leads to a slight decrease in light rain by about -1.92%, -1.11% and -3.98, respectively. However, the effect of black carbon pollution on light rain in Ouagadougou and Bamako is much more significant, with a decrease of about -9.66% and -6.63, respectively. On the other hand, in, Lungi black carbon pollution leads to a slight increase in light rain by about 4.80%. It's worth noting that black carbon pollution can have varying effects on different types of precipitation, and this information only applies to light rain in these specific locations.

Several studies have investigated the effects of black carbon on light precipitation in West Africa. The effects of black carbon on light precipitation in West Africa are complex and dependent on a number of factors, including the type and concentration of black carbon particles, the atmospheric moisture content, and the regional meteorological conditions. Further research is needed to better understand these effects and their potential impacts on water resources and agriculture in the region.

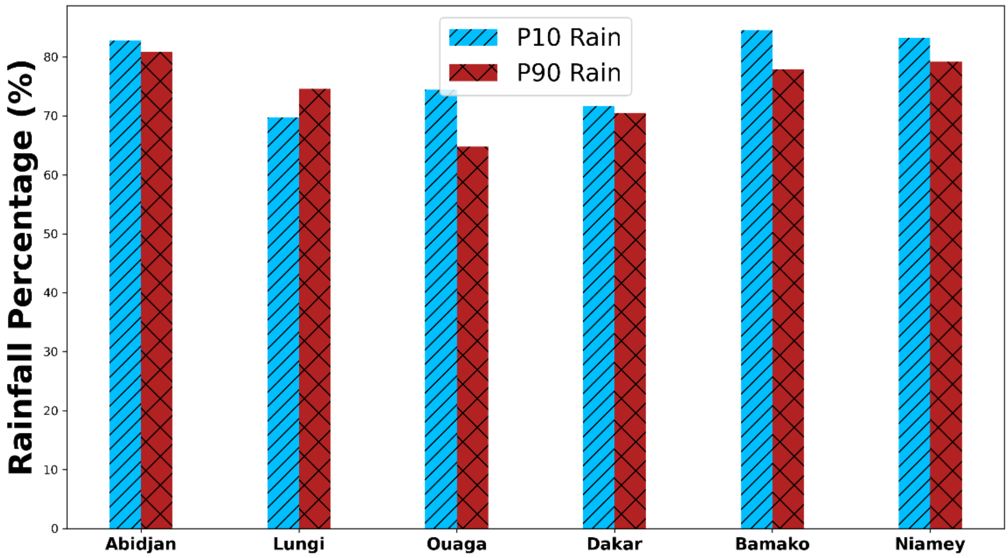

Figure 4.36: light precipitation frequency under black carbon C-case and P-case

4.7.3 Organic matter effects on light rain frequency

Organic matter is another type of aerosol that can have significant impacts on precipitation patterns in West Africa. Organic matter aerosols are typically associated with biomass burning, as well as other natural and anthropogenic sources. The effects of organic matter on precipitation are complex and depend on a number of factors, including the composition and concentration of the aerosols, atmospheric conditions, and the microphysical properties of clouds. Organic matter can act as cloud condensation nuclei, which can lead to the formation of smaller cloud droplets and a decrease in precipitation efficiency. The effects of organic matter pollution on light rain in different stations are different. In Abidjan and Dakar, there is a slight decrease in light rain by about -1.41% and -0.98%, respectively. While in Ouagadougou, Bamako, and Niamey, there is a more significant decrease of about -5.89%, -5.69% and -4.27, respectively. In Lungi, however, there is a slight increase in light rain by about 3.68%. The effects of organic matter pollution on precipitation are complex and can depend on various factors such as the chemical composition of the pollutants, the local weather patterns, and the topography of the region. Therefore, it is important to study the effects of pollution on precipitation on a case-by-case basis and to develop appropriate mitigation strategies based on local conditions. The effects of organic matter pollution on precipitation can have significant impacts on ecosystems and agriculture. Therefore, it is essential to reduce pollution levels and implement sustainable practices to protect the environment.

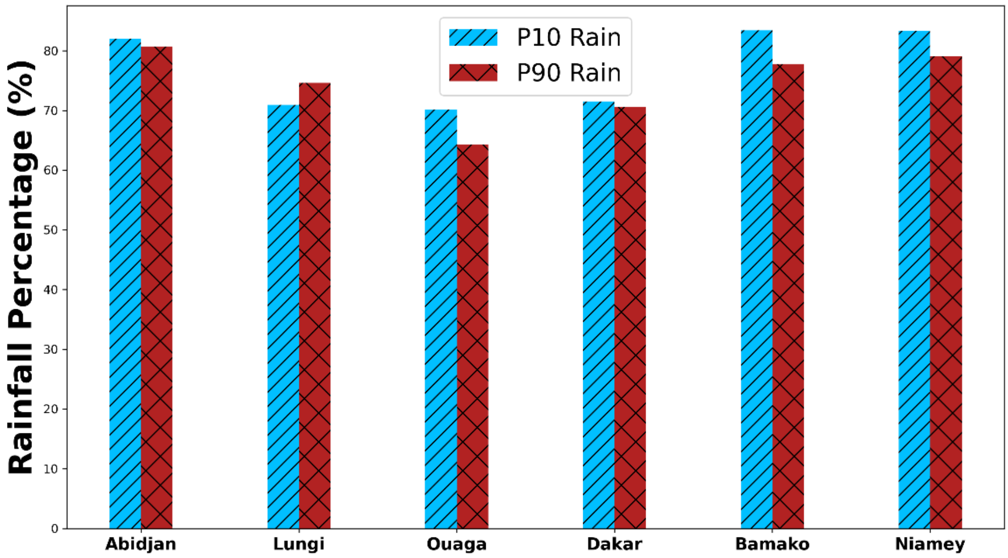

Figure 4.37: light precipitation frequency under organic matter C-case and P-case

4.7.4 Sulphate Effects on Light Rain Frequency

Sulphate aerosols can also have significant impacts on precipitation patterns in West Africa. Sulphate aerosols are typically associated with industrial pollution and fossil fuel combustion, as well as volcanic eruptions and other natural sources. Sulphate aerosols can act as cloud condensation nuclei, which can lead to the formation of smaller cloud droplets and a decrease in precipitation efficiency. It is important to note that the effects of sulphate pollution on precipitation can vary depending on the location and the type of precipitation. In this case, the effects of sulphate pollution on light rain in different stations are different. In Dakar and Niamey, there is a slight decrease in light rain by about -0.68%, -3.49% and -3.98, respectively. However, the effect of Sulphate pollution on light rain in Ouagadougou and Bamako is much more significant, with a decrease of about -5.57% and -7.47, respectively. In Abidjan, there is a slight increase in light rain frequency by about 0.37%. While in Lungi Sulphate pollution leads to a significant increase in light rain frequency by about 5.57%. It is important to study the effects of pollution on precipitation on a case-by-case basis and to develop appropriate mitigation strategies based on local conditions. Overall, reducing sulphate pollution is essential to mitigate its effects on light rain and other types of precipitation, and to protect the environment.

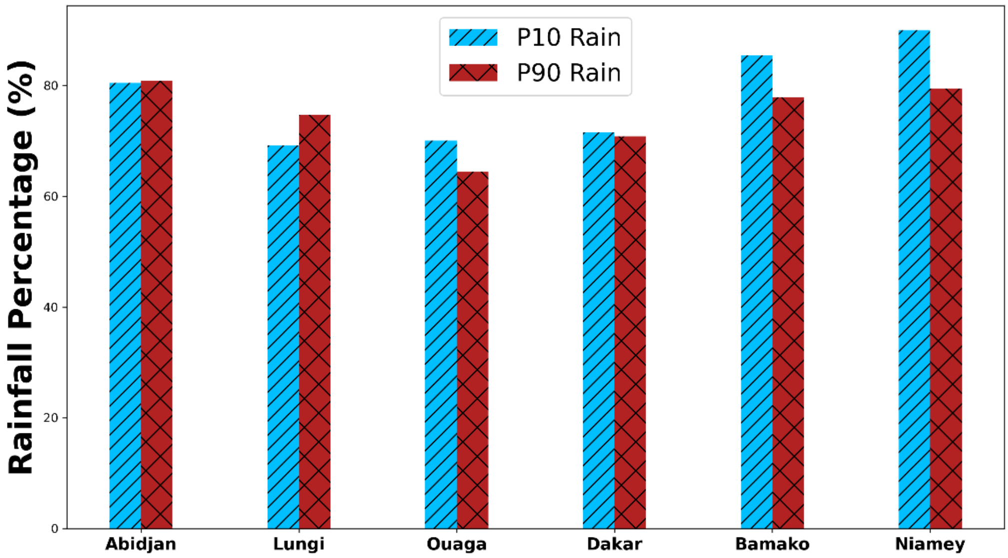

Figure 4.38: light precipitation frequency under sulphate C-case and P-case

4.7.5 Sea Salt Effects on Light Rain Frequency

Sea salt pollution has different effects on light rain in various stations. In Abidjan and Bamako Sea salt pollution leads to a slight decrease in light rain by about -1.36% and -0.17, respectively. However, the effect of Sea salt pollution on light rain in Lungi, Ouagadougou and Niamey is much more significant, with a decrease of about -4.53%, -7.73 and -4.96, respectively. On the other hand, in, Dakar Sea salt pollution leads to a slight increase in light rain by about 6.19%. The effects of sea salt pollution on precipitation can have significant impacts on ecosystems and agriculture. Therefore, it is essential to reduce pollution levels and implement sustainable practices to protect the environment.

4.7.6 Dust Pollution Effects on Moderate Rain Frequency

It appears that there is a difference in the effect of dust pollution on moderate rain frequency in different cities. Figure 4.40 shows that in Bamako, the effect is significant, with a 6.66% increase in moderate rain frequency due to dust pollution. In Abidjan, Lungi, Ouagadougou, and Niamey, the effect is less pronounced, with a slight increase of 1.25%, 3.01%, 1.62%, and 2.20%, respectively. However, in Dakar, dust pollution appears to have the opposite effect, leading to a slight decrease in moderate rain frequency of about -2.67%. It is important to note that these effects may be influenced by various factors, such as geography, climate, and local pollution levels.

Dust aerosols can have significant impacts on moderate precipitation in West Africa. Moderate precipitation events are typically associated with convective storms, which are important for agriculture and water resources in the region. Dust aerosols can affect precipitation patterns by altering the microphysical properties of clouds. In particular, dust aerosols can act as CCN,

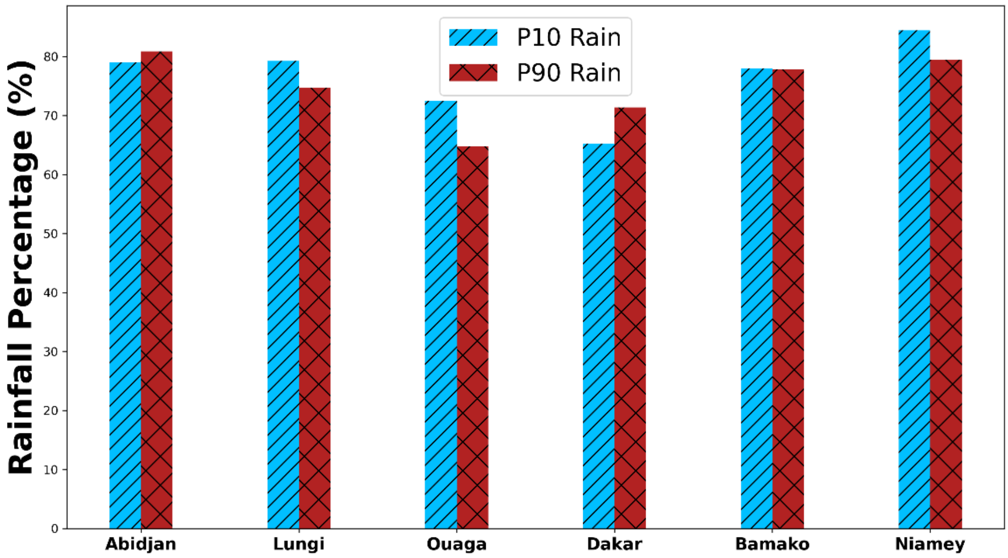

Figure 4.39: light precipitation frequency under sea salt C-case and P-case

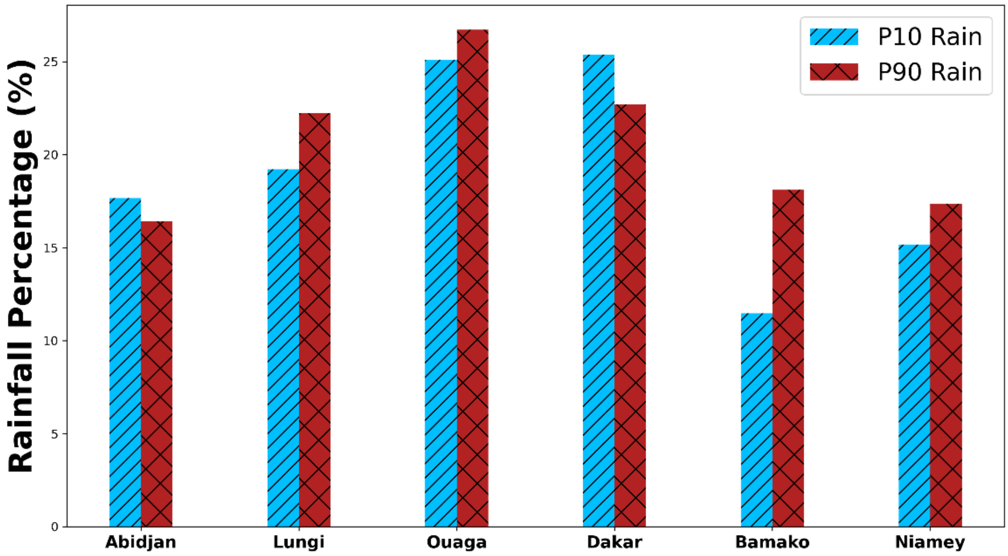

Figure 4.40: moderate precipitation frequency under dust C-case and P-case

which can lead to the formation of smaller cloud droplets and a decrease in precipitation efficiency.

4.7.7 Black Carbon Effects on Moderate Rain Frequency

Figure 4.41 shows that black carbon pollution on moderate rain frequency varies across different cities in the region. In Bamako and Ouagadougou, the effect of black carbon pollution is significant, leading to an increase in moderate rain frequency by 5.00% and 6.06%, respectively. In Abidjan, Dakar, and Niamey, the effect is less pronounced, with a slight increase in moderate rain frequency of 0.64%, 0.71%, and 2.05%, respectively. However, in Lungi, black carbon pollution appears to have a negative effect on moderate rain frequency, leading to a slight decrease of -2.99%.

4.7.8 Organic Matter Effects on Moderate Rain Frequency

Organic matter aerosols can have significant impacts on moderate precipitation in West Africa. Moderate precipitation events are typically associated with convective storms, which are important for agriculture and water resources in the region. Figure 4.42 shows that organic matter pollution on moderate rain frequency also varies across different cities in the region. In Bamako and Ouagadougou, the effect of organic matter pollution is significant, leading to an increase in moderate rain frequency by 4.63% and 4.21%, respectively. In Abidjan, Dakar, and Niamey, the effect is less pronounced, with a slight increase in moderate rain frequency of 0.65%, 0.67%, and 2.64%, respectively. However, in Lungi, organic matter pollution appears to have a negative effect on moderate rain frequency, leading to a slight decrease of -2.16%.

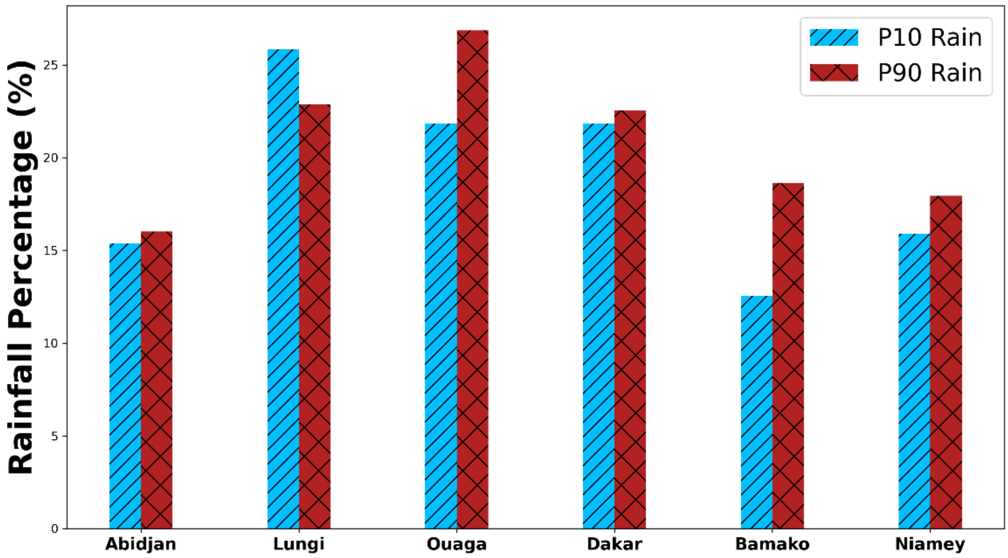

Figure 4.41: moderate precipitation frequency under black carbon C-case and P-case

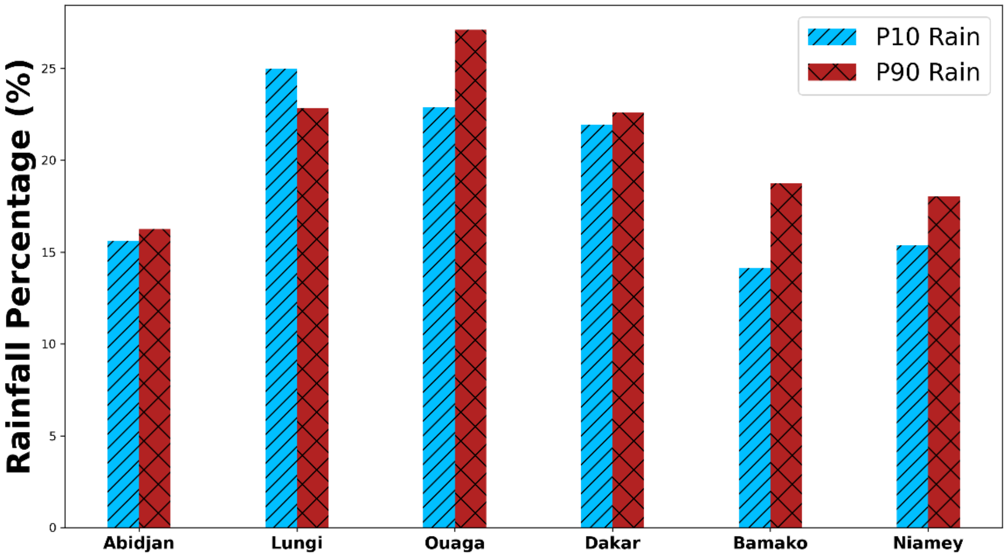

Figure 4.42: moderate precipitation frequency under organic matter C-case and P-case

4.7.9 Sulphate Effects on Moderate Rain Frequency

Sulphate aerosols can have significant impacts on moderate precipitation in West Africa. Sulphate aerosols can affect precipitation patterns by altering the microphysical properties of clouds. Figure 4.43 shows that the impact of sulphate pollution on moderate rain frequency also varies across different cities in the region. In Bamako, the effect of sulphate pollution is significant, leading to an increase in moderate rain frequency by 4.88%. In Ouagadougou and Niamey, the effect is less pronounced, with a slight increase in moderate rain frequency of 2.77% and 2.48%, respectively. However, in Dakar, sulphate pollution appears to have a negative effect on moderate rain frequency, leading to a slight decrease of -1.58%. In Lungi, the effect of sulphate pollution on moderate rain frequency is even more significant, with a decrease of about -4.85%.

