Modeling the Influence of Biomass Burning Haze on Extreme Rainfall Events

DISSERTATION

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Abstract

Biomass burning is a major contributor to atmospheric aerosols globally, releasing over 2 Pg C annually, with West Africa experiencing widespread biomass burning during the December-February dry season that results in a thick haze layer known as the "Harmattan." This seasonal phenomenon significantly impacts air quality and regional climate across the region, with major cities like Lagos, Nigeria (population exceeding 14 million) being particularly vulnerable to compounding impacts of seasonal biomass burning pollution. Devastating flood events, such as those occurring on July 10, 2011, and July 16, 2021, have resulted in significant infrastructural damage and loss of human life in Lagos. While growing evidence suggests that the Saharan Air Layer and Harmattan haze may play a crucial role in modulating West African monsoon patterns and rainfall intensity, there remains a critical knowledge gap regarding the specific impacts of biomass burning emissions on extreme precipitation events and urban flooding in rapidly developing coastal megacities. Despite emerging insights into aerosol-climate interactions, limited research has quantified the direct influence of long-range transported biomass-burning aerosols within the Harmattan haze layer on anomalous precipitation and flooding in coastal population centers.

This research aims at studying the intercorrelation between biomass burning haze and regional climate in Lagos, Nigeria, with particular focus on extreme rainfall events that led to devastating floods in July 2011 and July 2021 using numerical modeling and simulations. Despite growing evidence of the influence of atmospheric aerosols on weather patterns, there remains a critical knowledge gap regarding the specific impacts of biomass burning emissions on extreme precipitation events and urban flooding in rapidly developing coastal megacities like Lagos. This study addresses this gap by using a numerical model, Weather Research and Forecasting (WRF) model to simulate these significant flooding episodes and examining the underlying meteorological mechanisms that contribute to urban flooding.

Using the WRF model with different microphysics schemes (Thompson and WSM6), the research evaluates the model's capability to simulate extreme precipitation events and examines the complex interactions between biomass burning haze, atmospheric dynamics, and precipitation processes. The study employs a multi-faceted methodological approach combining satellite

remote sensing, numerical modeling, and statistical validation. The Thompson scheme showed superior overall performance, achieving RMSE reductions of 15-31% during the 2011 event and 11-25% during 2021 compared to the WSM6 scheme. Analysis revealed significant changes in precipitation patterns between the two events, with maximum flood intensity decreasing from 1,053.37mm in 2011 to 760.47mm in 2021, accompanied by a spatial shift in flood vulnerability from western to eastern districts.

Key findings indicate substantial transformations in Lagos's urban climate system over the decade, including modifications in Land Surface Temperature (LST) patterns, with maximum LST in western regions decreasing from 42.85°C to 39.47°C, coinciding with increased surface albedo from 0.15 to 0.22. The research also identified strengthened correlations between aerosol patterns and precipitation ($\rho = 0.468$, $p = 1.44e-28$ in 2021, compared to $\rho = -0.215$, $p = 1.17e-06$ in 2011), suggesting enhanced aerosol-cloud-precipitation interactions.

The spatiotemporal evolution of fire events showed significant changes between the 2011 and 2021 study periods. In 2011, the pre-flood period recorded 11 fire events with a mean daily occurrence of 2.75, while the subsequent flood period showed an increase to 20 events and a mean daily occurrence of 5.00. In contrast, the 2021 data exhibited a different pattern with 21 fire events in the pre-flood period (mean daily occurrence of 10.50), followed by a sharp decline to just 1 event during the flood period. Statistical comparisons confirmed significant differences between the pre-flood and flood periods in both years (Mann-Whitney U test, $p < 0.05$).

Further analysis of fire characteristics revealed notable changes over the decade. The mean Fire Radiative Power (FRP) decreased from 26.88 MW in 2011 to 17.09 MW in 2021, while the spatial clustering of fire events intensified (Moran's I increased from 0.38 to 0.45, $p < 0.001$). The relationship between fire metrics also strengthened, with regression models showing improved predictive power (R^2 increasing from 0.80 to 0.981). These evolving fire patterns, including decreased intensity but increased spatial clustering, coincided with the transformation in flood characteristics observed between the two study periods.

The research also revealed complex interactions between microphysical processes, land-sea dynamics, and urban effects that fundamentally influence extreme precipitation events in Lagos.

Aerosol-cloud interactions demonstrated significant impact on precipitation efficiency. Cloud condensation nuclei (CCN) concentrations increased by 35% from 2011 to 2021 (550 cm^{-3} to 742 cm^{-3}), modifying cloud microphysical properties. This enhancement correlates with increased cloud liquid water content ($r = 0.84$, $p < 0.001$) and reduced warm rain efficiency in shallow convection.

The study's findings have significant implications for flood prediction and management in rapidly growing coastal cities, highlighting the need for enhanced monitoring systems, updated infrastructure specifications, and adaptive urban planning strategies. The research shows that successful operational implementation of flood forecasting requires real-time monitoring of sea surface temperatures and urban heat island intensity which has become crucial for accurate prediction of convective initiation and evolution.

This research contributes to the understanding of the complex interactions between biomass burning, urban development, and extreme weather events in tropical coastal environments, providing valuable insights for improving flood resilience in vulnerable urban areas. The findings suggest that significant improvements in flood prediction and response are achievable, provided appropriate consideration is given to local conditions and resources.

Keywords: Biomass burning, Weather Research and Forecasting (WRF) model, extreme precipitation, urban flooding, Lagos, microphysics schemes, aerosol-cloud interactions.

1 Chapter - Introduction

1.1 Background of Study

West Africa has experienced rapid population growth and ongoing deforestation, with the transformation of natural landscapes linked to extensive agricultural expansion and urbanization (Herrmann et al., 2020). A concern is the observed increasing trend in biomass burning during the winter dry season, as it rips through degraded forests and brushlands, whereas agricultural waste burning is adopted to rapidly clear fields between crops (van der Werf et al., 2017). Biomass is an organic substance derived from plants and animals and contains stored solar energy and commonly found in agricultural practices. Biomass contributes to attempts to reduce reliance on fossil fuels and combat climate change, while its sustainability and environmental impact might vary depending on how it is generated and used. This adds significant loads of light-absorbing black carbon and organic carbon particulate matter to the regional atmosphere (Eckhardt et al., 2019), which are then entrained within the Harmattan transcontinental plume and transported westward towards Nigeria and other southern Guinea coastal countries.

The seasonal evolution of the West African Monsoon comprises complex interactions between the prevailing winter Harmattan winds transporting hot and dusty air from the Sahara and meeting relatively cooler and moisture-rich air advected from the tropical Atlantic (Knippertz et al. 2017). However, this balance has come under threat from disruptions caused by climate change, which alters the natural progression and inland penetration of the seasonal monsoon (Knippertz et al., 2013). The strength and variability of the monsoon system influence the mesoscale storm organization and embedded propagating squall lines responsible for heavy precipitation events during the spring and summer months (Marsham, 2013).

Within coastal cities experiencing rapid population growth and infrastructure deficits, such as Lagos, Nigeria, extreme rainfall events often cause devastating flash flooding with considerable property damage and risks to human health (Lawanson et al., 2022). The underlying drivers of flooding disasters are complex and involve both natural climate variability and anthropogenic factors. Natural oscillations in dust and rainfall intensity are escalating regional signatures of climate change tied to land use changes, including extensive deforestation, fire-enabled agricultural practices, and coastal urban air pollutant emissions (Abiodun et al., 2013).

Atmospheric modeling indicates that precipitation extremes over West Africa are expected to intensify under warmer conditions (Weber et al., 2018). However, significant uncertainties remain regarding how elevated smoke particulate emissions from biomass burning interact with, and potentially magnify, the severity of these monsoon precipitation anomalies (Otoho et al., 2021). Smoke plumes can influence cloud microphysics through new particle formation processes from biomass burning vapors, whereas direct solar absorption by black carbon may enhance thermal gradients and influence mesoscale storm dynamics (Wang et al. 2015). Boundary layer ventilation of hot and dry air associated with absorbing smoke plumes could also potentially mask land-sea breeze fronts critical for the ascent of tropical waves emerging off Africa (Das et al., 2017). Further complexity arises from the limited knowledge of how smoke transport interacts with or directly alters the normally expected radiative effects of Saharan mineral dust, which also display considerable interannual variability and influence on regional atmospheric dynamics (Li et al., 2020).

This study aims to address these critical knowledge gaps by researching the attributable risk from seasonal pollution intensifying extreme weather exposures for vulnerable populations in southern Nigeria and similar West African cities that are critically underprepared to manage the growing threat of climate change. Through a combination of observational analysis and high-resolution climate modeling, this study explains the mechanisms by which unusually dense Harmattan smoke plumes may modulate monsoon progression and trigger devastating flood events in coastal megacities such as Lagos.

Importantly, the regional climate modeling approach employed in this study will allow the isolation of the specific impacts of biomass burning aerosols on monsoon dynamics and precipitation. By conducting sensitivity tests that systematically vary the radiative effects, concentration, and vertical structure of smoke particulates, researchers can understand the complexes through which the Harmattan haze layer causes extreme rainfall and flooding. This process-level understanding is crucial for improving the predictability of such high-impact events and informing climate adaptation strategies for vulnerable coastal cities.

Furthermore, this study has significant societal implications beyond advancing scientific knowledge. These findings have the potential to guide regional policy discussions on coordinating early season burning restrictions, as model-based assessments of smoke load reductions can avoid extreme rainfall events. Additionally, an improved understanding of smoke-monsoon interactions can inform the development of better early warning systems and infrastructure planning to enhance the resilience of rapidly growing urban centers such as Lagos. Addressing the disproportionate vulnerability of marginalized communities to climate-exacerbated disasters is a critical environmental justice concern for achieving sustainable development goals.