4.7.10 Sea Salt Effects on Moderate Rain Frequency

Figure 4.44 shows that the impact of sea salt pollution on moderate rain frequency varies across different cities in the region. In Lungi, the effect of sea salt pollution is significant, leading to an increase in moderate rain frequency by 4.55%. In Abidjan, Bamako, and Niamey, the effect is less pronounced, with a slight increase in moderate rain frequency of 2.81%, 0.77%, and 3.16%, respectively. On the other hand, the effect of sea salt pollution on moderate rain frequency in Ouagadougou and Dakar appears to be more significant, with a decrease of about -4.48% and -7.01%, respectively.

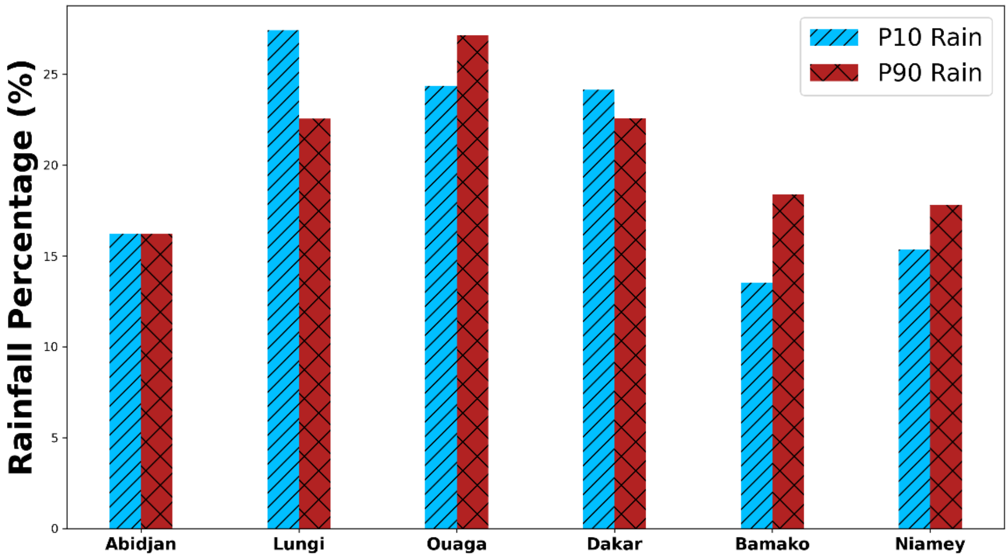

Figure 4.43: moderate precipitation frequency under sulphate C-case and P-case

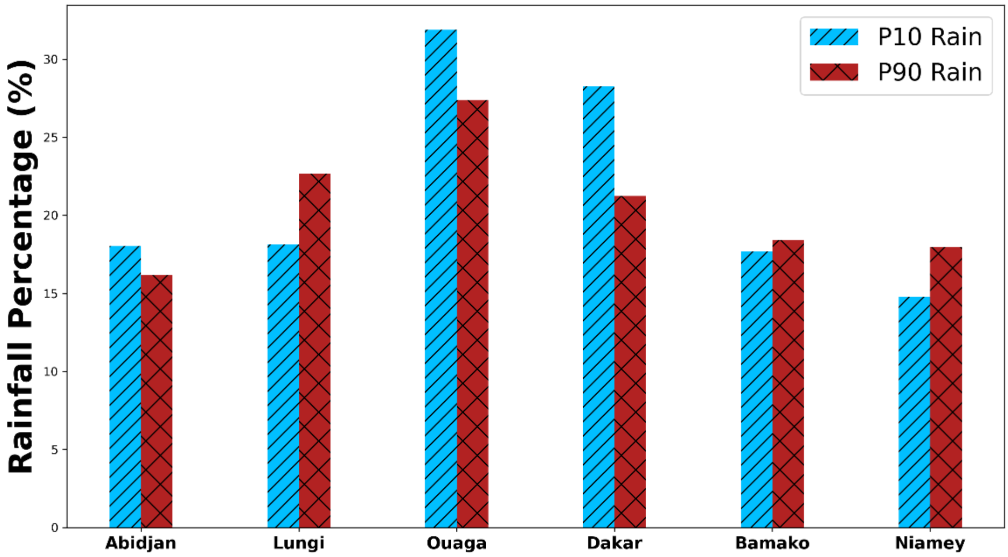

Figure 4.44: moderate precipitation frequency under sea salt C-case and P-case

4.7.11 Dust Pollution Effects on Heavy Rain Frequency

Figure 4.45 depict heavy rain event variation from the C-case to the P-case varies across different cities in the region. In Ouagadougou, the effect of dust pollution is significant, leading to an increase in heavy rain frequency by 4.59%. In Abidjan, Lungi, Dakar, Bamako, and Niamey, the effect is less pronounced, with a slight increase in heavy rain frequency of 0.70%, 0.39%, 0.90%, 2.03%, and 0.61%, respectively. It is worth noting that heavy rain events can have significant impacts on the environment and human infrastructure, such as causing floods and landslides. Therefore, understanding the factors that influence the frequency and intensity of heavy rain events is crucial for developing effective strategies for disaster risk reduction and management. Rainfall rates comprised between 10 mm/h to less than 50 mm/h are considered heavy rain.

Dust particles play an important role in the hydrological cycle over West Africa, as they act as cloud condensation nuclei, affecting the amount of precipitation that occurs in the region. The effects of dust on precipitation are complex and are dependent on the dust particle size and composition, as well as the meteorological conditions in the region. The dust particles over West Africa are mainly composed of silicates, with a small fraction of carbonaceous material and other minerals. The particles range in size from 0.1 to 10 micrometres in diameter, with most of the particles being between 0.2 and 1 micrometre in diameter. The dust particles act as cloud condensation nuclei, allowing for the formation of larger cloud droplets, which can then coalesce into larger drops that are more likely to reach the ground as precipitation. The meteorological conditions in West Africa also play an important role in the effects of dust on precipitation. The amount of dust in the atmosphere is dependent on the strength of the winds, and the time of year, as dust levels tend to be higher in the dry season.

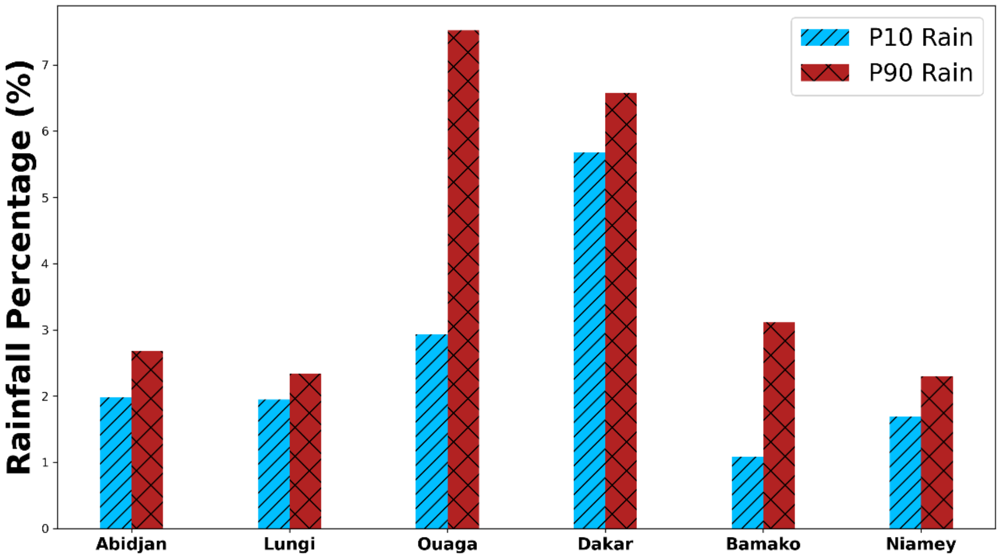

Figure 4.45: moderate precipitation frequency under dust C-case and P-case

4.7.12 Black Carbon Effects on Heavy Rain Frequency

Black carbon aerosols can have complex effects on heavy precipitation in West Africa. Black carbon aerosols can affect precipitation patterns by altering the microphysical properties of clouds. Figure 4.46 shows that in Ouagadougou, the increase in heavy rain frequency due to black carbon pollution is significant at 4.28%. This suggests that black carbon pollution may play a significant role in influencing weather patterns in this region. In Abidjan, Bamako, and Niamey, the increase in heavy rain frequency due to black carbon pollution is relatively small, at about 1.00%, 0.37%, and 1.79%, respectively. Although the increase is not as significant as in Ouagadougou, it still suggests that black carbon pollution may have some impact on the weather patterns in these regions. In Lungi, black carbon pollution leads to a slight decrease in heavy rain by about -1.42%. This suggests that black carbon pollution may actually have a negative impact on the weather patterns in this region. It's unclear what the effect of black carbon pollution is on heavy rain in Dakar.

4.7.13 Organic Matter Effects on Heavy Rain Frequency

Figure 4.47 shows the impacts of organic matter pollution on heavy rain in different regions. In Abidjan, organic matter pollution leads to a slight increase in heavy rain by about 0.48%, which is a relatively small effect compared to other regions. In Ouagadougou, organic matter pollution leads to a slightly higher increase in heavy rain, at 1.30%. This suggests that organic matter pollution may have a more significant impact on weather patterns in this region. Similarly, in Bamako and Niamey, organic matter pollution leads to increases in heavy rain by about 0.87% and 1.51%, respectively. These effects are also relatively small but suggest that organic matter pollution may be a factor in influencing weather patterns in these regions. In contrast, in Lungi, organic matter pollution leads to a slight decrease in heavy rain by about -1.17%. This is interesting because organic matter is typically associated with increased moisture and

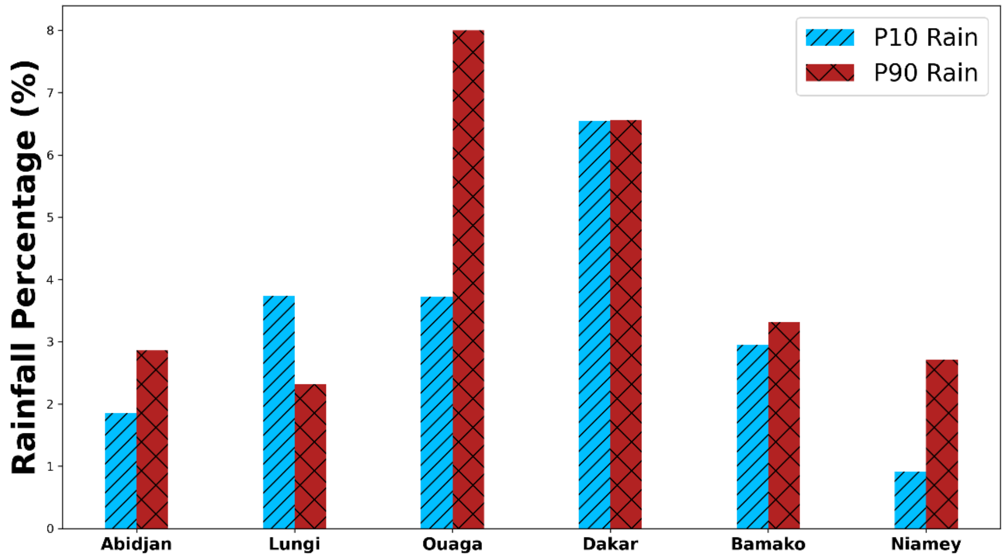

Figure 4.46: heavy precipitation frequency under black carbon C-case and P-case

precipitation, so this suggests that other factors may be at play in Lungi. In Dakar, the effect of organic matter pollution on heavy rain is minimal, with a slight decrease of only -0.07%. This suggests that organic matter pollution may not have a significant impact on weather patterns in this region.

4.7.14 Sulphate Effects on Heavy Rain Frequency

Sulphate aerosols can have complex effects on heavy precipitation in West Africa. Figure 4.48 shows the impacts of sulphate pollution on heavy rain in different regions. In Ouagadougou, Dakar, Bamako, and Niamey, sulphate pollution leads to a slight increase in heavy rain, with the largest increase being in Ouagadougou at 2.93%. This suggests that sulphate pollution may be a factor in increasing heavy rain in these regions. However, in Abidjan and Lungi, sulphate pollution leads to a slight decrease in heavy rain, with the largest decrease being in Lungi at -0.72%. This suggests that sulphate pollution may have a negative impact on heavy rain in these regions. It's worth noting that the magnitude of the effects of sulphate pollution on heavy rain varies across the different regions, with the largest effects seen in Ouagadougou, Dakar, and Bamako, and smaller effects seen in Niamey, Abidjan, and Lungi.

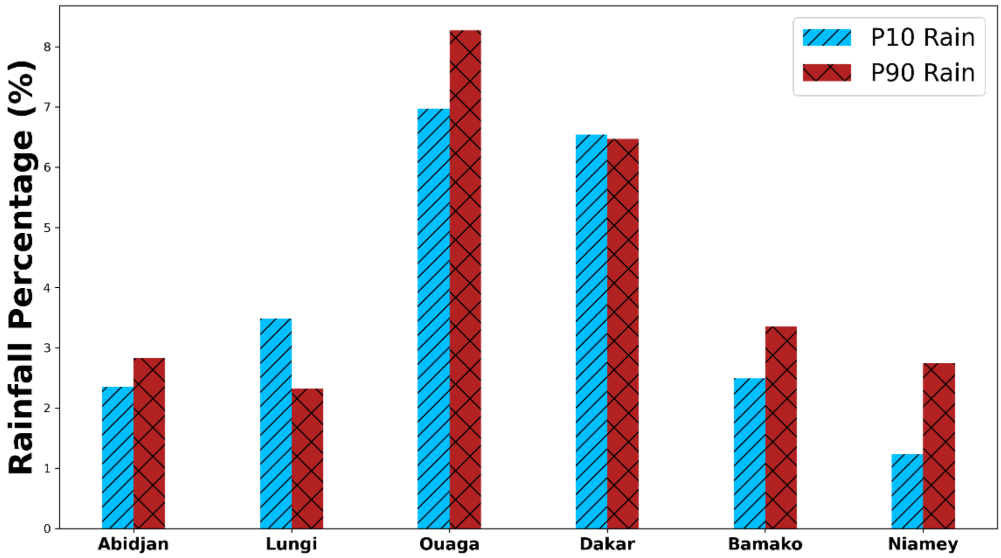

Figure 4.47: heavy precipitation frequency under organic matter C-case and P-case

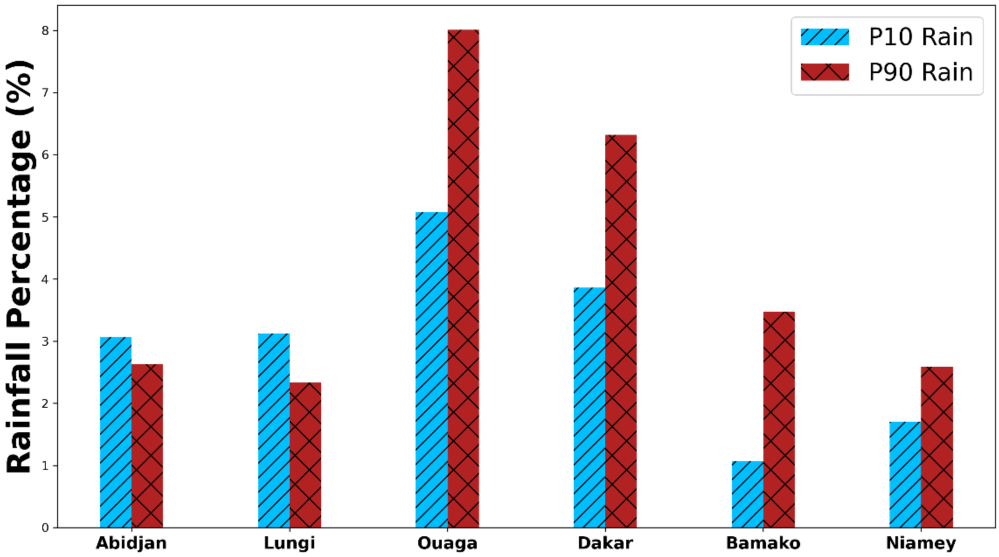

Figure 4.48: heavy precipitation frequency under sulphate C-case and P-case

4.7.15 Sea Salt Effects on Heavy Rain Frequency

Sea salt aerosols can have complex effects on heavy precipitation in West Africa. Figure 4.49 shows the impact of sea salt pollution on heavy rain in different regions. It's interesting to note that the effects of sea salt pollution on heavy rainfall are not consistent across all regions. In Lungi, Dakar, and Niamey, sea salt pollution leads to a slight increase in heavy rain, ranging from 0.13% to 2.04%. This suggests that sea salt may play a role in increasing heavy rainfall in these regions. However, in Abidjan, Ouagadougou, and Bamako, sea salt pollution leads to a slight decrease in heavy rain, ranging from -0.80% to -3.33%. This suggests that sea salt may have a negative impact on heavy rainfall in these regions, or that other factors may be at play. It's important to note that the effects of sea salt pollution on heavy rainfall are generally small, compared to the effects of other types of pollution such as sulphate and black carbon pollution.