1.2 Problem Statement

Biomass burning is a major contributor to atmospheric aerosols and trace gases on a global scale, releasing over 2 Pg C annually (van Marle et al., 2017). The emissions from biomass burning have the potential to impact regional climate patterns by engaging in complex relationships with the radiation budget and cloud microphysical processes. These biomass-burning emissions can affect the regional climate through complex interactions with the radiation budget and cloud microphysical processes. West Africa frequently experiences widespread biomass burning from agricultural and savanna burning practices during the December-February dry season, resulting in a thick haze layer known as the "Harmattan" that significantly impacts visibility, air quality, and public health across the region (Yusuf et al., 2021). Major cities in southern Nigeria, such as Lagos, with over 14 million inhabitants, are particularly vulnerable to the impacts of seasonal biomass burning pollution (Dajuma et al., 2020). Elevated concentrations of Saharan dust and smoke within the Harmattan layer have been linked to extreme precipitation and flooding events in the coastal West Africa (Dajuma et al. 2020). For instance, on July 10, 2011, and July 16, 2021, Lagos experienced devastating floods that resulted in significant infrastructural damage and loss of human life (Adams, 2017; Higuera et al., 2021). While the general rainy season in West Africa and localized urban drainage issues are undoubtedly important factors contributing to these flood events, there is growing evidence that the Saharan Air Layer and Harmattan haze may also play a crucial role in modulating the West African monsoon pattern and rainfall intensity (Onyeisi, 2022). Specifically, by absorbing and scattering incoming solar radiation, the presence of elevated layers of Saharan and Sahelian smoke haze has been linked to decreased convective available potential energy (CAPE) and upper-level warming, which can increase the atmospheric stability over West Africa (Tosca et al., 2015). This could potentially disrupt the timing and intensity of West African Monsoon progression, with cascading effects on precipitation patterns.

However, despite these emerging insights, there has been limited research on quantifying the direct influence of long-range transport of biomass-burning aerosols within Harmattan on anomalous precipitation and flooding in coastal megacities, such as Lagos. While the general rainy season around July and inadequate drainage infrastructure clearly contribute to flood risk, recent studies suggest that biomass burning aerosols may play an under-recognized, yet potentially critical, role in exacerbating these extreme events. Addressing this knowledge gap is crucial because understanding the atmospheric mechanisms linking Harmattan smoke pollution to heavy precipitation events can improve the predictability of future flood disasters in Lagos and other vulnerable coastal cities in West Africa. Moreover, identifying the primary emission sources and regional climate impacts of biomass burning aerosols could inform targeted mitigation strategies to reduce the health and infrastructure risks posed by extreme weather in rapidly expanding urban areas. To date, regional climate modeling has not been extensively applied to investigate the sensitivity and microphysical mechanisms connecting the extent of the Harmattan haze to anomalous heavy precipitation events that affect megacities along the Guinea coast, such as Lagos (Pante et al., 2020). Through observational analysis and modeling, this study aims to analyze the intercorrelation between the Harmattan haze extent and aerosol optical depth with anomalous rainfall and flooding events in Lagos in 2011 and 2021. The primary goal was to determine the degree to which these high-impact floods are influenced by biomass-burning aerosols through microphysical and regional climate effects.

This will be accomplished using the advanced Weather Research and Forecasting (WRF) model to simulate the observed meteorological conditions leading up to and during flood episodes. The WRF model's capabilities in representing atmospheric processes, such as precipitation, wind patterns, and temperature variations, will be utilized to analyze the weather conditions contributing to these events. The simulations isolate the radiative and cloud microphysical impacts of smoke particulate concentrations representative of Harmattan conditions and characterize a range of flooding responses. These findings have the potential to enhance the predictability of future extreme weather in Lagos by constraining the impacts of biomass burning aerosols in regional modeling. Beyond improving scientific understanding, the societal implications of this study include identifying climate mitigation strategies to reduce the health and infrastructure impacts of extreme weather influenced by regional air pollution transport. The disproportionate vulnerability of marginalized communities in Lagos to climate-related disasters is a critical environmental justice concern that this study aims to address. Notably, the regional climate modeling approach used in this study allowed the isolation of the specific impacts of biomass-burning aerosols on monsoon dynamics and precipitation. By conducting sensitivity tests that systematically vary the radiative effects, concentration, and vertical structure of smoke particulates, researchers can break the complex ways through which the Harmattan haze layer can cause extreme rainfall and flooding. This process-level understanding is crucial for improving the predictability of such high-impact events and informing climate adaptation strategies for vulnerable coastal cities.

Despite the recognized importance of this issue, there has been limited research on quantifying the specific mechanisms and sensitivities connecting smoke pollution with monsoon dynamics and high-impact weather extremes. Addressing this knowledge gap through observational analysis and advanced regional climate modeling has the potential to improve the predictive capabilities, guide targeted mitigation strategies, and enhance the climate resilience of vulnerable urban populations.

1.3 Aims and Objectives of study

The main purpose of this research is to advance the scientific understanding of the influences and sensitivities of long-range transported biomass burning emissions within the Harmattan haze layer, as it relates to anomalous rainfall and flooding of coastal population centres in southern West Africa. Climate change is a growing threat in West Africa, affecting population vulnerabilities that are heightened by extensive poverty and gaps in critical infrastructure. Coastal megacities, such as Lagos, with complex dynamics between urbanization, air pollution, and extreme weather, are at the frontlines facing acute climate risks from flooding, heatwaves, water scarcity, and landslides. Identifying how anthropogenic activities increase the severity of these extreme events can allow for evidence-based adaptation initiatives that protect vulnerable residents and safeguard economic stability.

Given that the anthropogenic fires generate smoke pollution are entirely preventable through shifts in savanna and agricultural management practices, there is an urgent need to establish whether the density of these emissions reaching cities, such as Lagos, has a quantifiable climate impact that has provoked flood disasters in recent years that claim lives and critical infrastructure. Through the application of Earth observation data analysis combined with targeted climate modeling experiments, this research aims to reduce gaps in understanding the surrounding smoke-rainfall connections over West Africa. These findings can compel regional policy discussions regarding coordinated early season burning restrictions if modeled smoke load reductions show a reduction in extreme rainfall events.

Primary Research Aim: To evaluate the capability of the Weather Research and Forecasting (WRF) model in simulating extreme rainfall events that triggered severe flooding in Lagos, Nigeria, during July 2011 and July 2021.

Supporting Objectives:

1. To determine which microphysics parameterization scheme (Thompson or WSM6) provides more accurate rainfall predictions when modeling these intense precipitation episodes over the Lagos region.
2. To identify the synoptic-scale weather systems and local topographic/oceanic factors that contributed to the development of intense heavy rainfall.
3. To analyse the model's performance in simulating key meteorological variables (rainfall, temperature, wind speed) across six locations in Lagos during these flood events.

These findings have the potential to improve predictive capabilities, inform targeted mitigation strategies, and enhance the climate resilience of vulnerable urban populations facing compounding threats from urbanization, air pollution, and weather extremes.

1.4 Research Question

The objective of this research was to investigate the influence of long-range transported biomass burning aerosols within the Harmattan haze layer on anomalous rainfall and flooding in coastal West African cities, focusing on Lagos, Nigeria. To research this question, this study addresses the following key research questions:

1. How effective is the Weather Research and Forecasting (WRF) model, particularly using the Thompson microphysics scheme compared to WSM6, in simulating extreme rainfall events that led to flooding in Lagos during July 2011 and July 2021?
2. What are the specific meteorological mechanisms and atmospheric conditions that contributed to the development of extreme rainfall and subsequent flooding events in Lagos during these periods and how does the model represent these processes?
3. How do the spatial and temporal patterns of rainfall, temperature, and wind speeds differ between the July 2011 and July 2021 flooding events, and what implications do these patterns have for flood prediction in Lagos?
4. To what extent can the integration of satellite data (MERRA-2), ground-based measurements, and WRF model simulations improve our understanding and prediction capabilities of extreme rainfall events in Lagos's tropical coastal urban environment?

Hypothesis

This research is guided by a set of interrelated hypotheses that aim to explain the specific mechanisms through which the Harmattan haze layer and its anomalous characteristics can influence precipitation patterns and trigger extreme flooding events in coastal West African cities, such as Lagos.

Key Hypotheses:

1. **Primary Hypothesis:** The Thompson microphysics scheme in the WRF model provides more accurate predictions of extreme rainfall events in Lagos compared to the WSM6

scheme due to its more sophisticated representation of cloud microphysics and precipitation processes.

2. **Secondary Hypotheses:**

a) Coastal-Urban Interaction Hypothesis: The interaction between Lagos's coastal location and urban heat island effects creates unique meteorological conditions that intensify precipitation during extreme rainfall events, which can be better captured by the Thompson scheme.

b) Temporal Evolution Hypothesis: The spatial and temporal patterns of rainfall during flood events (July 2011 vs July 2021) show distinct characteristics that are influenced by changes in urban development and local climate patterns over the decade.

c) Model Performance Hypothesis: The WRF model's accuracy in predicting extreme rainfall events varies significantly across different locations within Lagos due to local topographical and land-use variations.

Systematic testing of these hypotheses through observational analysis and targeted modeling experiments will advance scientific understanding, provide valuable insights for regional policymakers, and contribute to improving the predictability of future flood disasters in vulnerable coastal populations

1.5 Significance of the Study

This study presents novel and innovative research on coupled regional climate modeling to characterize the process-level dynamics of how an exceptionally dense Harmattan haze layer interacts with the seasonal evolution of the West African monsoon and affects heavy precipitation anomalies associated with recent flooding disasters around Lagos. Although several literature studies the general impacts of smoke and dust on the regional radiation budget over West Africa, the specific sensitivities isolating the microphysical to synoptic-scale responses of severe biomass-burning pollution exist as a critical knowledge gap that involve the prediction capabilities for such high-impact events.

Constraining the modeled atmospheric mechanisms offers a guide to early burning restrictions or land management shifts, particularly regarding the optical and microphysical properties of dust-smoke mixtures and the transformation of organic species that alter cloud nucleation behavior (Ansmann et al., 2023). While general smoke and dust impacts on West African radiation budgets have been explored, the specific modeling sensitivities isolating biomass-burning pollution transport and particulate attributes modulating dynamics along critical weather fronts remain poorly understood.

Specific simulations were implemented to constrain the plausibility of smoke particulate-modifying features, such as marine layer depth, sea surface temperature distributions, convective available potential energy, mid-level lapse rates, capping inversions, or low-level shear. The development of these parameters influences the propagation timing and inland penetration fluxes of moisture, which fuels the training of convective cells or clustered supercells. By thoroughly sampling modeled microphysics schemes over areas where smoke particulates alter droplet concentrations, coalescence efficiencies, rainout rates, hydrometeor species interactions, and outflow strength, improved fidelity connecting aerosol perturbation with dynamics at gust fronts and propagating squall lines enables a more credible attribution of extreme tropical cyclogenesis or stalled training storms responsible for recording flooding.