Results suggest that aerosol pollution mostly decreases light rain and increases moderate and heavy rain over West Africa. Some studies have indicated that increased aerosol pollution tends to suppress light rainfall while enhancing moderate and heavy rainfall. This phenomenon is often referred to as the "aerosol invigoration effect" on rainfall. For example, Rosenfeld *et al.* (2008) conducted research in the Amazon rainforest and found that increased aerosol concentrations suppressed light rainfall but enhanced moderate and heavy rainfall. Another study by Lee *et al.* (2009) investigated the effects of aerosols on rainfall in East Asia and observed a similar pattern. They found that aerosol pollution reduced light rainfall events but increased the occurrence of moderate and heavy rainfall. Seigel *et al.* (2012) conducted research in Southeast Asia and found that aerosols tended to suppress light rain while enhancing moderate to heavy rainfall. They observed a shift in rainfall patterns toward more intense events due to the influence of aerosols. Another study by Fan *et al.* (2013) investigated the impact of aerosol pollution on rainfall in China and found that while light rainfall decreased with increased aerosol pollution, moderate to heavy rainfall increased. Li *et al.* (2016) found that increased aerosol pollution in eastern China was associated with a decrease in light rainfall and an increase in moderate and heavy rainfall.

4.8 RAIN FREQUENCY ANOMALY

High aerosol (dust, black carbon, organic matter and sulphate) concentration over West Africa decreases rain frequency (Dakar, Bamako, Ouagadougou, Liberia, Sierra Leone, Abidjan, Accra, Lomé and Cotonou) over 12 stations used in this study. Meaning that high concentrations of aerosols such as dust, black carbon, organic matter, and sulphate have led to a decrease in rain frequency in most of the stations studied. This suggests that these types of aerosols may be contributing to drought conditions in some areas of West Africa. However, it is interesting to note that high concentrations of sea salt appear to increase rain frequency over all 12 stations studied. This suggests that sea salt may have a positive impact on rain frequency in this region. It is also noteworthy that some stations, such as Niamey and Conakry, show an increase in rain frequency with high concentrations of black carbon and organic matter. This suggests that the impact of aerosols on rain frequency may be complex and depend on a variety of factors such as cloud types, Relative Humidity (RH), wind shear and buoyancy (Figure 4.50).

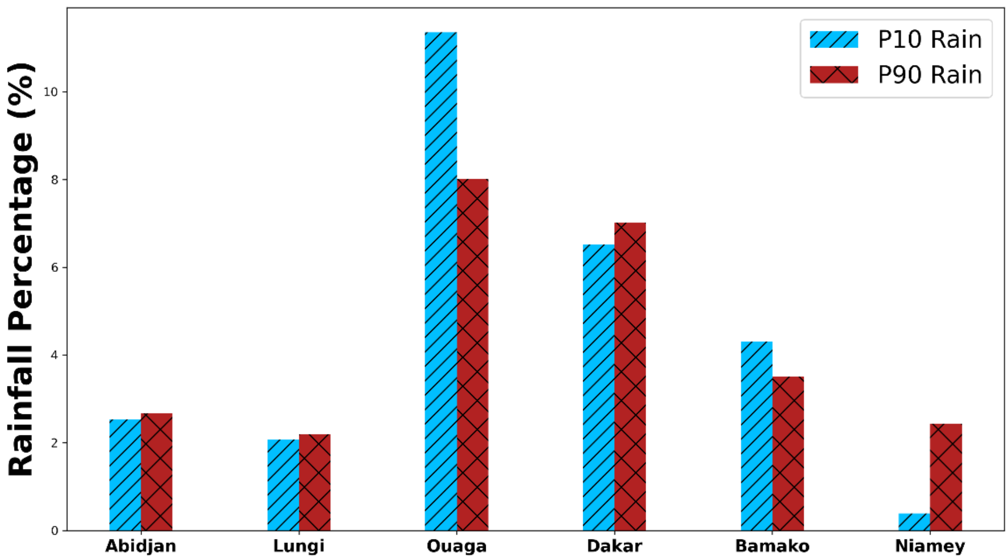

Figure 4.49: heavy precipitation frequency under sea salt C-case and P-case

Cloud types play a significant role in determining the effects of aerosols on precipitation. The interaction between aerosols and clouds can vary depending on the type of cloud and its microphysical characteristics. Here are some ways cloud types can affect aerosol effects on precipitation:

Convective clouds, such as cumulus clouds, are characterized by strong updrafts and vertical development. These clouds are more responsive to aerosol effects on precipitation. Aerosols can act as cloud condensation nuclei (CCN) or ice nuclei (IN) and influence the cloud microphysics. The presence of aerosols can enhance the formation of smaller cloud droplets, which may inhibit coalescence and precipitation processes. However, in certain conditions, aerosols can also promote the formation of larger cloud droplets and ice crystals, leading to more intense precipitation.

Stratiform clouds, such as nimbostratus or altostratus clouds, have a more uniform and widespread structure. Aerosol effects on precipitation in stratiform clouds are mainly associated with the suppression of precipitation. Aerosols can contribute to the stabilization of stratiform cloud layers by reducing the droplet size and suppressing the collision and coalescence processes necessary for precipitation formation. This can result in longer-lasting and more extensive cloud cover with reduced precipitation efficiency (Koren *et al.* 2014; Rosenfeld *et al.* 2008).

Relative humidity plays a critical role in the activation and growth of aerosol particles into cloud droplets or ice crystals. Higher relative humidity conditions promote the activation of aerosols as cloud condensation nuclei (CCN) or ice nuclei (IN), leading to the formation of cloud droplets or ice crystals. This can enhance the potential for precipitation formation (Khain *et al.* 2008). Relative humidity can influence the competition among different aerosol particles to act as CCN. Higher relative humidity conditions tend to favour the activation of a larger number of aerosol particles, which can lead to an increase in cloud droplet concentrations. This can affect cloud microphysics and the subsequent development of precipitation (Fan *et al.* 2016). Relative humidity influences the collision and coalescence processes that contribute to the growth of cloud droplets and the formation of precipitation. Higher relative humidity can facilitate the collision and coalescence of cloud droplets, allowing for more efficient precipitation formation. Conversely, lower relative humidity conditions can result in smaller cloud droplets and reduced collision and coalescence rates, potentially inhibiting precipitation formation (Zhang *et al.*, 2019).

Wind shear can enhance or suppress the formation and intensity of convective updrafts and downdrafts within clouds. Strong wind shear can tilt the updrafts, allowing for better separation of updraft and downdraft regions. This separation can lead to improved precipitation efficiency by reducing the entrainment of dry air into the updraft and promoting the growth of precipitation particles. Conversely, weaker wind shear may result in less efficient separation and weaker updrafts, potentially reducing precipitation formation (Fan *et al.* 2016). Wind shear influences the transport and advection of moisture within the atmosphere. Vertical wind shear can enhance the convergence of moist air at low levels, promoting the uplift and condensation of water vapour. This can contribute to the development and intensification of clouds, which can impact aerosol activation and subsequent precipitation processes (Rotunno *et al.* 1988). Wind shear affects the vertical velocity and turbulence within clouds. Strong wind shear can induce greater vertical motion, resulting in enhanced mixing and interaction between aerosols and cloud particles. This can impact the activation of aerosols as cloud condensation nuclei (CCN) or ice nuclei (IN) and influence precipitation formation (Feng *et al.* 2019). Wind shear affects the horizontal advection of moisture, which can influence cloud water content. Variations in cloud water content can impact the activation of aerosols and subsequent precipitation processes (Di Giuseppe *et al.* 2019).

Buoyancy plays a crucial role in determining the strength and intensity of updrafts within clouds. Strong buoyancy, resulting from warm and moist air parcels, promotes stronger updrafts. Enhanced updrafts can enhance the activation of aerosols as cloud condensation nuclei (CCN) or ice nuclei (IN), leading to increased cloud droplet or ice crystal concentrations and potentially influencing precipitation processes (Storer *et al.* 2020). Buoyancy influences the vertical growth and development of clouds. When an air parcel is buoyant, it rises and expands, which promotes cloud formation and vertical extent. This can impact the activation of aerosols and subsequent precipitation processes within the cloud system (Khain *et al.* 2004). Buoyancy affects the condensation and coalescence processes within clouds. In buoyant conditions, air parcels ascend, and as they rise, they cool. This cooling promotes the condensation of water vapor onto aerosol particles, leading to cloud droplet formation. Buoyancy also affects the collision and coalescence of cloud droplets, which are essential for the formation of precipitation particles. Buoyancy instabilities within clouds, such as convective overturning or turbulence, can influence aerosol effects on precipitation. These instabilities can enhance vertical mixing and interaction between aerosols and cloud particles, affecting the activation of aerosols and subsequent precipitation processes (Fan *et al.* 2010). Buoyancy-driven entrainment and mixing processes can impact aerosol effects on precipitation. When less buoyant air or drier air entrains into a cloud, it can dilute the cloud droplets and impact the precipitation efficiency. Conversely, buoyant air parcels can enhance vertical mixing and entrainment of moisture, potentially influencing the development and intensity of precipitation (Grabowski *et al.* 2003).

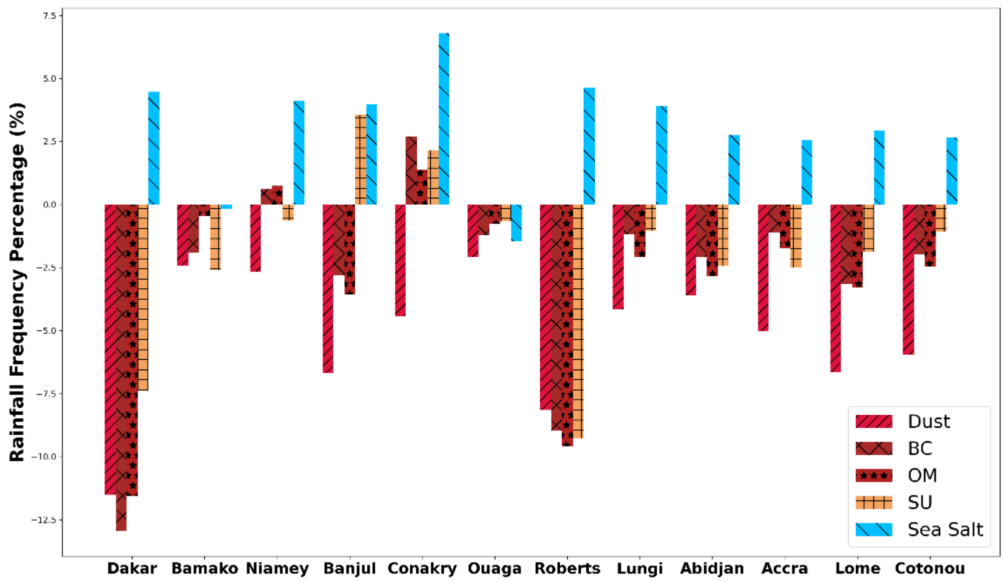

Figure 4.50: Rain frequency difference of the C-case and P-case over West Africa. BC means Black Carbon, OM means Organic Matter and SU means Sulphate

4.8.1 Light rain frequency anomaly

High dust concentration leads to a decrease in light rain frequency over West Africa except in stations such as Dakar, Liberia and Abidjan. This suggests that dust may be a contributing factor to the dry conditions in some areas of West Africa. Sea salt pollution also has the same impact on the light rain frequency over the region except in Dakar and Cotonou where it has a different effect. This suggests that sea salt may also be contributing to the dry conditions in some parts of West Africa. The impact of other aerosols such as black carbon, organic matter, and sulphate on light rain frequency appears to be complex and dependent on various factors such as relative humidity. For example, high concentrations of these aerosols generally lead to a decrease in light rain events over the Sahel (low relative humidity), except in Conakry where high sulphate concentration increases them. Meanwhile, over the Guinea region (high relative humidity), these aerosols generally increase light rain events, except in Abidjan where black carbon and organic matter pollution decreases light rain frequency (figure 4.51).

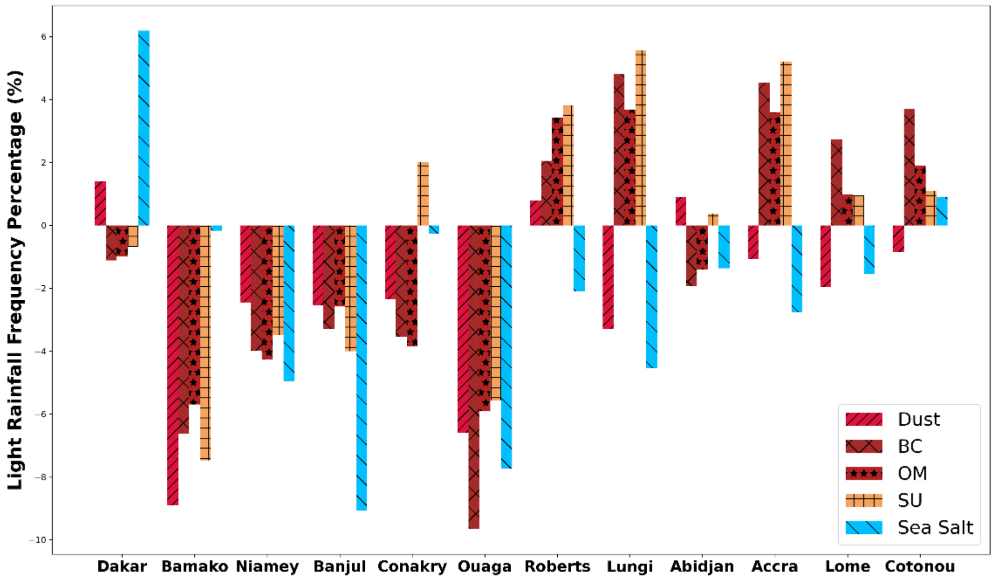

Figure 4.51: Light rain frequency difference of the C-case and P-case over West Africa

4.8.2 Moderate rain frequency anomaly

It is interesting to note that an increase in dust concentration can actually enhance moderate rain events at most stations, with the exception of Lomé. This suggests that the impact of dust on rainfall may depend on the intensity of the rainfall events, with higher concentrations potentially promoting more moderate rain events. Similarly, it is notable that sea salt pollution appears to enhance moderate rain events over most of the region, with the exception of Dakar, Ouagadougou, and Cotonou. This suggests that sea salt may play a role in promoting more moderate rainfall in some parts of West Africa. The impact of other aerosols such as black carbon, organic matter, and sulphate on moderate rain events also appears to be complex and dependent on various factors such as relative humidity. For example, high concentrations of these aerosols generally increase moderate rain events over the Sahel, except in Dakar and Conakry where high sulphate concentration decreases them. Meanwhile, over the Guinea region, these aerosols generally decrease moderate rain events, except in Abidjan where black carbon and organic matter pollution increase moderate rain frequency (figure 4.52).

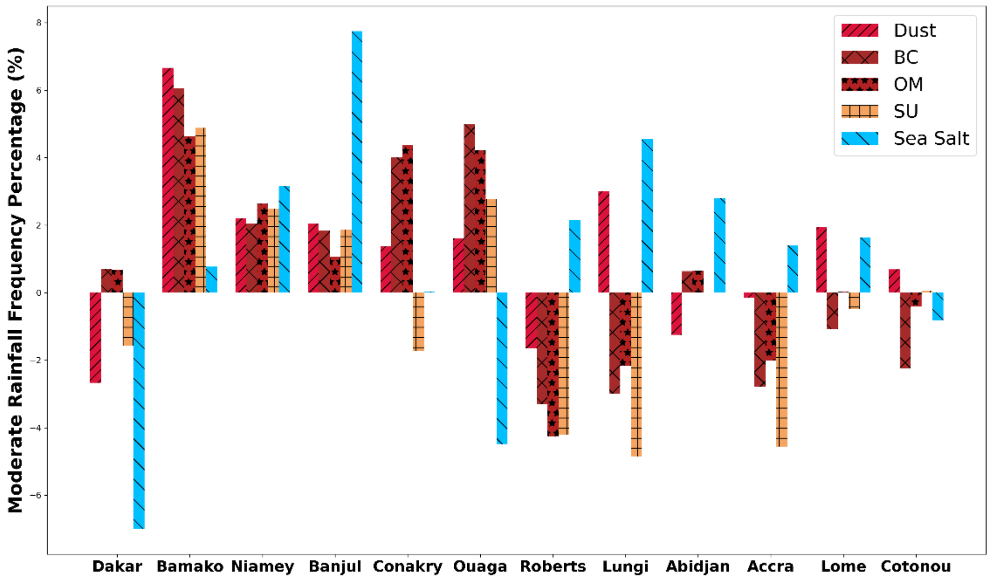

Figure 4.52: Moderate rain frequency difference of the C-case and P-case over West Africa

4.8.3 Heavy Rain Frequency Anomaly

Results provided suggest that dust concentration generally enhances heavy rain events across various stations in the region except for Dakar, Liberia, and Abidjan. However, the effects of high sea salt concentration on heavy rain events are not clear as it enhances them in some stations over the Sahel (Dakar, Niamey, Banjul, Liberia, Sierra Leone and Accra), and Guinea but reduces them in others (Bamako, Ouagadougou, Abidjan, Lomé and Cotonou). Furthermore, high concentrations of black carbon, organic matter, and sulphate generally increase heavy rain events over the Sahel region except in Conakry. However, these pollutants decreased heavy rain events over the Guinea region, except in Liberia, where black carbon, organic matter, and sulphate, and in Abidjan, where black carbon and organic matter pollution enhance heavy rain frequency. It is worth noting that the relationships between these different types of atmospheric particles and heavy rain events are complex and may depend on various factors such as the type of particles present, the concentration levels, and the specific location of the stations in question (figure 4.53).

This finding is consistent with the results presented in the statement regarding the impact of aerosol concentrations on rain frequency over West Africa. Koren *et al.* (2008) examined the impact of smoke particles on clouds over the Amazon. The study found that smoke particles could both invigorate and inhibit cloud formation, depending on the size and concentration of the particles. This finding supports the idea that the impact of aerosols on rainfall events can vary depending on the specific characteristics of the aerosol particles. A study by Chen *et al.* (2016) examined the impact of sea salt aerosols on rainfall in the North Pacific. The study found that sea salt particles acted as cloud condensation nuclei, promoting the formation of rain droplets. This finding supports the idea presented in the statement that high sea salt concentrations can increase rain frequency. A study by Chen *et al.* (2018) found that dust aerosols could enhance moderate rainfall events by increasing the number of cloud condensation nuclei, which promotes cloud formation and precipitation. Another study by Lee *et al.* (2018) found that sea salt particles could enhance rainfall by acting as cloud condensation nuclei and promoting cloud development. Additionally, the study found that the impact of aerosols on moderate rain events varied depending on the region.