The results surrounding circulation anomalies and rainfall triggers promise societal value guiding resilience initiatives, while showcasing the disproportionate vulnerability of expanding African cities facing climate risks exacerbated by seasonal pollution originating from remote distances. Beyond the theoretical contributions reconciling plume transport with rainfall intensification rooted in smoke-monsoon feedback, the findings have the potential to aid municipal resilience initiatives through probabilistic flood early warning systems or infrastructure investments resilient against future exposure risks exacerbated by climatic and land-use changes.

Furthermore, the innovative modeling approach employed in this study offers significant methodological contributions. The systematic testing of hypotheses through WRF sensitivity experiments, guided by comprehensive observational data, offers a robust framework for investigating interactions between aerosols and monsoonal dynamics. This approach can be extended to other regions experiencing similar meteorological challenges. The insights gained regarding the relative importance of radiative and microphysical effects as well as the role of smoke aging processes can inform the development of more accurate parameterizations in regional climate models.

Beyond the West African context, the findings of this study may provide valuable insights for understanding and mitigating the challenges posed by biomass burning pollution and extreme weather in other parts of the world. Similar dynamics have been observed in regions such as Southeast Asia, where haze from agricultural and forest fires has been linked to disruptions in monsoon patterns and increased flood risk in densely populated coastal cities (Hertwig et al., 2021).

The implications also raise environmental justice concerns over how marginalized urban groups disproportionately shoulder first and worst damages from extreme events compounded by seasonal pollution often originating thousands of kilometers away. By identifying the pathways through which smoke pollution amplifies flood risk, this study can inform equitable adaptation strategies to protect the most vulnerable populations.

1.6 Delimitation of the Study

This study is geographically delimited to focus on West Africa, particularly analyzing the influence of biomass burning emissions transported within the Harmattan air layer over southern Nigeria and the populated coastal city of Lagos. This regional focus is justified by the significant vulnerability of West African cities, such as Lagos, to the compounding impacts of climate change, urbanization, and air pollution, as evidenced by devastating flood events in recent years.

The temporal scope of the study is concentrated in the summer monsoon season from June to July, when the westward progression of Harmattan occurs with the onset of heavy seasonal precipitation. This period is crucial for understanding the interactions between the Harmattan haze layer and the West African Monsoon system, which governs rainfall patterns and flood risk for coastal cities.

Regarding the target flood events, the delimitation encompasses two recent historical episodes in Lagos that occurred on July 10, 2011, and July 16, 2021. While other African cities may experience similar flooding, the case events are limited to Lagos because of the availability of high-quality observational data, including rain gauge records and detailed accounts of the infrastructure impacts, which warrant further investigation.

In terms of the modeling approach, the WRF simulations implemented in this study utilized boundary conditions from the MERRA-2 reanalysis data from March- September of the focus years. This temporal range is adequate to resolve the meteorological interactions leading up to the flooding episodes while also capturing the seasonal evolution of the Harmattan haze layer and its potential influence on the West African Monsoon progression.

Regarding the analysis of atmospheric processes, this study primarily focused on lower-tropospheric dynamics, particularly planetary boundary layer evolution, cloud microphysics, thermodynamic profiles, and mesoscale convective systems underlying the observed precipitation rates and flooding potential in Lagos.

The microphysics schemes tested in WRF focused on warm rain production tied to changes in aerosol activation, condensation, collision-coalescence efficiencies, precipitation formation rates, and below-cloud evaporation processes modulated by biomass-burning smoke--particle interactions. Cloud-aerosol indirect effects linked to smoke that modified storm intensity were prioritized over the detailed direct radiative forcing from particulate absorption alone. This targeted approach enabled a more thorough exploration of the microphysical pathways through which Harmattan smoke can influence precipitation patterns and trigger flooding in coastal cities.

Concerning the chemical composition of aerosols, this study focused on constraining the emissions and transport of smoke particulate matter from open burning practices, including wildfires and agricultural residue fires in West Africa during the summer monsoon season. Although mineral dust and sea salt particles showed significant spatiotemporal variability, the total aerosol representations were simplified by isolating the contributions of biomass burning to the simulated composition, hygroscopicity, and optical properties of the intruding Harmattan haze layers influencing southern Nigeria.

While the study is geographically and temporally delimited, the findings and methodological approaches have broader applicability. The insights gained regarding the interactions between biomass burning aerosols and monsoon systems may provide valuable lessons for understanding and mitigating similar challenges in other regions facing compounding threats of climate change, urbanization, and air pollution.

1.7 Organization of Thesis

This thesis is organized into five chapters that cohesively present the research objectives, methodologies, findings, and implications of the study, examining the influence of Harmattan smoke pollution on flooding events in coastal West African cities, with a focus on Lagos.

Chapter 1 provides the necessary background, problem statements, and research questions for the study. This establishes the critical context of rapid urbanization, deforestation, and increasing biomass burning in West Africa, and how these factors contribute to the formation and transport of the Harmattan haze layer. This chapter also shows the vulnerability of coastal megacities, such as Lagos, to the compounding impacts of extreme weather, air pollution, and climate change. Importantly, it identifies the key knowledge gaps surrounding the quantification of smoke-monsoon-precipitation linkages and the need for advanced regional climate modeling to explain these complex mechanisms.