A study by Liu *et al.* (2011) found that dust aerosols could reduce rainfall by inhibiting cloud formation and precipitation. Another study by Rosenfeld *et al.* (2013) found that black carbon particles could reduce precipitation efficiency by suppressing the coalescence of cloud droplets. Another study by Hsu *et al.* (2012) examined the impact of aerosols on rainfall in East Asia. The study found that high concentrations of aerosols, particularly sulfate and black carbon, were associated with decreased rainfall. A study by Rosenfeld *et al.* (2008) has highlighted the impact of aerosols on precipitation patterns. It found that aerosols can reduce the size and lifetime of clouds, leading to a decrease in precipitation. Another study by Koren *et al.* (2010) showed that aerosols can suppress rainfall over continental regions by inhibiting the formation of clouds and reducing the amount of moisture available for precipitation.

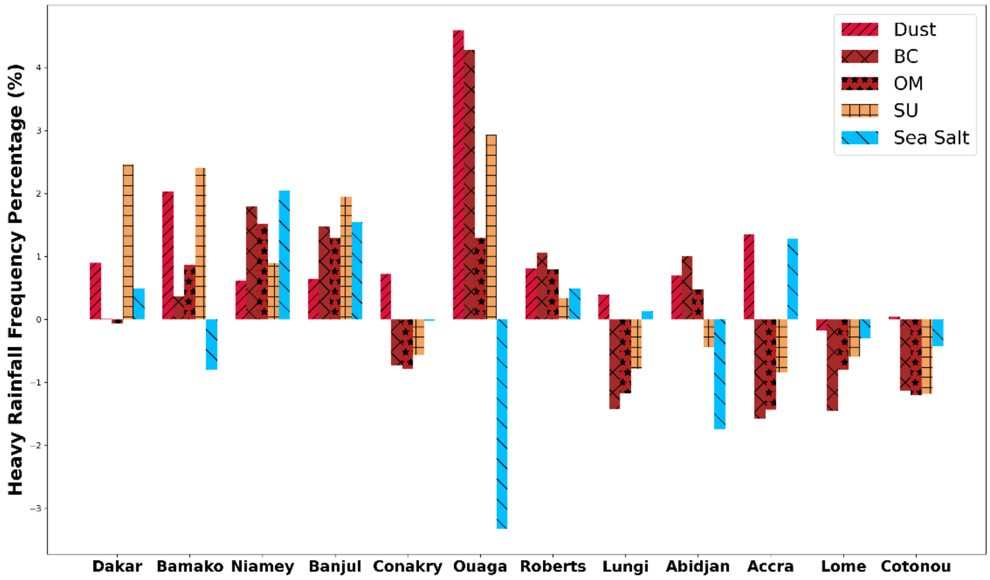

Figure 4.53: Heavy rain frequency difference of the C-case and P-case over West Africa

The tables present rain events percentage, three hourly time steps from 2003 to 2019 and rain events percentage of the clean (C-case) and polluted (P-case) cases of (4.2) dust effects on rain; (4.3) black carbon effects on rain; (4.4) organic matter effects on rain; (4.5) sulphate effects on rain; and (4.6) sea salt effects on rain for twelve (12) stations over West Africa.

Table 4.2*: rain events percentage of the clean (C-case) and polluted (P-case) cases of dust*

STATIONS	P10 RAIN EVENTS	P10 EVENTS	P10 (%)	P90 RAIN EVENTS	P90 EVENTS	P90 (%)
DAKAR	264	1252	21.09	1079	11260	9.58
BAMAKO	279	2081	13.41	2057	18727	10.98
NIAMEY	415	2118	19.59	3171	18727	16.93
BANJUL	553	2969	18.63	3129	26193	11.95
CONAKRY	410	2563	16.00	2439	22400	10.89
OUAGADOUGOU	239	2911	8.21	1609	26194	6.14
ROBERTS FIELD	808	3757	21.51	4498	33660	13.36
LUNGI	411	2509	16.38	2735	22399	12.21
ABIDJAN	504	4180	12.06	3168	37454	8.46
ACCRA	538	3336	16.13	3335	29990	11.12
LOME	531	3343	15.88	2759	29865	9.24
COTONOU	481	2898	16.60	2778	26071	10.66

__Table 4.3__: rain events percentage of the clean (C-case) and polluted (P-case) cases of black carbon

STATIONS	P10 RAIN EVENTS	P10 EVENTS	P10 (%)	P90 RAIN EVENTS	P90 EVENTS	P90 (%)
DAKAR	275	1252	21.96	1052	11260	9.34
BAMAKO	271	2082	13.02	2079	18727	11.10
NIAMEY	327	2081	15.71	3058	18727	16.33
BANJUL	406	2911	13.95	2918	26193	11.14
CONAKRY	190	2489	7.63	2317	22399	10.34
OUAGADOUGOU	215	2916	7.37	1612	26193	6.15
ROBERTS FIELD	809	3746	21.60	4252	33660	12.63
LUNGI	321	2489	12.90	2628	22399	11.73
ABIDJAN	429	4163	10.31	3077	37454	8.22
ACCRA	374	3332	11.22	3036	29988	10.12
LOME	377	3319	11.36	2449	29865	8.20
COTONOU	339	2897	11.70	2536	26071	9.73

Table 4.4: *rain events percentage of the clean (C-case) and polluted (P-case) cases of organic matter*

STATIONS	P10 RAIN EVENTS	P10 EVENTS	P10 (%)	P90 RAIN EVENTS	P90 EVENTS	P90 (%)
DAKAR	260	1252	20.77	1036	11260	9.2
BAMAKO	241	2082	11.58	2086	18727	11.14
NIAMEY	325	2081	15.62	3063	18727	16.36
BANJUL	438	2911	15.05	3007	26193	11.48
CONAKRY	224	2489	9.00	2327	22399	10.39
OUAGADOUGOU	201	2912	6.90	1609	26193	6.14
ROBERTS FIELD	846	3741	22.61	4381	33660	13.02
LUNGI	344	2489	13.82	2631	22400	11.75
ABIDJAN	468	4162	11.24	3145	37454	8.40
ACCRA	402	3332	12.06	3094	29988	10.32
LOME	393	3321	11.83	2549	29865	8.54
COTONOU	358	2898	12.35	2576	26071	9.88

Table 4.5*: rain events percentage of the clean (C-case) and polluted (P-case) cases of sulphate*

STATIONS	P10 RAIN EVENTS	P10 EVENTS	P10 (%)	P90 RAIN EVENTS	P90 EVENTS	P90 (%)
DAKAR	207	1253	16.52	1028	11260	9.13
BAMAKO	281	2081	13.5	2044	18727	10.91
NIAMEY	352	2082	16.91	3047	18727	16.27
BANJUL	220	2911	7.56	2933	26193	11.20
CONAKRY	222	2489	8.92	2483	22400	11.08
OUAGADOUGOU	197	2911	6.77	1599	26193	6.10
ROBERTS FIELD	847	3740	22.65	4507	33660	13.39
LUNGI	321	2489	12.90	2655	22399	11.85
ABIDJAN	456	4162	10.96	3190	37455	8.52
ACCRA	445	3334	13.35	3254	29989	10.85
LOME	362	3323	10.89	2690	29865	9.01
COTONOU	329	2902	11.34	2674	26072	10.26

Table 4.6*: rain events percentage of the clean (C-case) and polluted (P-case) cases of sea salt*

STATIONS	P10 RAIN EVENTS	P10 EVENTS	P10 (%)	P90 RAIN EVENTS	P90 EVENTS	P90 (%)
DAKAR	46	1266	3.63	913	11260	8.11
BAMAKO	232	2091	11.1	2050	18732	10.94
NIAMEY	257	2119	12.13	3041	18730	16.24
BANJUL	218	2915	7.48	3005	26193	11.47
CONAKRY	102	2541	4.01	2421	22400	10.81
OUAGADOUGOU	229	2961	7.73	1646	26195	6.28
ROBERTS FIELD	277	3746	7.39	4043	33661	12.01
LUNGI	193	2517	7.67	2593	22399	11.58
ABIDJAN	225	4206	5.35	3035	37455	8.10
ACCRA	256	3428	7.47	3004	29988	10.02
LOME	199	3348	5.94	2428	29865	8.13
COTONOU	204	2906	7.02	2527	26071	9.69

4.9 PRECIPITATION TIME RESPONSE TO AEROSOL

The analysis suggests that aerosols have a significant impact on precipitation, and the response time depends on the type and concentration of the aerosols. In Abidjan, the response time for dust, sulphate, and sea salt is one day, while it is three days for black carbon and organic matter (Table 4.7). In Lungi station, the response time for dust, black carbon, organic matter, and sulphate is three days, while it is one day for sea salt (Table 4.9). In Ouagadougou, the response time for black carbon, organic matter, sulphate, and sea salt is some hours, but it is one day for dust (Table 4.8). In Niamey, the response time for dust, black carbon, organic matter, and sulphate is three days, while it is some hours for sea salt (Table 4.10). In Dakar, the response time for dust, black carbon, and organic matter is some hours, but it is one day for sulphate and sea salt ((Table 4.11)). It is important to note that the response time may vary depending on the location and the meteorological conditions.

The interaction between aerosols and clouds occurs over different time scales. Aerosols need sufficient time to act as cloud condensation nuclei (CCN) or ice nuclei (IN) and influence cloud microphysics, which can subsequently impact precipitation formation. The time required for aerosols to activate and interact with cloud processes can vary depending on aerosol properties, cloud characteristics, and environmental conditions (Stevens *et al.* 2016, Fan *et al.* 2013).

Cloud development and lifetime play a significant role in the precipitation time response to aerosols. It takes time for clouds to form, grow, and reach a sufficient level of maturity for precipitation to occur. Aerosols can influence cloud development and persistence, affecting the time it takes for precipitation to form within the cloud system (Rauber *et al.* 2007, Rosenfeld *et al.* 2018). Aerosols can affect cloud dynamics and microphysics, which, in turn, influence precipitation processes. Aerosols can impact cloud droplet size distribution, cloud particle growth, and the collision and coalescence of particles, all of which contribute to the formation of precipitation. The time response of precipitation to aerosols is linked to these complex processes and the time it takes for them to occur (Morrison *et al.* 2005, Rosenfeld *et al.* 2008).

The atmospheric stability and moisture conditions also influence the time response of precipitation to aerosols. Stable atmospheric conditions may inhibit or delay precipitation formation, while unstable conditions can promote faster and more intense precipitation development. Aerosols can interact with atmospheric stability and moisture content, modulating the time it takes for precipitation to occur (Rotunno *et al.* 2016, Tao *et al.* 2019). The time response of precipitation to aerosols can vary depending on regional and local climate characteristics. Factors such as the presence of specific weather systems, geographic location, prevailing wind patterns, and seasonal variations can all influence the time it takes for aerosol-induced changes in precipitation to manifest (Koren *et al.* 2014, Andreae *et al.* 2004).

Table 4.7: *Correlation of different precipitation time responses to the aerosol of Abidjan*

Aerosols	**0-day lag**	**1-day lag**	**3-day lag**	**5-day lag**
Ultrafine dust	-0.031	-0.042	-0.042	-0.035
Fine dust	-0.030	-0.041	-0.041	-0.034
Coarse dust	-0.011	-0.029	-0.028	-0.016
Black carbon	0.001	0.005	0.054	0.011
Organic matter	-0.023	-0.020	0.023	-0.015
Sulphate	-0.017	-0.031	-0.017	-0.014
Ultrafine salt	0.014	0.020	0.015	0.011
Fine salt	0.032	0.041	0.034	0.029
Coarse salt	0.014	0.044	0.023	0.017

***Table 4.8**: Correlation of different precipitation time responses to the aerosol of Ouagadougou*

Aerosols	0-day lag	1-day lag	3-days lag	5-days lag
Ultrafine dust	-0.017	-0.027	-0.026	-0.008
Fine dust	-0.016	-0.026	-0.026	-0.006
Coarse dust	-0.001	-0.017	-0.019	0.009
Black carbon	-0.026	-0.024	0.010	-0.021
Organic matter	-0.029	-0.029	-0.011	-0.029
Sulphate	-0.013	-0.006	0.005	0.008
Ultrafine salt	-0.045	-0.035	-0.022	-0.036
Fine salt	-0.042	-0.030	-0.015	-0.031
Coarse salt	-0.024	-0.014	-0.013	-0.016

Table 4.9: *Correlation of different precipitation time responses to the aerosol of Lungi*

Aerosols	**0-day lag**	**1-day lag**	**3-days lag**	**5-days lag**
Ultrafine dust	-0.031	-0.036	-0.045	-0.028
Fine dust	-0.028	-0.034	-0.043	-0.026
Coarse dust	-0.010	-0.016	-0.027	-0.009
Black carbon	0.012	0.028	0.029	0.012
Organic matter	0.004	0.018	0.020	0.004
Sulphate	0.005	0.010	0.017	0.010
Ultrafine salt	0.054	0.067	0.050	0.052
Fine salt	0.055	0.068	0.052	0.054
Coarse salt	0.038	0.046	0.019	0.045

Table 4.10*: Correlation of different precipitation time responses to the aerosol of Niamey*

Aerosols	0-day lag	1-day lag	3-days lag	5-days lag
Ultrafine dust	-0.007	-0.021	-0.031	-0.010
Fine dust	-0.007	-0.020	-0.031	-0.010
Coarse dust	0	-0.014	-0.027	-0.004
Black carbon	0.011	0.031	0.050	0.024
Organic matter	0.009	0.029	0.047	0.021
Sulphate	0.020	0.011	0.021	0
Ultrafine salt	-0.009	-0.005	-0.001	-0.009
Fine salt	-0.008	-0.005	-0.002	-0.009
Coarse salt	0.008	0.004	-0.004	-0.004

Table 4.11: *Correlation of different precipitation time responses to the aerosol of Dakar*

Aerosols	0-day lag	1-day lag	3-days lag	5-days lag
Ultrafine dust	-0.100	-0.082	-0.016	-0.024
Fine dust	-0.100	-0.082	-0.017	-0.024
Coarse dust	-0.091	-0.076	-0.022	-0.022
Black carbon	-0.066	-0.040	0.007	-0.012
Organic matter	-0.055	-0.040	0.003	-0.015
Sulphate	-0.033	-0.052	-0.001	-0.014
Ultrafine salt	0.020	0.095	0.017	0.002
Fine salt	0.022	0.098	0.016	-0.001
Coarse salt	0.022	0.112	0.014	0.006

4.10 AEROSOL EFFECTS ON PRECIPITATION QUALITY

4.10.1 Rainwater pH

Chemical lab rainwater analysis illustrates that pH of West African rainwater (5 samples) from Bamako (5.9, 6.1, 5.8, 6.3 and 6.2), Dakar (6.3, 6.5, 5.9, 6,6 and 6.5), Ibadan (5.8, 5.9, 6.1, 6.2 and 6.1) and Niamey (6.2, 5.9, 6.1, 5.8 and 6.1) are between threshold range of 5.5 to 8. It shows that Ouagadougou (5.8, 6.2, 5.4, 6.1 and 6.2) experienced acid rain (sample 3) during the rainy season of 2022. The pH of rainwater in Ouagadougou was measured at 5.4, which is below the threshold range of 5.5 to 8 (Figure 4.54). A pH below 5.5 indicates that the rainwater is acidic, which can have harmful effects on the environment, including damaging crops and affecting aquatic life. It is important to continue monitoring the pH of rainwater in Ouagadougou and taking measures to reduce acid rain, such as reducing emissions of sulphur dioxide and nitrogen oxides.

4.10.2 Sulphate of Rainwater

Lab analysis of rainwater in Ouagadougou (4.0, 3.1, 7.3, 3.1 and 3.2), Bamako (2.9, 4.2, 0.45, 3.8 and 1.3), Ibadan (4.3, 4.1, 3.8, 3.9 and 3.2), Niamey (1.9, 2.1, 1.9, 2.8 and 2.0) and Dakar (1.3, 1.1, 2.0, 1,5 and 0.9) indicates that the levels of sulphate in the rainwater samples were normal and under the threshold of 8 mg/L during the rainy season of 2022, but its concentration is high in the third sample of Ouagadougou station (Figure 4.55). This can be confirmed by the spatiotemporal distribution of sulphate in Figures 4.7 show high sulphate concentration over Burkina Faso. This suggests that there may be sources of sulphur emissions in this area that are contributing to the elevated sulphate levels in the rainwater. High levels of sulphate in rainwater can have negative impacts on the environment contributing to acid rain. It is important to

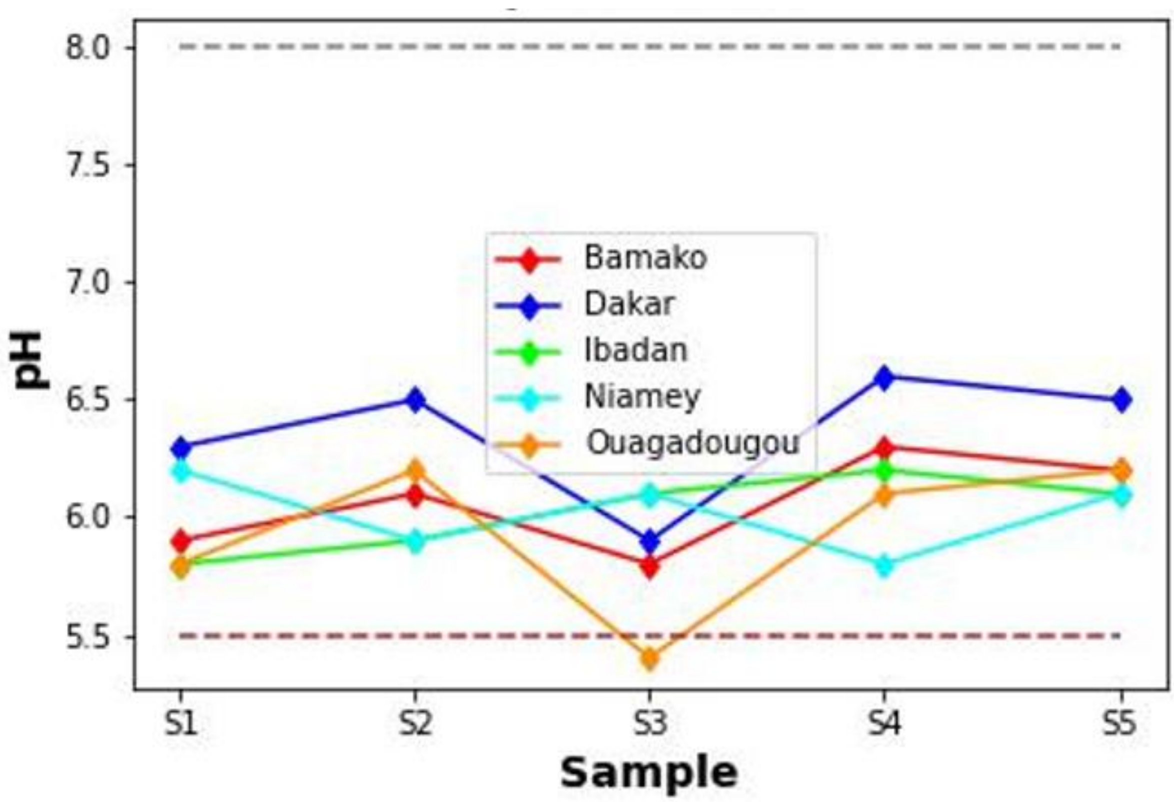

Figure 4.54: Potential of Hydrogen (pH) in rainwater over West Africa

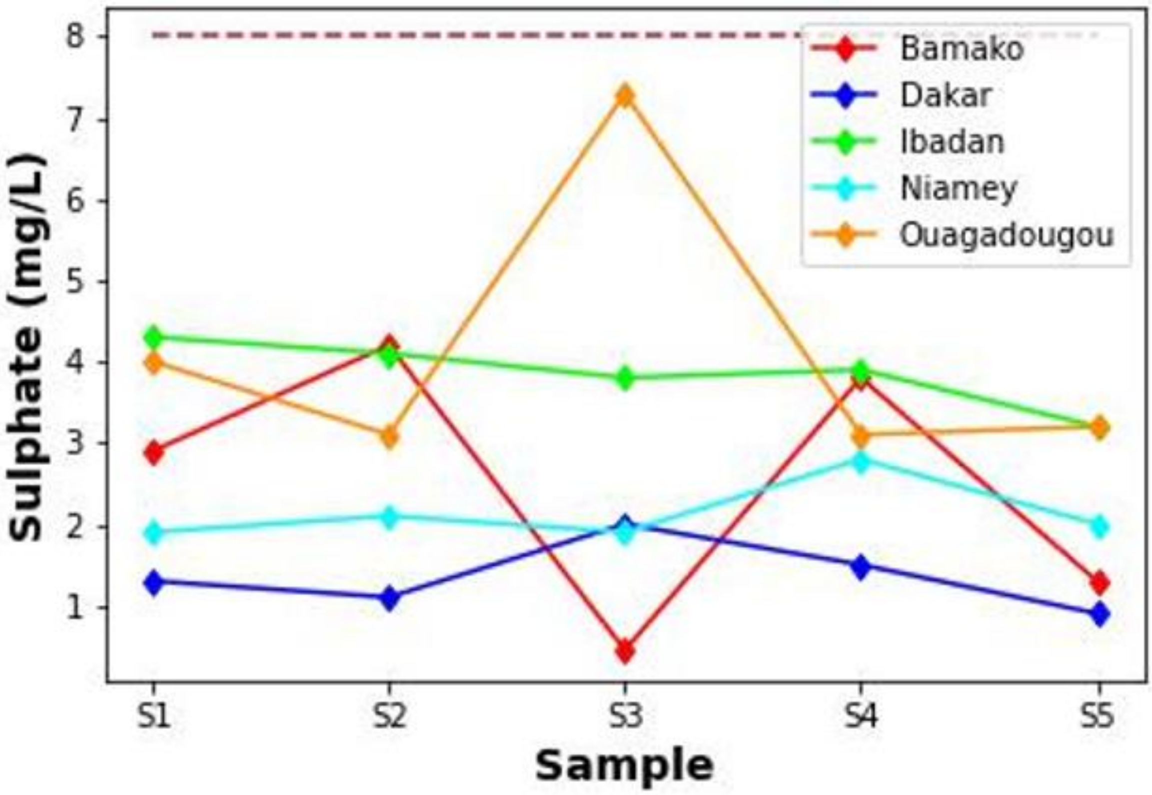

Figure 4.55: Sulphate in rainwater over West Africa

identify and address the sources of sulphur emissions in these areas to reduce the levels of sulphate in the rainwater and mitigate the potential impacts.

4.10.3 Potassium in Rainwater

Lab analysis of rainwater in the five towns over West Africa indicates that the levels of potassium in the rainwater samples in Bamako (0.5, 0.6, 0.3, 0.4 and 0.5), Dakar (0.4, 0.3, 0.5, 0.35 and 0.6), Ibadan (0.3, 0.5, 0.4, 0.3 and 0.5), Niamey (0.6, 0.5, 0.4, 0.7 and 0.5) and Ouagadougou (0.6, 0.4, 0.6, 0.4 and 0.7) were normal and under the threshold of 0.8 during the rainy season of 2022 (Figure 4.56). Potassium is an essential nutrient for plant growth, and it is naturally present in the environment. Therefore, it is expected to be found in rainwater in small amounts. The fact that the levels of potassium in the rainwater samples were within the normal range suggests that there were no significant sources of potassium contamination in the area during the rainy season of 2022. However, it is still important to continue monitoring the levels of potassium in rainwater and other environmental samples to ensure that they remain within safe and acceptable levels.

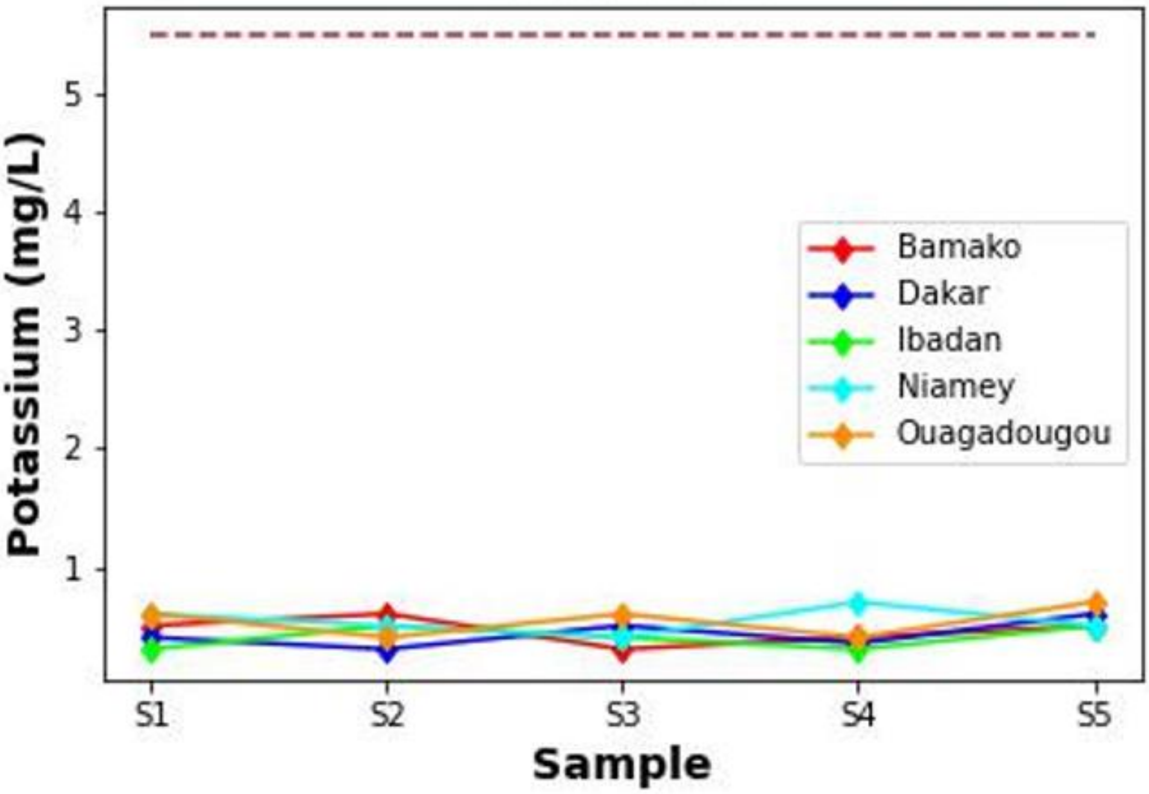

Figure 4.56: Potassium in rainwater over West Africa

4.10.4 Sodium in Rainwater

Lab analysis of rainwater in the five towns over West Africa indicates that the levels of sodium in the rainwater samples in Bamako (0.05, 0.07, 0.15, 0.09 and 0.15), Dakar (1.7, 1.5, 1.7, 1.4 and 1.8), Ibadan (0.07, 0.09, 0.08, 0.1 and 0.1), Niamey (0.03, 0.07, 0.05, 0.08 and 0.05) and Ouagadougou (0.08, 0.1, 0.05, 0.11 and 0.05) were within the normal range and under the threshold of 1.6 during the rainy season of 2022, except for Dakar (Figure 4.57). The rainwater sample from Dakar showed sodium levels above the threshold, which could be an indication of potential sources of sodium contamination in the area. The fact that Dakar is a coastal area may have contributed to the higher levels of sodium in the rainwater samples, as sodium is naturally present in seawater and can be transported by winds to coastal areas. Results from the spatiotemporal distribution of sea salt in Figures 4.8 to 4.10 show high sea salt concentration over West African coast. However, it is still important to identify potential sources of sodium contamination in the area to ensure that the levels remain within safe and acceptable limits.

4.10.5 Nitrate of Rainwater

Lab analysis of rainwater in the five towns over West Africa indicates that the levels of nitrate in the rainwater samples in Bamako (1.35, 3.9, 2.7, 4.0 and 2.9), Ibadan (3.7, 3.5, 2.6, 2.3 and 2.5), Niamey (3.1, 4.5, 4.2, 4.9 and 4.3) and Ouagadougou (4.2, 3.9, 4.5, 4.0 and 3.9) were within the normal range but rainwater in Dakar (2.1, 1.2, 3.8, 1.1 and 2.6) shows that the levels of nitrate in the rainwater samples were below the nitrate thresholds of 1.5 and 5 in the rainy season of 2022 (Figure 4.58). However, it is still important to monitor nitrate levels in rainwater to enhance agriculture in this area. Nitrate has to be released in the Dakar atmosphere in order to increase nitrate in the rainwater of this area to provide additional nutrients for plants.

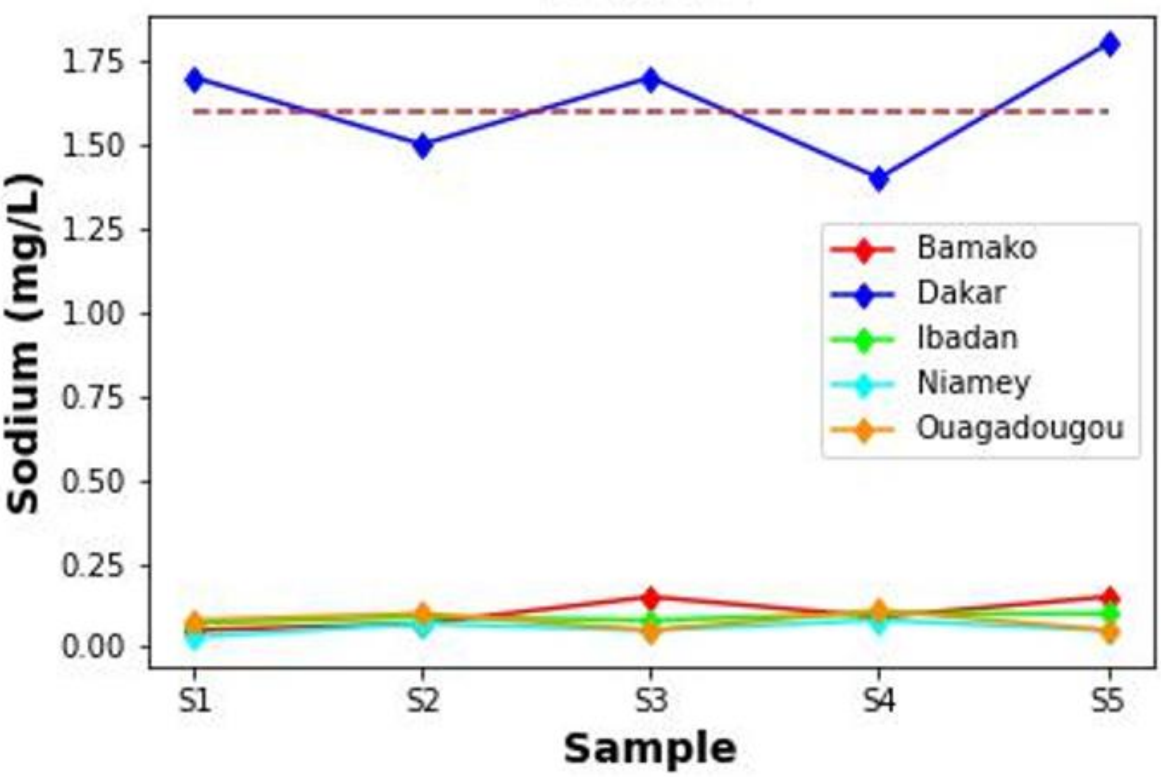

Figure 4.57: Sodium in rainwater over West Africa

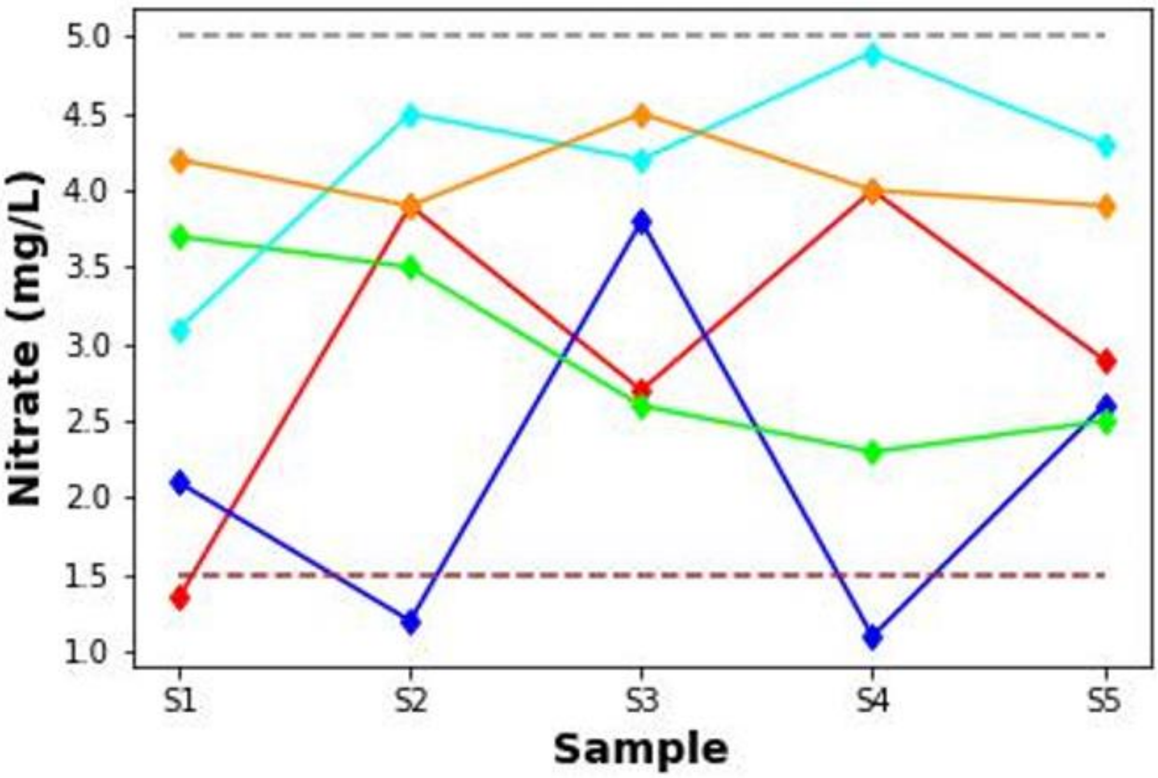

Figure 4.58: Nitrate in rainwater over West Africa

4.10.6 Ammonium of Rainwater

An analysis of rainwater samples from five towns in West Africa showed that the rainwater in Ibadan (0.029, 0.04, 0.018, 0.03 and 0.021) and Niamey (0.015, 0.02, 0.028, 0.024 and 0.021) had normal levels of ammonium, while the rainwater in Dakar (0.1, 0.023, 0.021, 0.04 and 0.02), Bamako (0.35, 0.02, 0.10, 0.20 and 0.023), and Ouagadougou (0.019, 0.017, 0.4, 0.021 and 0.02) had levels of ammonium above the threshold of 0.022 during the rainy season of 2022 (Figure 4.59). The results of the analysis suggest that further investigation may be warranted in Dakar, Bamako, and Ouagadougou to determine the sources of the elevated ammonium levels and to identify measures that can be taken to reduce them if necessary.

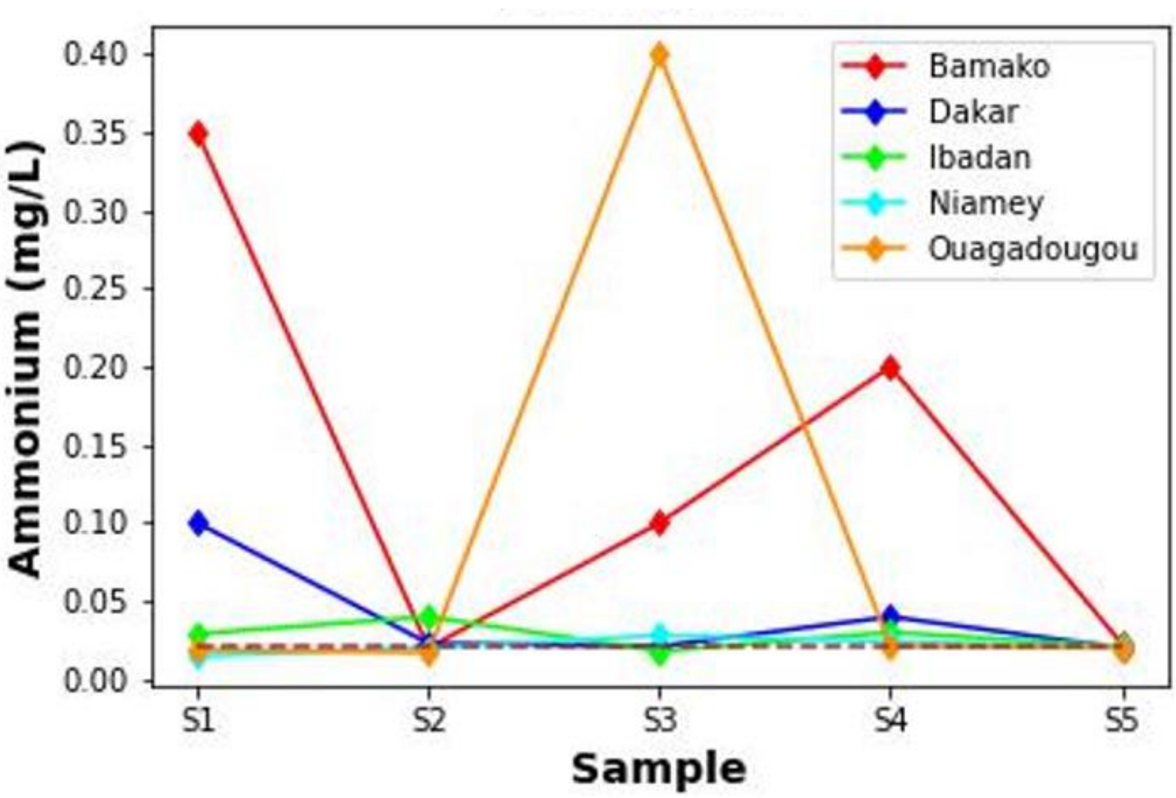

Figure 4.59: Ammonium in rainwater over West Africa

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Aerosol impacts on precipitation over West Africa was investigated in this study. This study answered these research questions: (1) What are the trends and spatiotemporal variations in the chemical components of aerosols and precipitation over West Africa? (2) What are the dominant aerosols and the precipitation time response to aerosol over West Africa? And (3) What are the effects of atmospheric aerosol on precipitation? Specific objectives of this study are: (1) examine the trends and spatiotemporal variations in the chemical components of aerosols and precipitation over West Africa; (2) examine the dominant aerosols and the precipitation time response to aerosol over West Africa; and (3) clarify the effects of atmospheric aerosol on the West African precipitation. This study clarified the aerosol effects on precipitation amount, frequency and quality. Results provide conditions in which clouds seeding and dissipation are working in West Africa subregions such as the Sahel and Guinea. They also clarified that model equations on aerosols should be different for the Sahel and Guinea regions.