Building on this foundation, Chapter 2 offers a full review of the relevant literature, covering topics such as the West African climate system, the characteristics and impacts of biomass burning emissions, and the current scientific understanding of aerosol-monsoon interactions. This chapter synthesizes existing knowledge and provides a theoretical basis for the hypotheses guiding the research.

Chapter 3 outlines the methodological approach employed in this study. It details the observational data sources, including satellite remote sensing and ground-based measurements, used to characterize the Harmattan haze layer during selected flood events in Lagos. Additionally, it describes the implementation of the coupled meteorology atmospheric WRF model, the optimization of model performance using observational constraints, and the design of targeted sensitivity experiments to isolate the impacts of smoke pollution on regional climate and precipitation patterns.

The results of the observational analysis and modeling experiments are presented in Chapter 4. This chapter shows the exceptional nature of the Harmattan haze during flood events, quantifying the anomalies in aerosol optical depth, particulate concentrations, and vertical plume structure compared to seasonal norms. It then investigates the findings from WRF simulations, elucidating the specific atmospheric mechanisms and meteorological thresholds through which Harmattan smoke pollution modulates monsoon dynamics and triggers extreme precipitation over Lagos.

Section 5 discusses the broader implications of the research findings. It situates the study within the current scientific discourse on extreme weather event attribution, showing novel contributions to understanding smoke-monsoon-precipitation linkages. This chapter also explores the potential policy relevance of the results, including the identification of emission reduction strategies and the development of early warning systems and climate-resilient infrastructure for vulnerable coastal cities. Furthermore, it addresses environmental justice concerns raised by the disproportionate exposure of marginalized urban communities to climate-exacerbated disasters driven by long-range air pollution transport.

Finally, The appendix contains the list of terms used throughout the study period and the terms and defined for better understanding of the study.

Throughout the thesis, the organization follows a logical progression, building from the problem statement and research objectives in Chapter 1 to the theoretical foundations in Chapter 2, the detailed methodology in Chapter 3, the presentation of results in Chapter 4, and finally, the discussion of implications and conclusions in Chapter 5. The structure permits an extensive and thorough investigation of the research subject, incorporating observational analysis, modeling experiments, and policy-driven perspectives in a cohesive manner.

2 Chapter - Literature Review

Biomass burning has become a growing concern in recent decades, owing to its impact on regional and global climates (Yadav et al., 2017). Smoke and air pollution generated by biomass burning can spread over large areas, leading to decreased air quality, public health hazards, and changes in weather patterns and climate. Understanding the complex relationship between biomass burning aerosols and regional climate dynamics is an important research area (Brown et al., 2021). Biomass burning refers to the burning of living and dead vegetation including forests, grasslands, and crop residues (Yadav et al., 2017). It is a global phenomenon caused by both natural and anthropogenic factors. Wildfires ignited by lightning strikes are a natural source of biomass burning (Yadav et al., 2017). However, Roy et al. (2022) observed that a significant portion of biomass burning results from anthropogenic activities such as deforestation, shifting cultivation, and burning of agricultural waste. Biomass burning occurs in every inhabited continent and releases large amounts of trace gases and aerosols into the atmosphere (Voulgarakis et al. 2015). Studies have estimated that biomass burning contributes–25-35% of the global CO2 emissions from combustion (Vicente and Alves, 2018). It is also responsible for 30% of total global emissions of carbon monoxide, particulate organic carbon, and non-methane volatile organic compounds (Andreae, 2019). The bulk of present-day biomass burning occurs in tropical regions of Africa, South America, and Southeast Asia. Specific regions with high fire activity include the forests of the Amazon basin, savannas of sub-Saharan Africa, and the forests and peatlands of Indonesia. The main gases released from biomass burning include carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), volatile organic compounds (VOCs), nitric oxide (NO), and nitrous oxide (N2O) (Andreae, 2019). The key aerosols and particulates emitted include organic carbon, black carbon, potassium, and ammonium (Reddington et al. 2016).

Biomass-burning aerosols contain light-absorbing compounds, such as black carbon, that heat the atmosphere (Brown et al., 2021). They also include light-scattering components such as organic carbon and sulfates, which cool the atmosphere by reflecting incoming solar radiation (Wu, 2021). The exact quantities and properties of the emissions depend on the combustion conditions and fuel type. For example, flaming fires such as wildfires emit increased levels of CO2, CO, CH4, and black carbon because of their higher combustion efficiency (Wiggins et al., 2021).

In contrast, smoldering peat fires release more methane and volatile organic compounds (VOC) owing to lower oxygen availability and incomplete combustion (Raza et al., 2023). The chemical composition of vegetation also affects the nature of the particulate matter released (Raza et al., 2023). The physics and chemistry of biomass burning plumes are complex. Gases and aerosols undergo chemical transformations in the atmosphere via oxidation and photolysis (Gen et al., 2022). Smoke particles interact with water vapor to form cloud condensation nuclei, which eventually develop into clouds (Raza et al., 2023). The radiative effects of biomass burning aerosols can change surface temperatures and precipitation patterns over thousands of kilometers downwind (Huang et al., 2023). Overall, biomass burning significantly alters the atmospheric chemistry and Earth's radiative balance on a regional to global scale.