Precipitation reduction is observed during the seasons of DJF and JJA over West Africa. Additionally, results suggest that precipitation reduction is also observed during MAM and SON seasons, but to a lesser extent compared to DJF and JJA seasons. The analysis suggests that aerosols have impacts on precipitation, and the response time over West Africa depends on the type and concentration of the aerosols and locations. Results show that dust is the dominant aerosol over all stations used in this study. Organic matter is the second most significant aerosol in this region, which contributes to atmospheric pollution. They show that the dust concentration increased in the Sahel region in the MAM and SON season with different magnitudes, at the same time precipitation has significantly increased rainfall. However, the aerosol concentration decreased during the DJF and JJA seasons. Results suggests that the aerosol concentration has impact in rainfall in West Africa. They show also that black carbon and organic matter concentration increased, while sulphate increased during the DJF and JJA seasons with precipitation reduction. On the other hand, during the MAM and SON seasons, results noticed a decrease in black carbon and organic matter concentration, while sulphate increased with precipitation enhancement. This may suggest that the West African atmospheric black carbon, organic matter and sulphate variation affect the amount of seasonal rainfall. However, the increase in sea salt particles during SON, when there is higher rainfall, could be related to the role of sea salt particles as cloud condensation nuclei, which could influence the amount and timing of rainfall in the region.

In the Sahel region when there is more dust, ultrafine sea salt and sulphate in the air, precipitation intensity tends to increase, but the opposite effect is noticed with fine and coarse sea salt. In contrast, in the Guinea zone when there is more dust and sulphate in the air, precipitation intensity tends to decrease, but the opposite effect is noticed with sea salt. This study found that more black carbon and organic matter in the air tends to significantly lower precipitation intensity in the both regions investigated.

This study suggests that dust, black carbon, organic matter, and sulphate pollution are associated with a reduction in rain frequency in West Africa. It suggests that the reduction in rain event percentages due to dust pollution is more significant in some cities. However, sea salt pollution is associated with an increase in rain frequency. High aerosol concentration over West Africa decreases rain frequency. This suggests that these types of aerosols may be contributing to drought conditions in some areas of West Africa. However, it is interesting to note that high concentrations of sea salt appear to increase rain frequency over the region. This suggests that sea salt may have a positive impact on rain frequency in this region. Rainfall rates between 0.1 mm/h to less than 2.5 mm/h is considered light rain. Dust pollution increases light rain frequency in some cities but decreases it in others. Black carbon pollution decreases light rain frequency over West Africa. Organic matter and sulphate pollution mostly decreases light rain frequency in some cities but increases it in others. Sea salt pollution mostly decreases light rain frequency in some cities but increases it in other coastal cities. High aerosol concentration generally leads to a decrease in light rain events over the Sahel (low relative humidity). Meanwhile, over the Guinea region (high relative humidity), these aerosols generally increase light rain frequency. Rainfall rates between 2.5 mm/h to less than 10 mm/h is considered moderate rain. Dust, sea salt and sulphate pollution increase moderate rain frequency in some cities, but decreases it in others. Black carbon and organic matter pollution mostly increases moderate rain frequency in some cities but decreases it in others. High aerosol concentration generally leads to an increase in moderate rain events over the Sahel (low relative humidity). Meanwhile, over the Guinea region (high relative humidity), these aerosols generally decrease moderate rain frequency. Rainfall rates between 10 mm/h to less than 50 mm/h is considered heavy rain. Dust pollution increases heavy rain frequency over West Africa. Black carbon and organic matter pollution mostly increases heavy rain frequency in some cities but decreases it in others. Sulphate and sea salt pollution increase heavy rain frequency in some cities but decreases it in others. Results provided suggest that dust concentration generally enhances heavy rain events across various stations. However, the effects of high sea salt concentration on heavy rain events are not clear as it enhances them in some stations but reduces them in others. Furthermore, high concentrations of black carbon, organic matter, and sulphate generally increase heavy rain events over the Sahel region. However, these pollutants decreased heavy rain events over the Guinea region.

Chemical lab rainwater quality analysis illustrates that Ouagadougou experienced acid rain during the rainy season of 2022. The pH of rainwater in Ouagadougou was measured at 5.4, which is below the threshold range of 5.5 to 8. A pH below 5.5 indicates that the rainwater is acidic. Lab analysis of rainwater in some cities indicates that the levels of sulphate in the rainwater samples were above the threshold of 0.022. This suggests that there may be sources of sulphur emissions in these areas that are contributing to the elevated sulphate levels in the rainwater. It indicates also that the levels of potassium in the rainwater samples were normal and under the threshold of 0.8. It indicates also that the levels of sodium in the rainwater samples were within the normal range and under the threshold of 1.6, except for Dakar. The rainwater sample from Dakar showed sodium levels above the threshold, which could be an indication of potential sources of sodium contamination in the area. It indicates also that the levels of nitrate in the rainwater samples were within the normal range in most cities, but rainwater in some cities shows that the levels of nitrate in the rainwater samples were below the nitrate thresholds of 1.5 and 5. It indicates also that the rainwater in some cities had normal levels of ammonium, while the rainwater in others had levels of ammonium above the threshold of 0.022 during the rainy season of 2022.

5.2 RECOMMENDATIONS

More research is needed to better understand the economic and environmental effects of light, moderate and heavy precipitation in West Africa. This includes studying the effects of rain classes on agriculture, breeding, industrial activities, health and so on. Understanding these issues is essential for developing effective strategies to rain enhancement or reduction in the region. CMIP6 models and observations can be used to better understand future aerosol concentration in the region and to develop strategies for adapting and mitigating their effects.

One of the best ways to prevent the formation of sulphate in rainwater is to reduce the amount of sulphur dioxide released into the atmosphere. This can be done by reducing the use of fossil fuels, such as coal and oil, and by increasing the use of renewable energy sources, such as solar and wind power. In addition, governments can also implement regulations to limit the amount of sulphur dioxide that is released into the atmosphere. This can include regulations on the burning of fossil fuels, and the use of scrubbers and other technologies to reduce the amount of sulphur dioxide released into the atmosphere. There are a number of steps that can be taken to reduce the amount of potassium in rainwater. One of the most effective methods is to reduce the amount of fertilizer and other chemicals that are used on crops. Additionally, steps can be taken to reduce the amount of runoff from fields, which can help to reduce the amount of potassium in rainwater. It is also important to monitor the amount of potassium in rainwater to ensure that it is not too high. Nitrate pollution can be prevented by reducing the use of fertilizers and other agricultural products that contain nitrates. Other measures that can be taken to reduce nitrate pollution include reducing runoff from agricultural fields and improving sewage and septic systems. In addition, it is important to monitor nitrate levels in drinking water and other sources of water. However, it is still important to monitor nitrate levels in rainwater to enhance agriculture in this area. Nitrate has to be released in some cities in order to increase nitrate in the rainwater of this area to provide additional nutrients for plants. It is important to identify and address the sources of sulphur emissions in these areas to reduce the levels of sulphate in the rainwater and mitigate the potential impacts. It is important to continue monitoring the pH of rainwater in some cities and taking measures to reduce acid rain, such as reducing emissions of sulphur dioxide and nitrogen oxides. But more studies are needed to develop effective strategies for reducing or enhancing some chemical components emissions in the region.

REFERENCES

Abdul-Razzak, H., & Ghan, S. J. (2000). A parameterization of aerosol activation: 2. Multiple aerosol types. Journal of Geophysical Research, 105(D5), 6837–6844. doi:10.1029/1999JD901161.

Ackerman, A. S., Kirkpatrick, M. P., Stevens, D. E., & Toon, O. B. (2004). The impact of humidity above stratiform clouds on indirect aerosol climate forcing. Nature, 432, 1014–1017. doi:10.1038/nature03174.

Ackerman, A. S., Toon, O. B., Stevens, D. E., Heymsfield, A. J., Ramanathan, V., & Welton, E. J. (2000). Reduction of tropical cloudiness by soot. Science, 288, 1042–1047. doi:10.1126/science.288.5468.1042.

Adebiyi, A. A., Zuidema, P., & Platnick, S. (2015). Observational evidence of aerosol enhancement of lightning activity and convective invigoration. Geophysical Research Letters, 42(12).

Adesina, A. J., et al. (2018). Seasonal variability and sources of aerosol black carbon in a Sahelian city (Ile-Ife) of Nigeria. Environmental Science and Pollution Research, 25(6), 5397-5410.

Adeyeri, O. E., et al. (2019). West African rainfall variability and its connection to Atlantic climate variability and Saharan dust. Climate Dynamics, 53(5-6), 3043-3061.

Akinyoola, J. A., Ajayi, V. O., Abiodun, B. J., Ogunjobi, K. O., Gbode, I. E., & Ogungbero, S. B. (2019). Dynamic response of monsoon precipitation to mineral dust radiative forcing in West Africa. Modeling Earth Systems and Environment. https://doi.org/10.1007/s40808-019-00620-z

Albrecht, B. A. (1989). Aerosols, cloud microphysics and fractional cloudiness. Science, 245, 1227–1230. doi:10.1126/science.245.4923.1227.

Alpert, P., Halfon, N., & Levin, Z. (2008). Does air pollution really suppress precipitation in Israel? Journal of Applied Meteorology and Climatology, 47, 933–943. doi:10.1175/2007JAMC1803.1.

Andreae, M. O., & Rosenfeld, D. (2008). Aerosol-Cloud-Precipitation interactions. Part 1. The nature and sources of cloud-active aerosols. Earth Science Reviews, 89, 13–41.

Andreae, M. O., Rosenfeld, D., Artaxo, P., Costa, A. A., Frank, G. P., Longo, K. M., & Silva-Dias, M. A. F. (2004). Smoking rain clouds over the Amazon. Science, 303, 1337–1342. doi:10.1126/science.1092779.

Ayers, G. P. (2005). Air pollution and climate change: Has air pollution suppressed rainfall over Australia? Clean Air and Environmental Quality, 39(2), 51–57.

Babatunde, F. O., et al. (2017). Characterization of aerosol optical properties and classification of air mass types at a Sahelian site: Niamey, Niger. Atmospheric Pollution Research, 8(3), 551-563.

Barahona, D., & Nenes, A. (2007). Parameterization of cloud droplet formation in large-scale models: Including effects of entrainment. Journal of Geophysical Research, 112, D16206. doi:10.1029/2007JD008473.

Baron, J. S., Rueth, H. M., Wolfe, A. M., Nydick, K. R., Allstott, E. J., Minear, J. T., & Moraska, B. (2000). Ecosystem responses to nitrogen deposition in the Colorado Front Range. Ecosystems, 3, 352–368.

Barthlott C., Zarboo A., Matsunobu T., & Keil C. (2022). Importance of aerosols and shape of the cloud droplet size distribution for convective clouds and precipitation. Atmospheric Chemistry and Physics, 22, 2153–2172. https://doi.org/10.5194/acp-22-2153-2022.

Bell, T. L., Rosenfeld, D., Kim, K. M., Yoo, J. M., Lee, M. I., & Hahnenberger, M. (2008). Midweek increase in U.S. summer rain and storm heights suggests air pollution invigorates rainstorms. Journal of Geophysical Research, 113, D02209. doi:10.1029/2007JD008623.

Biasutti, M., et al. (2019). West African monsoon dynamics and precipitation: The competition between global SST warming and CO2 increase in CMIP5 idealized simulations. Journal of Climate, 32(9), 2561-2580.

Bollasina, M., & Nigam, S. (2009). Indian Ocean SST, evaporation, and precipitation during the South Asian summer monsoon in IPCC-AR4 coupled simulations. Climate Dynamics, 33, 1017–1032. doi:10.1007/s00382-008-0477-4.

Brenguier, J.-L., Pawlowska, H., Schüller, L., Preusker, R., Fischer, J., & Fouquart, Y. (2000). Radiative properties of boundary layer clouds: Droplet effective radius versus number concentration. Journal of Atmospheric Sciences, 57, 803–821. doi:10.1175/1520-0469(2000)057<0803:RPOBLC>2.0.CO;2.

Carrió, G. G., van den Heever, S. C., & Cotton, W. R. (2007). Impacts of nucleating aerosol on anvil-cirrus clouds: A modeling study. Atmospheric Research, 84, 111–131. doi:10.1016/j.atmosres.2006.06.002.

Chen, C., Lei, H., Li, Y., Li, L., & Sun, T. (2018). Dust aerosol effects on cloud and precipitation in East Asia: A review. Atmospheric Research, 202, 195-209.

Chen, R., Chen, F. L., Li, Z., Ferraro, R., & Weng, F. (2007). The impact of vertical variation of cloud droplet size on estimation of cloud liquid water path and detection of warm raining cloud. Journal of Atmospheric Sciences, 64, 3843–3853. doi:10.1175/2007JAS2126.1.

Chen, R., Li, Z., Kuligowski, R. J., Ferraro, R., & Weng, F. (2011). A study of warm rain detection using A-Train satellite data. Geophysical Research Letters, 38, L04804. doi:10.1029/2010GL046217.

Chen, X., Sun, L., Wang, Y., Wang, T., & Fu, Q. (2016). Sea salt aerosol, wind speed, and rainfall over the North Pacific. Scientific Reports, 6(1), 1-11.

Coakley, J. A., & Walsh, C. D. (2002). Limits to the aerosol indirect radiative effect from observations of ship tracks. Journal of Atmospheric Sciences, 59, 668–680. doi:10.1175/1520-0469(2002)059<0668:LTTAIR>2.0.CO;2.

Diallo, I., Bain, C. L., Gaye, A. T., Moufouma-Okia, W., Niang, C., Dieng, M. D. B., & Graham, R. (2014). Simulation of the West African monsoon onset using the HadGEM3-RA regional climate model. Climate Dynamics, 43, 575–594.

Dias, V. R. D., Sanches, L., Alves, M. D., & Nogueira, J. D. (2012). Spatio-temporal variability of anions in wet precipitation of Cuiaba, Brazil. Atmospheric Research, 107, 9–19.

Ebenso, I. E., et al. (2019). Aerosol pollution and its potential impacts on air quality and climate over West Africa: A review. SN Applied Sciences, 1(11), 1313.

Evan, A. T., et al. (2015). West African monsoon precipitation variability and the Atlantic Multidecadal Oscillation. Journal of Geophysical Research: Atmospheres, 120(17), 8573-8587.

Fan J., Zhang Y., Li Z., Hu J. & Rosenfeld D. (2020). Urbanization-induced land and aerosol impacts on sea-breeze circulation and convective precipitation. Atmospheric Chemistry and Physics, 20, 14163–14182. https://doi.org/10.5194/acp-20-14163-2020.

Fan, J., Yuan, T., Comstock, J. M., Ghan, S., Khain, A., Leung, L. R., Li, Z., Martins, V. J., & Ovchinnikov, M. (2009). Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. Journal of Geophysical Research, 114, D22206. doi:10.1029/2009JD012352.

Fan, J., Zhang, R., Li, G., & Tao, W. K. (2007a). Effects of aerosols and relative humidity on cumulus clouds. Journal of Geophysical Research, 112, D14204. doi:10.1029/2006JD008136.

Fan, J., Zhang, R., Li, G., Tao, W. K., & Li, X. (2007b). Simulation of cumulus clouds using a spectral microphysics cloud resolving model. Journal of Geophysical Research, 112, D04201. doi:10.1029/2006JD007688.

FAO. (1996). Rome Declaration and World Food Summit Plan of Action. Food and Agricultural Organization of the United Nations (FAO) World Food Summit, Rome, Italy. 13-17 November 1996, FAO, Rome, Italy. Retrieved from http://www.fao.org/docrep/003/w3613e/w3613e00.HTM

Feingold, G., Cotton, W. R., Kreidenweis, S. M., & Davis, J. T. (1999). The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: Implications for cloud radiative properties. Journal of Atmospheric Sciences, 56, 4100–4117. doi:10.1175/1520-0469(1999)056<4100:TIOGCC>2.0.CO;2.

Fenn, M. E., Poth, M. A., Aber, J. D., Baron, J. S., Bormann, B. T., Johnson, D. W., Lemly, A. D., McNulty, S. G., Ryan, D. E., & Stottlemyer, R. (1998). Nitrogen excess in North American ecosystems: Predisposing factors, ecosystem responses, and management strategies. Ecological Applications, 8, 706–733.

Fink, A. H., et al. (2004). The 2003 summer monsoon season in the West African Sudan-Sahel region. Tellus A, 56(4), 400-422.

Fisher, L. B. (2004). Climatological validation of TRMM TMI and PR monthly rain products over Oklahoma. Journal of Applied Meteorology, 43, 519–535.

Fitzgerald, J. W., & Spyers-Duran, P. A. (1973). Changes in cloud nucleus concentration and cloud droplet size distribution associated with pollution from St. Louis. Journal of Applied Meteorology, 12, 511–516. doi:10.1175/1520-0450(1973)012<0511:CICNCA>2.0.CO;2.

Fletcher, N. H. (1962). The Physics of Rainclouds. Cambridge University Press.

Fontaine, B., et al. (2019). Decadal evolution of coastal upwelling in the Guinea Dome based on satellite observations: Oceanic and atmospheric drivers. Journal of Geophysical Research: Oceans, 124(7), 4509-4528.

Gettelman, A., Morrison, H., & Ghan, S. J. (2008). A new two moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model, version 3 (CAM3): Part II. Single-column and global results. Journal of Climate, 21, 3660–3679. doi:10.1175/2008JCLI2116.1.

Giannini, A., Biasutti, M., Verstraete, M. M., & Koster, R. D. (2003). A climate model-based review of drought in the Sahel: Desertification, the re-greening and climate change. Global and Planetary Change, 26(1-3), 67-77.

Hagos, S. M., Leung, L. R., Xue, Y., Boone, A., de Sales, F., Neupane, N., ... & Wang, S. (2013). Dynamics of West African Monsoon jump. Journal of Climate, 26(12), 4316-4334.

Han, Q. Y., Rossow, W. B., Zeng, J., & Welch, R. (2002). Three different behaviors of liquid water path of water clouds in aerosol-cloud interactions. Journal of Atmospheric Sciences, 59, 726–735. doi:10.1175/1520-0469(2002)059<0726:TDBOLW>2.0.CO;2.

Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset. Scientific Data, 7, 109.

Haywood, J. M., & Boucher, O. (2000). Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review. Reviews of Geophysics, 38, 513–543. doi:10.1029/1999RG000078.

Hocking, L. M. (1959). The collision efficiency of water drops. Quarterly Journal of the Royal Meteorological Society, 85, 44–50. doi:10.1002/qj.49708536305.

Hoose, C., Kristjánsson, J. E., Iversen, T., Kirkevåg, A., Seland, Ø., & Gettelman, A. (2009). Constraining cloud droplet number concentration in GCMs suppresses the aerosol indirect effect. Geophysical Research Letters, 36, L12807. doi:10.1029/2009GL038568.

Hsu, N. C., Lee, J., Sayer, A. M., Kim, W. V., Bettenhausen, C., & Tsay, S. C. (2012). An evaluation of MODIS 3 km aerosol optical depth for estimating surface particulate matter concentrations. Atmospheric Environment, 46, 135-145.

https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-ghg-reanalysis-egg4?tab=overview https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-atmospheric-composition-forecasts?tab=overview

Huang, H., Adams, A., Wang, C., & Zhang, C. (2009). Aerosol and West African monsoon precipitation: Observations and simulations. Annals of Geophysics, 27, 4171–4181. doi:10.5194/angeo-27-4171-2009.

Huang, J., Lin, B., Minnis, P., Wang, T., Wang, X., Hu, Y., Yi, Y., & Ayers, J. K. (2006a). Satellite-based assessment of possible dust aerosols semi-direct effect on cloud water path over East Asia. Geophysical Research Letters, 33, L19802. doi:10.1029/2006GL026561.

Huang, J., Minnis, P., Lin, B., Wang, T., Yi, Y., Hu, Y., Sun-Mack, A., & Ayers, K. (2006b). Possible influences of Asian dust aerosols on cloud properties and radiative forcing observed from MODIS and CERES. Geophysical Research Letters, 33, L06824. doi:10.1029/2005GL024724.

Huang, J., Minnis, P., Yan, H., Yi, Y., Chen, B., Zhang, L., & Ayers, J. (2010). Dust aerosol effect on semi-arid climate over northwest China detected from A-Train satellite measurements. Atmospheric Chemistry and Physics, 10, 6863–6872.

Huang, J., Zhang, C., & Prospero, J. (2009b). Large-scale effect of aerosol on precipitation in the West African monsoon region. Quarterly Journal of the Royal Meteorological Society, 135, 581–594. doi:10.1002/qj.391.

Huang, J., Zhang, C., & Prospero, J. (2009c). Aerosol-induced large-scale variability in precipitation over the tropical Atlantic. Journal of Climate, 22, 4970–4988. doi:10.1175/2009JCLI2531.1.

Huang, J., Zhang, C., & Prospero, J. M. (2009). African aerosol and large-scale precipitation variability over West Africa. Environmental Research Letters, 4, 015006. doi:10.1088/1748-9326/4/1/015006.

Huang, J., Zhang, C., & Prospero, J. M. (2009a). African aerosol and large-scale precipitation variability over West Africa. Environmental Research Letters, 4, 015006. doi:10.1088/1748-9326/4/1/015006.

Hui, W. J., Cook, B. I., Ravi, S., Fuentes, J. D., & D'Odorico, P. (2008). Dust-rainfall feedbacks in the West African Sahel. Water Resources Research, 44, W05202. doi:10.1029/2008WR006885.

IPCC. (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jiang, H., Xue, H., Teller, A., Feingold, G., & Levin, Z. (2006). Aerosol effects on the lifetime of shallow cumulus. Geophysical Research Letters, 33, L14806. doi:10.1029/2006GL026024.

Johnson, D. B. (1982). The role of giant and ultra-giant aerosol particles in warm rain initiation. Journal of Atmospheric Sciences, 39, 448–460. doi:10.1175/1520-0469(1982)039<0448:TROGAU>2.0.CO;2.

Jones, A., Haywood, J. M., & Boucher, O. (2007). Aerosol forcing, climate response and climate sensitivity in the Hadley Centre climate model. Journal of Geophysical Research, 112, D20211. doi:10.1029/2007JD008688.

Jones, T. A., & Christopher, S. A. (2010). Statistical properties of aerosol-cloud-precipitation interactions in South America. Atmospheric Chemistry and Physics, 10, 2287–2305. doi:10.5194/acp-10-2287-2010.

Kärcher, B., & Lohmann, U. (2003). A parameterization of cirrus cloud formation: Heterogeneous freezing. Journal of Geophysical Research, 108(D14), 4402. doi:10.1029/2002JD003220.

Kaufman, Y. J., Boucher, O., Tanré, D., Chin, M., Remer, L. A., & Takemura, T. (2005). Aerosol anthropogenic component estimated from satellite data. Geophysical Research Letters, 32, L17804. doi:10.1029/2005GL023125.

Kaufman, Y. J., et al. (2005). Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. Journal of Geophysical Research: Atmospheres, 110(D10), D10S04.

Khain, A. D., BenMoshe, N., & Pokrovsky, A. (2008). Factors determining the impact of aerosols on surface precipitation from clouds: An attempt at classification. Journal of Atmospheric Sciences, 65, 1721–1748. doi:10.1175/2007JAS2515.1.

Khain, A. P. (2009). Notes on state of the art investigations of aerosol effects on precipitation: A critical review. Environmental Research Letters, 4, 015004. doi:10.1088/1748-9326/4/1/015004.

Khain, A., Pokrovsky, A., Pinsky, M., Seigert, A., & Phillips, V. (2004). Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus cloud model: Part I. Model description and possible applications. Journal of Atmospheric Sciences, 61, 2983–3001. doi:10.1175/JAS-3281.1.

Khain, A., Roseenfeld, D., & Pokrovsky, A. (2005). Aerosol impact on the dynamics and microphysics of deep convective clouds. Quarterly Journal of the Royal Meteorological Society, 131, 2639–2663. doi:10.1256/qj.04.62.

Kiehl, J. T., Schneider, T. L., Rasch, P. J., & Barth, M. C. (2000). Radiative forcing due to sulfate aerosols from simulations with the National Center for Atmospheric Research Community Climate Model, Version 3. Journal of Geophysical Research, 105, 1441–1457. doi:10.1029/1999JD900495.

Konare, A., Zakey, A. S., Solmon, F., Giorgi, F., Rauscher, S., Ibrah, S., & Bi, X. (2008). A regional climate modeling study of the effect of desert dust on the West African monsoon. Journal of Geophysical Research D, 113(12), Article ID D12206. doi:10.1029/2007JD009322.

Koren, I., Feingold, G., & Remer, L. A. (2010a). The invigoration of deep convective clouds over the Atlantic: Aerosol effect, meteorology, or retrieval artifact? Atmospheric Chemistry and Physics, 10, 8855–8872. doi:10.5194/acp-10-8855-2010a.

Koren, I., Kaufman, Y. J., Remer, L. A., & Martins, J. V. (2004). Measurements of the effect of Amazon smoke on inhibition of cloud formation. Science, 303, 1342–1345.

Koren, I., Kaufman, Y. J., Rosenfeld, D., Remer, L. A., & Rudich, Y. (2005). Aerosol invigoration and restructuring of Atlantic convective clouds. Geophysical Research Letters, 32, L14828. doi:10.1029/2005GL023187.

Koren, I., Kaufman, Y. J., Rosenfeld, D., Remer, L. A., & Rudich, Y. (2010). Aerosol invigoration and restructuring of Atlantic convective clouds. Geophysical Research Letters, 37(4).

Koren, I., Martins, J. V., Remer, L. A., & Afargan, H. (2008). Smoke invigoration versus inhibition of clouds over the Amazon. Science, 321(5891), 946-949.

Kristjánsson, J. E. (2002). Studies of the aerosol indirect effect from sulfate and black carbon aerosols. Journal of Geophysical Research, 107(D15), 4264. doi:10.1029/2001JD000887.

L'Ecuyer, T. S., Berg, W., Haynes, J., Lebsock, M., & Takemura, T. (2009). Global observations of aerosol impacts on precipitation occurrence in warm maritime clouds. Journal of Geophysical Research, 114, D09211. doi:10.1029/2008JD011273.

Lasher-Trapp, S. G., Knight, C. A., & Straka, J. M. (2001). Early radar echoes from ultragiant aerosol in a cumulus congestus: Modeling and observations. Journal of Atmospheric Sciences, 58, 3545–3562. doi:10.1175/1520-0469(2001)058<3545:EREFUA>2.0.CO;2.

Lau, K. M., & Kim, K. M. (2006). Observational relationships between aerosol and Asian monsoon rainfall, and circulation. Geophysical Research Letters, 33, L21810. doi:10.1029/2006GL027546.

Lau, K. M., Kim, K. M., Sud, Y. C., & Walker, G. K. (2009). A GCM study of the response of the atmospheric water cycle of West Africa and the Atlantic to Saharan dust radiative forcing. Annales Geophysicae, 27(10), 4023–4037.

Lau, K. M., Kim, M. K., & Kim, K. M. (2006). Asian monsoon anomalies induced by aerosol direct effects. Climate Dynamics, 26, 855–864. doi:10.1007/s00382-006-0114-z.

Lebsock, M. D., Stephens, G. L., & Kummerow, C. (2008). Multisensor satellite observations of aerosol effects on warm clouds. Journal of Geophysical Research, 113, D15205. doi:10.1029/2008JD009876.

Lee, S. S. (2011). Dependence of aerosol-precipitation interactions on humidity in a multiple-cloud system. Atmospheric Chemistry and Physics, 11, 2179–2196. doi:10.5194/acp-11-2179-2011.

Lee, S. S., Donner, L. J., & Phillips, V. T. J. (2009). Impacts of aerosol chemical composition on microphysics and precipitation in deep convection. Atmospheric Research, 94, 220–237. doi:10.1016/j.atmosres.2009b.05.015.

Lee, S. S., Donner, L. J., Phillips, V. T. J., & Ming, Y. (2008). The dependence of aerosol effects on clouds and precipitation on cloud-system organization, shear, and stability. Journal of Geophysical Research, 113, D16202. doi:10.1029/2007JD009224.

Lee, S., Hwang, D. W., Hong, J. W., & Kim, B. J. (2018). Effect of sea salt aerosol on cloud droplet formation and cloud properties. Atmospheric Chemistry and Physics, 18(5), 3403-3416.

Legrand, M., & Mayewski, P. (1997). Glaciochemistry of polar ice cores: A review. Reviews of Geophysics, 35, 219–243.

Levin, Z., & Cotton, W. R. (2009). Aerosol pollution impact on precipitation. Springer.

Liu L., Cheng Y., Wang S., Wei C., Pöhlker M. L., Pöhlker C., Artaxo P., Shrivastava M., Andreae M. O., Pöschl U., & Su H (2020). Impact of biomass burning aerosols on radiation, clouds, and precipitation over the Amazon: relative importance of aerosol–cloud and aerosol–radiation interactions. Atmospheric Chemistry and Physics, 20, 13283–13301. https://doi.org/10.5194/acp-20-13283-2020.

Liu, G., Shao, H., Coakley Jr., J. A., Curry, J. A., Haggerty, J. A., & Tschudi, M. A. (2003). Retrieval of cloud droplet size from visible and microwave radiometric measurements during INDOEX: Implication to aerosols' indirect radioactive effect. Journal of Geophysical Research, 108(D1), 4006. doi:10.1029/2001JD001395.

Liu, J., Zheng, Y., Li, Z., & Cribb, M. (2011). Analysis of cloud condensation nuclei properties at a polluted site in southeastern China during the AMF-China Campaign. Journal of Geophysical Research, 116, D00K35. doi:10.1029/2011JD016395.

Liu, X., & Penner, J. E. (2005). Ice nucleation parameterization for global models. Meteorologische Zeitschrift, 14, 499–514. doi:10.1127/0941-2948/2005/0059.

Liu, X., Hsu, N. C., Tsay, S. C., Holben, B. N., Lu, D., & Luo, Y. (2011). A study of natural and anthropogenic dust aerosol radiative effects over East Asia from satellite remote sensing. Journal of Geophysical Research: Atmospheres, 116(D24).

Liu, Y., & Daum, P. H. (2002). Indirect warming effect from dispersion forcing. Nature, 419, 580–581. doi:10.1038/419580a.

Lohmann, U. (2008). Global anthropogenic aerosol effects on convective clouds in ECHAM-HAM. Atmospheric Chemistry and Physics, 8, 2115–2131. doi:10.5194/acp-8-2115-2008.

Lohmann, U., & Diehl, K. (2006). Sensitivity studies of the importance of dust ice nuclei for the indirect aerosol effect on stratiform mixed-phase clouds. Journal of Atmospheric Sciences, 63, 968–982.

Lohmann, U., & Feichter, J. (2005). Global indirect aerosol effects: A review. Atmospheric Chemistry and Physics, 5, 715–737. doi:10.5194/acp-5-715-2005.

Lohmann, U., Stier, P., Hoose, C., Ferrachat, S., Kloster, S., Roeckner, E., & Zhang, J. (2007). Cloud microphysics and aerosol indirect effects in the global climate model ECHAM5-HAM. Atmospheric Chemistry and Physics, 7, 3425–3446. doi:10.5194/acp-7-3425-2007.

Martin, G. M., Johnson, D. W., & Spice, A. (1994). The measurement and parameterization of effective radius of droplets in warm stratocumulus clouds. Journal of Atmospheric Sciences, 51, 1823–1842. doi:10.1175/1520-0469(1994)051<1823:TMAPOE>2.0.CO;2.

Matichuk, R., Barbaris, B., Betterton, E. A., Hori, M., Murao, N., Ohta, S., & Ward, D. (2006). A decade of aerosol and gas precursor chemical characterization at Mt. Lemmon, Arizona (1992 to 2002). Journal of the Meteorological Society of Japan, 84, 653–670.

Matsui, T., Masunaga, H., Kreidenweis, S. M., Pielke Sr., R. A., Tao, W. K., Chin, M., & Kaufman, Y. J. (2006). Satellite-based assessment of marine low cloud variability associated with aerosol, atmospheric stability, and the diurnal cycle. Journal of Geophysical Research, 111, D17204. doi:10.1029/2005JD006097.

McCumber, M., Tao, W. K., Simpson, J., Penc, R., & Soong, S. T. (1991). Comparison of ice-phase microphysical parameterization schemes using numerical simulations of tropical convection. Journal of Applied Meteorology, 30, 985–1004. doi:10.1175/1520-0450-30.7.985.

Menon, S., & Del Genio, A. D. (2007). Evaluating the impacts of carbonaceous aerosols on clouds and climate. In Human-Induced Climate Change. Cambridge University Press, UK.

Menon, S., Del Genio, A. D., Koch, D., & Tselioudis, G. (2002). GCM simulations of the aerosol indirect effect: Sensitivity to cloud parameterization and aerosol burden. Journal of

Atmospheric Sciences, 59, 692–713. doi:10.1175/1520-0469(2002)059<0692:GSOTAI>2.0.CO;2.

Menon, S., Hansen, J., Nazarenko, L., & Luo, Y. (2002). Climate effects of black carbon aerosol in China and India. Science, 297, 2250–2253.

Ming, Y., Ramaswamy, V., Ginoux, P. A., Horowitz, L. H., & Russell, L. M. (2005). Geophysical Fluid Dynamics Laboratory general circulation model investigation of the indirect radiative effects of anthropogenic sulfate aerosol. Journal of Geophysical Research, 110, D22206. doi:10.1029/2005JD006161.

Morrison, H., & Gettelman, A. (2008). A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model, version 3 (CAM3): Part I. Description and numerical tests. Journal of Climate, 21, 3642–3659. doi:10.1175/2008JCLI2105.1.

Nakajima, T., Higurashi, A., Kawamoto, K., & Penner, J. (2001). A possible correlation between satellite-derived cloud and aerosol microphysical parameters. Geophysical Research Letters, 28, 1171–1174. doi:10.1029/2000GL012186.

Neff, J. C., Ballantyne, A. P., Farmer, G. L., Mahowald, N. M., Conroy, J. L., Landry, C. C., Overpeck, J. T., Painter, T. H., Lawrence, C. R., & Reynolds, R. L. (2008). Increasing eolian dust deposition in the western United States linked to human activity. Nature Geoscience, 1, 189–195.

Nenes, A., & Seinfeld, J. H. (2003). Parameterization of cloud droplet formation in global climate models. Journal of Geophysical Research, 108(D14), 4415. doi:10.1029/2002JD002911.

Nenes, A., Murray, B., & Bougiatioti, A. (2014). Mineral dust and its microphysical interactions with clouds. In Mineral Dust: A Key Player in the Earth System (pp. 103–121). Springer.

O'Dowd, C. D., Smith, M. H., Consterdine, I. E., & Lowe, J. A. (1997). Marine aerosol, sea-salt, and the marine sulphur cycle: A short review. Atmospheric Environment, 31, 73–80. doi:10.1016/S1352-2310(96)00106-9.

Olivier, S., Blaser, C., Brutsch, S., Frolova, N., Gaggeler, H. W., Henderson, K. A., Palmer, A. S., Papina, T., & Schwikowski, M. (2006). Temporal variations of mineral dust, biogenic tracers, and anthropogenic species during the past two centuries from Belukha ice core, Siberian Altai. Journal of Geophysical Research, 111, D05309. doi:10.1029/2005JD005830.