This literature review aims to understand current research on the sources and extent of biomass burning worldwide. It will examine the composition of biomass burning haze and its impacts on the regional climate and air quality. This review analyzes the correlations between biomass burning and changes in regional temperatures, rainfall, and extreme weather events. The environmental and human health implications of these interconnections are discussed. Finally, this review summarizes the state of knowledge on this topic and shows areas requiring further research, with the goal of informing science-based policies to mitigate the climate impacts of biomass burning. A detailed review of the literature is required to fully elucidate the intricate linkages between biomass burning patterns and climatic effects on a regional scale.

Biomass burning has become a major contributor to climate change, accounting for a significant portion of carbon dioxide and other greenhouse gas emissions (Chen et al., 2017). However, the impact of biomass burning exceeds its contribution to global climate change. Smoke and particulate matter released from forest and savanna fires can affect the regional climate through changes in surface albedo, cloud formation, and precipitation patterns (Artaxo et al., 2022).

Recognizing the interrelationships between biomass burning and regional climatic consequences is of paramount importance for several reasons. This knowledge can significantly improve climate modeling and prediction capabilities, particularly for vulnerable regions prone to wildfires, as climate models must incorporate the regional climatic effects of smoke aerosols to generate accurate forecasts. Additionally, this understanding directly informs mitigation strategies designed to reduce the impact of biomass burning on climate, ensuring that policies targeting reductions in deforestation fires or agricultural burning account for the coupled effects on regional climate systems.

From a public health perspective, this research reveals the risks of smoke pollution and helps guide preparedness efforts, as knowledge of how smoke episodes may exacerbate heatwaves or droughts can substantially improve public health planning and response strategies. Furthermore, these understanding aids attribution studies of climate extremes affected by fire emissions, ranging from severe storms to heatwaves, where detecting the influence of biomass burning enhances scientific understanding of these complex events and contributes to more accurate prediction and assessment of future climate risks.

2.1 Theoretical Framework

Several key theoretical frameworks provide a context for investigating biomass burning-monsoon interactions. The aerosol-cloud-precipitation paradigms posit complex microphysical linkages between elevated smoke particulate emissions and storm development processes tied to rainfall rates (Rosenfeld et al., 2008). Related pollution-weather regimes examine the boundary layer impacts that provoke mesoscale anomalies (Lin et al., 2006). Climatic feedback frameworks link biogeophysical impacts of land-use changes that escalate seasonal burning (Ghazoul et al. 2004). At the system level, a coupled modeling approach leverages synergies across these frameworks, integrating source emission dynamics with chemical transport and radiation modulation, which subsequently forces shifts in stability, circulation, and convective triggering that ultimately connect back to the precipitation efficiency.

Specifically, for West Africa, the strong evidence on Saharan dust modulation provides an analog with biomass burning, which requires layered theoretical treatment regarding mixtures, transport pathways, and wet deposition rates from Harmattan advance relative to baseline conditions (Lau et al., 2009).

The theoretical frameworks that can be applied to the influence of biomass burning emissions on West African monsoon rainfall and flooding events are as follows:

Aerosol-Cloud Interactions Framework examines how aerosol particles influence cloud microphysical processes such as droplet nucleation, condensation and coalescence rates, precipitation efficiency, and storm dynamics (Albrecht, 1989; Rosenfeld et al., 2008). This is particularly relevant when studying smoke interaction. The Aerosol-Precipitation Interactions Framework focuses on micro-to-synoptic-scale feedback between pollution particulates and precipitation formation, distribution, and intensity (Tao et al., 2012). Applicable to constraining smoke effects on rainfall. Land-Atmosphere Interactions Framework investigates two-way coupling surrounding changes in vegetation, soil moisture, and surface energy balance impacts on regional climate through boundary layer, stability, and circulation modulation (Findell et al., 2006). It can elucidate the climate effects from escalating seasonal fires. Weather modification frameworks are centered on intentional and inadvertent changes in cloud microphysics, storm intensities, and rainfall patterns from atmospheric particulate matter pollution, which alter moisture and heat fluxes (Cotton and Pielke, 2007). The number of studies examining the attribution of climate forcing to aerosol emissions has increased.

2.1.1 Aerosol-Cloud Interactions Framework

The aerosol-cloud interaction (ACI) framework establishes the theoretical underpinnings related to how the increased loading of fine suspension particles, such as those from biomass burning smoke plumes, can alter cloud droplet nucleation, growth, and precipitation efficiency (Albrecht, 1989). This, in turn, affects cloud lifetime/distribution, albedo, dynamics, and ultimately, rainfall patterns. Increased particulate numbers serve as additional cloud condensation nuclei (CCN) which affect droplet number concentrations, a fundamental cloud microphysical attribute modulating rainfall formation, storm structure, and radiative transfer (Hobbs, 1993). Smaller droplets require longer timescales for efficient collision-coalescence, delaying the onset of precipitation, which generates clouds with a greater liquid water path and depth, and an aerosol indirect effect (Liu and Daum, 2002). The contemporary importance of the ACI framework emerges from the escalating anthropogenic particulate pollution, which interacts with global weather and climate dynamics (Tao et al., 2012). In West Africa, increased seasonal smoke may intensify rain downwind of dense plumes through more vigorous coalescence with warm rain processes while delaying onset elsewhere from CCN suppression (Hodnebrog et al., 2016). ACI-realistic simulations better project changes in extreme event frequencies as both climate and land-use forces interact.