Orville, R. E., Zhang, R., Gammon, J. N., Collins, D., Ely, B., & Steiger, S. (2001). Enhancement of cloud-to-ground lightning over Houston, Texas. Geophysical Research Letters, 28(13), 2597–2600. doi:10.1029/2001GL012990.

Penner, J. E., Quaas, J., Storelvmo, T., Takemura, T., Boucher, O., Guo, H., Kirkevåg, A., Kristjánsson, J. E., & Seland, Ø. (2006). Model intercomparison of indirect aerosol effects. Atmospheric Chemistry and Physics, 6, 3391–3405. doi:10.5194/acp-6-3391-2006.

Persad G. G. (2023). The dependence of aerosols' global and local precipitation impacts on the emitting region. Atmospheric Chemistry and Physics, 23, 3435–3452. https://doi.org/10.5194/acp-23-3435-2023.

Phillips, V. T. J., Choularton, T. W., Blyth, A. M., & Latham, J. (2002). The influence of aerosol concentrations on the glaciation and precipitation of a cumulus cloud. Quarterly Journal of the Royal Meteorological Society, 128(581), 951–971. doi:10.1256/0035900021643601.

Posselt, R., & Lohmann, U. (2008). Influence of giant CCN on warm rain processes in the ECHAM5 GCM. Atmospheric Chemistry and Physics, 8, 3769–3788. doi:10.5194/acp-8-3769-2008.

Prashantha Kumar K. & Manjunatha B. R. (2021). Impact of Aerosols on Precipitation over Western Ghats. Aerosol Science and Engineering, 41810-021-00111-8. https://doi.org/10.1007/s41810-021-00111-8.

Preunkert, S., Wagenbach, D., & Legrand, M. (2003). A seasonally resolved alpine ice core record of nitrate: Comparison with anthropogenic inventories and estimation of preindustrial emissions of NO in Europe. Journal of Geophysical Research, 108, 4681. doi:10.1029/2003JD003475.

Prospero, J. M., et al. (2002). Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Reviews of Geophysics, 40(1), 2-1 to 2-31.

Qian, Y., Gong, D., Fan, J., Leung, L. R., Bennartz, R., Chen, D., & Wang, W. (2009). Heavy pollution suppresses light rain in China: Observations and modeling. Journal of Geophysical Research, 114, D00K02. doi:10.1029/2008JD011575.

Quaas, J., Ming, Y., Menon, S., Takemura, T., Wang, M., Penner, J. E., Gettelman, A., Lohmann, U., Bellouin, N., Boucher, O., Sayer, A. M., Thomas, G. E., McComiskey, A., Feingold, G., Hoose, C., Kristjánsson, J. E., Liu, X., Balkanski, Y., Donner, L. J., Ginoux, P. A., Stier, P., Grandey, B., Feichter, J., Sednev, I., Bauer, S. E., Koch, D., Grainger, R. G., Kirkevåg, A., Iversen, T., Seland, Ø., Easter, R., Ghan, S. J., Rasch, P. J., Morrison, H., Lamarque, J. F., Iacono, M. J., Kinne, S., & Schulz, M. (2009). Aerosol indirect effects—

General circulation model intercomparison and evaluation with satellite data. Atmospheric Chemistry and Physics, 9, 8697–8717. doi:10.5194/acp-9-8697-2009.

Radke, L. F., Coakley Jr., J. A., & King, M. D. (1989). Direct and remote sensing observations of the effects of ships on clouds. Science, 246, 1146–1149. doi:10.1126/science.246.4934.1146.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, Y. G., & Solomon, S. (2001). Radiative forcing of climate change. In J. T. Houghton et al. (Eds.), Climate Change 2001: The Scientific Basis—Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (pp. 349–416). Cambridge University Press.

Rasch, P. J., & Kristjánsson, J. E. (1998). A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations. Journal of Climate, 11, 1587–1614. doi:10.1175/1520-0442(1998)011<1587:ACOTCM>2.0.CO;2.

Ravi, S., D'Odorico, P., Breshears, D. D., Field, J. P., Goudie, A. S., Huxman, T. E., Li, J., Okin, G. S., Swap, R. J., Thomas, A. D., Van Pelt, S., Jeffrey, J., Whicker, J. J., & Zobeck, T. M. (2011). Aeolian processes and the biosphere. Reviews of Geophysics, 49, RG3001. doi:10.1029/2010RG000328.

Rogers, R. R., & Yau, M. K. (1989). A Short Course in Cloud Physics. Pergamon.

Rosenfeld, D. (1999). TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. Geophysical Research Letters, 26, 3105–3108. doi:10.1029/1999GL006066.

Rosenfeld, D., & Lensky, I. (1998). Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. Bulletin of the American Meteorological Society, 79, 2457–2476. doi:10.1175/1520-0477(1998)079<2457:SBIIPF>2.0.CO;2.

Rosenfeld, D., & Woodley, W. L. (2000). Convective clouds with sustained highly supercooled liquid water down to -37°C. Nature, 405, 440–442. doi:10.1038/35013030.

Rosenfeld, D., Kaufman, Y. J., Rudich, Y., & Koren, I. (2008). Drop precipitation and the aerosol indirect effect over the Amazon. Geophysical Research Letters, 35(13).

Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. O., Kulmala, M., Fuzzi, S., Reissell, A., & Andreae, M. O. (2008). Flood or drought: How do aerosols affect precipitation? Science, 321, 1309–1313. doi:10.1126/science.1160606.

Rosenfeld, D., Rudich, Y., & Lahav, R. (2001). Desert dust suppressing precipitation: A possible desertification feedback loop. Proceedings of the National Academy of Sciences, 98, 5975–5980. doi:10.1073/pnas.101122798.

Rosenfeld, D., Rudich, Y., & Lahav, R. (2008). Desert dust suppressing precipitation: A possible desertification feedback loop. Proceedings of the National Academy of Sciences, 105(9), 3519-3524.

Rosenfeld, D., Sherwood, S., Wood, R., & Donner, L. (2013). Climate effects of aerosol-cloud interactions. Science, 340(6138), 1055-1060.

Rotstayn, L. D. (2000). On the tuning of autoconversion parameterizations in climate models. Journal of Geophysical Research, 105, 15,495–15,507. doi:10.1029/2000JD900129.

Rotstayn, L. D., & Penner, J. E. (2001). Indirect aerosol forcing, quasiforcing, and climate response. Journal of Climate, 14, 2960–2975. doi:10.1175/1520-0442(2001)014<2960:IAFQFA>2.0.CO;2.

Rutledge, S. A., Houze Jr., R. A., Biggerstaff, M. I., & Matejka, T. (1988). The Oklahoma-Kansas mesoscale convective system of 10–11 June 1985: Precipitation structure and single-Doppler radar analysis. Monthly Weather Review, 116, 1409–1430.

Schwikowski, M., Doscher, A., Gaggeler, H. W., & Schotterer, U. (1999). Anthropogenic versus natural sources of atmospheric sulphate from an Alpine ice core. Tellus B, 51, 938–951.

Seifert, A., & Beheng, K. D. (2006). A two-moment cloud microphysics parameterization for mixed-phase clouds: Part 2. Maritime vs. continental deep convective storms. Meteorology and Atmospheric Physics, 92, 67–82. doi:10.1007/s00703-005-0113-3.

Sekiguchi, M., Nakajima, T., Suzuki, K., Kawamoto, K., Higurashi, A., Rosenfeld, D., Sano, I., & Mukai, S. (2003). A study of the direct and indirect effects of aerosols using global satellite data sets of aerosol and cloud parameters. Journal of Geophysical Research, 108(D22), 4699. doi:10.1029/2002JD003359.

Shepherd, J. M. (2005). A review of current investigations of urban-induced rainfall and recommendations for the future. Earth Interactions, 9(12), 1–27. doi:10.1175/EI156.1.

Solmon, F., et al. (2015). Modeling dust and soluble iron deposition to the South Atlantic Ocean. Atmospheric Chemistry and Physics, 15(9), 5445-5465.

Solomon, S., Qin, M., Manning, Z., Chen, M., Marquis, K. B., Averyt, M. T., & Miller, H. L. (2007). Summary for policymakers. In Climate Change 2007: The Physical Science Basis;

Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., & Miller, H. L. (Eds.); Cambridge University Press.

Song, X., & Zhang, G. J. (2011). Microphysics parameterization for convective clouds in a global climate model: Description and single-column model tests. Journal of Geophysical Research, 116, D02201. doi:10.1029/2010JD014833.

Sorooshian, A., Feingold, G., Lebsock, M. D., Jiang, H., & Stephens, G. (2009). On the precipitation susceptibility of clouds to aerosol perturbations. Geophysical Research Letters, 36, L13803. doi:10.1029/2009GL038993.

Sorooshian, A., Shingler, T., Harpold, A., Feagles, C. W., Meixner, T., & Brooks, P. D. (2013). Aerosol and precipitation chemistry in the southwestern US. Atmospheric Chemistry and Physics, 13, 7361–7379. doi:10.5194/acp-13-7361-2013.

Sorooshian, A., Wonaschutz, A., Jarjour, E. G., Hashimoto, B. I., Schichtel, B. A., & Betterton, E. A. (2011). An aerosol climatology for a rapidly growing arid region (southern Arizona): Major aerosol species and remotely sensed aerosol properties. Journal of Geophysical Research, 116, 19205. doi:10.1029/2011jd016197.

Squires, P. (1958). The microstructure and colloidal stability of warm clouds. Tellus, 10, 256–271.

Squires, P., & Twomey, S. (1966). A comparison of cloud nucleus measurements over central North America and Caribbean Sea. Journal of Atmospheric Sciences, 23, 401–404. doi:10.1175/1520-0469(1966)023<0401:ACOCNM>2.0.CO;2.

Steiger, S. M., & Orville, R. E. (2003). Cloud-to-ground lightning enhancement over southern Louisiana. Geophysical Research Letters, 30(19), 1975. doi:10.1029/2003GL017923.

Stevens, B., & Feingold, G. (2009). Untangling aerosol effects on clouds and precipitation in a buffered system. Nature, 461, 607–613. doi:10.1038/nature08281.

Storelvmo, T., Kristjánsson, J. E., Myhre, G., Johnsrud, M., & Stordal, F. (2006). Combined observational and modeling-based study of the aerosol indirect effect. Atmospheric Chemistry and Physics, 6, 3583–3601. doi:10.5194/acp-6-3583-2006.

Storer, R. L., van den Heever, S. C., & Stephens, G. L. (2010). Modeling aerosol impacts on convection under differing storm environments. Journal of the Atmospheric Sciences, 67, 3904–3915. doi:10.1175/2010JAS3363.1.

Stull, R. (2017). Practical Meteorology: An Algebra-based Survey of Atmospheric Science. Version 1.02b. Vancouver, Canada.

Sultan, B., & Janicot, S. (2003). The West African Monsoon dynamics. Part II: The "preonset" and "onset" of the summer monsoon. Journal of Climate, 16(21), 3407-3427.

Sun Y. & Zhao C. (2021). Distinct impacts on precipitation by aerosol radiative effect over three different megacity regions of eastern China. Atmospheric Chemistry and Physics, 21, 16555–16574. https://doi.org/10.5194/acp-21-16555-2021.

Sylla, M. B., Faye, A., Klutse, N. A. B., & Dimobe, K. (2018). Projected increased risk of water deficit over major West African river basins under future climates. Climate Change, Springer Nature B.V. https://doi.org/10.1007/s10584-018-2308-x.

Takemura, T., Nozawa, T., Emori, S., Nakajima, T. Y., & Nakajima, T. (2005). Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model. Journal of Geophysical Research, 110, D02202. doi:10.1029/2004JD00502.

Tao, W. K. (2007). Cloud resolving modeling. Journal of the Meteorological Society of Japan, 85B, 305–330. doi:10.2151/jmsj.85B.305.

Tao, W.-K., Li, X., Khain, A., Matsui, T., Lang, S., & Simpson, J. (2007). Role of atmospheric aerosol concentration on deep convective precipitation: Cloud-resolving model simulations. Journal of Geophysical Research, 112, D24S18. doi:10.1029/2007JD008728.

Teixeira, E. C., Migliavacca, D., Pereira, S., Machado, A. C. M., & Dallarosa, J. B. (2008). Study of wet precipitation and its chemical composition in South of Brazil. Anais da Academia Brasileira de Ciências, 80, 381–395.

Teller, A., & Levin, Z. (2006). The effects of aerosols on precipitation and dimensions of subtropical clouds: A sensitivity study using a numerical cloud model. Atmospheric Chemistry and Physics, 6, 67–80. doi:10.5194/acp-6-67-2006.

Touré, N. E., Konaré, A., & Silué, S. (2012). Intercontinental Transport and Climatic Impact of Saharan and Sahelian Dust. Advances in Meteorology, 2012, Article ID 157020, 14 pages.

Twohy, C. H., Petters, M. D., Snider, J. R., Stevens, B., Tahnk, W., Wetzel, M., Russell, L., & Burnet, F. (2005). Evaluation of the aerosol indirect effect in marine stratocumulus clouds: Droplet number, size, liquid water path, and radiative impact. Journal of Geophysical Research, 110, D08203. doi:10.1029/2004JD005116.

van den Heever, S. C., & Cotton, W. R. (2007). Urban aerosol impacts on downwind convective storms. Journal of Applied Meteorology and Climatology, 46, 828–850. doi:10.1175/JAM2492.1.

van den Heever, S. C., Carrio, G., Cotton, W. R., DeMott, P. J., & Prenni, A. J. (2006). Impacts of nucleating aerosol on Florida convection: Part I. Mesoscale simulations. Journal of the Atmospheric Sciences, 63, 1752–1775. doi:10.1175/JAS3713.1.

van den Heever, S. C., Stephens, G. L., & Wood, N. B. (2011). Aerosol indirect effects on tropical convection characteristics under conditions of radiative-convective equilibrium. Journal of the Atmospheric Sciences, 68, 699–718. doi:10.1175/2010JAS3603.1.

Wake, C. P., Mayewski, P. A., Wang, P., Yang, Q. H., Han, J. K., & Xie, Z. H. (1992). Anthropogenic sulfate and Asian dust signals in snow from Tien-Shan, northwest China. Annals of Glaciology, 16, 45–52.

Wang, C. (2005). A model study of the response of tropical deep convection to the increase of CCN concentration: 1. Dynamics and microphysics. Journal of Geophysical Research, 110, D21211. doi:10.1029/2004JD005720.

Wang, C., & Chang, J. S. (1993). A three-dimensional numerical model of cloud dynamics, microphysics, and chemistry: 1. Concepts and formulation. Journal of Geophysical Research, 98, 14,827–14,844. doi:10.1029/92JD01393.

Wang, M., & Penner, J. (2009). Aerosol indirect forcing in a global model with particle nucleation. Atmospheric Chemistry and Physics, 9, 239–260. doi:10.5194/acp-9-239-2009.

Wang, M., & Penner, J. E. (2010). Cirrus clouds in a global climate model with a statistical cirrus cloud scheme. Atmospheric Chemistry and Physics, 10, 5449–5474. doi:10.5194/acp-10-5449-2010.

Warner, J. (1968). A reduction in rainfall associated with smoke from sugar-cane fires: An inadvertent weather modification? Journal of Applied Meteorology, 7, 247–251. doi:10.1175/1520-0450(1968)007<0247:ARIRAW>2.0.CO;2.

Warner, J., & Twomey, S. (1967). The production of cloud nuclei by cane fires and the effects on cloud droplet concentration. Journal of the Atmospheric Sciences, 24, 704–706. doi:10.1175/1520-0469(1967)024<0704:TPOCNB>2.0.CO;2.

Wilcox, E. M., Lau, K. M., & Kim, K. M. (2010). A northward shift of the North Atlantic Ocean Intertropical Convergence Zone in response to summertime Saharan dust outbreaks. Geophysical Research Letters, 37, L04804. doi:10.1029/2009GL041774.

Williams, E., Rosenfeld, D., Madden, N., Gerlach, J., Gears, N., Atkinson, L., Dunnemann, N., Frostrom, G., Antonio, M., Biazon, B., Camargo, R., Franca, H., Gomes, A., Lima, M., Machado, R., Manhaes, S., Nachtigall, L., Piva, H., Quintiliano, W., Machado, L., Artaxo, P., Roberts, G., Renno, N., Blakeslee, R., Bailey, J., Boccippio, D., Betts, A., Wolff, D., Roy, B., Halverson, J., Rickenbach, T., Fuentes, J., & Avelino, E. (2002). Contrasting convective regimes over the Amazon: Implications for cloud electrification. Journal of Geophysical Research, 107(D20), 8082. doi:10.1029/2001JD000380.

Wolfe, A. P., Van Gorp, A. C., & Baron, J. S. (2003). Recent ecological and biogeochemical changes in alpine lakes of Rocky Mountain National Park (Colorado, USA): a response to anthropogenic nitrogen deposition. Geobiology, 1, 153–168.

Xue, H., & Feingold, G. (2006). Large-eddy simulations of trade wind cumuli: Investigation of aerosol indirect effects. Journal of the Atmospheric Sciences, 63, 1605–1622. doi:10.1175/JAS3706.1.

Yu, Q. R., Zhang, F., Li, J., & Zhang, J. (2019). Analysis of sea-salt aerosol size distributions in radiative transfer. Journal of Aerosol Science, 129, 71–86.

Yuan, T., Remer, L. A., Pickering, K. E., & Yu, H. (2011). Observational evidence of aerosol enhancement of lightning activity and convective invigoration. Geophysical Research Letters, 38, L04701. doi:10.1029/2010GL046052.

Zhang, F., Yu, Q.-R., Mao, J.-L., Dan, C., Wang, Y., He, Q., Cheng, T., Chen, C., Liu, D., & Gao, Y. (2020). Possible mechanisms of summer cirrus clouds over the Tibetan Plateau. Atmospheric Chemistry and Physics, 20, 11799–11808. https://doi.org/10.5194/acp-20-11799-2020.

Zhang, L., Fu, T.-M., Tian, H., Ma, Y., Chen, J.-p., Tsai, T.-C., et al. (2020). Anthropogenic aerosols significantly reduce mesoscale convective system occurrences and precipitation over Southern China in April. Geophysical Research Letters, 47, e2019GL086204. https://doi.org/10.1029/2019GL086204.

Zhang, M.; Deng, X.; Zhu, R.; Ren, Y.; Xue, H. (2021). The Impact of Aerosol Vertical Distribution on a Deep Convective Cloud. *Atmosphere*, *12*, 675. https://doi.org/10.3390/atmos12060675.