2.1.2 Aerosol-Precipitation Interactions Framework

The aerosol-precipitation interaction (API) framework examines the mechanisms by which increased atmospheric particulate matter (e.g., smoke and dust) modifies precipitation patterns across spatiotemporal scales through direct and indirect effects on cloud microphysics and regional hydrologic cycle processes (Tao et al., 2012). Fundamentally, aerosols influence the formation, intensity, and global distribution of rainfall through complex non-linear interaction pathways. Dust and smoke plumes exhibit distinctive microphysical properties compared with background environments, necessitating a layered approach (Rosenfeld et al., 2008). Absorbing smoke warms the air, preferentially lofting some plumes, whereas broad sub-saturations from high CCN loading can suppress nearby convection in others (Koren et al., 2014). The API framework is becoming increasingly useful for disentangling rainfall variability over West Africa, with seasonal pulses of Saharan dust now overlaid with intensifying regional biomass burning. Constraining the interaction mechanisms, thresholds, and downwind impacts enables a more accurate prediction of precipitation, flooding, and drought risks as the competition between natural and anthropogenic aerosols evolves (Lau and Kim, 2006). An API-grounded modeling approach for coastal West African cities facing escalating climate threats and pollution levels helps account for how exceptional particulate loading years may disrupt rainfall patterns (Kim et al., 2020). These findings can guide urban infrastructure adaptations that are more resilient to future exposure risk.

2.1.3 Land-Atmosphere Interactions Framework

The land–atmosphere interaction (LAI) framework is a research area that investigates the two-way coupling between changes in vegetation, soil moisture, and related impacts on surface energy balance, which, in turn, affect regional climate through boundary layer changes, stability modulation, and circulation patterns (Seneviratne et al., 2010). LAI emerged from the early challenges of climate modeling in representing land processes and the need for realistic parameterization of fluxes between soils, plant communities, and the atmosphere at the interface (Findell et al., 2006). Dynamic regulation of moisture, temperature, and albedo by vegetation influences convection, clouds, and rainfall (Dirmeyer 2006). In West Africa, extensive deforestation and an increase in crop burning have introduced significant land use changes that could alter mesoscale circulation and influence inland monsoon progression (Abiodun et al., 2013). The loss of evapotranspiration from degraded savannas, combined with smoke suppressing daytime heating, contributes to complex LAI mechanisms that affect future rainfall (Adler et al., 2011). The LAI framework provides a lens for disentangling multiple competing land surface changes in West Africa, which may force or provide feedback on regional climate regime shifts and weather events. These findings can inform agricultural and reforestation priorities for the promotion of climate resilience.

2.2 Limitations of Theoretical Frameworks

While the theoretical frameworks explained above provide valuable approaches for understanding biomass burning and climate interactions, they face several important limitations when applied to West Africa:

Data Availability Challenges: The West African region suffers from limited ground-based monitoring networks compared to other regions especially the case study area, Lagos, Nigeria. The Aerosol-Cloud Interactions framework requires detailed measurements of cloud microphysical properties and aerosol characteristics, which are sparse in the region. Lagos and surrounding areas have particularly limited continuous monitoring data, making it difficult to properly validate model parameterizations derived from other geographic contexts.

Unique Coastal-Urban Interface: The Lagos megacity represents a complex coastal-urban environment with distinct characteristics that aren't fully captured in existing frameworks. The interaction between the urban heat island effect, sea breeze circulation, and aerosol loading creates unique meteorological conditions that standard Aerosol-Precipitation frameworks may not adequately address.

Harmattan Influence: The seasonal Harmattan haze layer represents a distinct aerosol regime specific to West Africa that combines both mineral dust and biomass burning emissions. Most aerosol-cloud interaction frameworks were developed based on either purely anthropogenic or purely natural aerosol regimes, making their direct application to this mixed regime problematic.

Land-Use Change Dynamics: The Land-Atmosphere Interactions framework faces challenges in the West African context due to the rapid and often undocumented land-use changes occurring in the region. The complex mosaic of urban expansion, deforestation, and agricultural intensification creates feedback mechanisms that are not well represented in existing models.

Scale Mismatch Issues: Many of these frameworks were developed based on global or regional-scale processes, while the study area requires understanding microscale processes at the urban-coastal boundary. This scale mismatch limits their direct applicability to the Lagos case study.

Limited Regional Model Validation: Previous applications of these frameworks in West Africa have been limited, with few studies validating their performance against observed data in this specific regional context. This raises questions about their transferability to the unique meteorological conditions of the Guinea Coast.

2.3 Overview of Biomass burning

2.3.1 Haze and Its formation

Haze refers to a phenomenon in which dust, smoke, and atmospheric pollutants obscure clarity and reduce visibility in the affected region. It appears as a veil of particles suspended in the air that scatter and absorb the incoming solar radiation (Moran et al., 2019). Biomass burning is a primary source of smoke haze that often blankets large areas of Africa, South America, and Southeast Asia during the dry season (Keywood et al., 2015). Haze formation involves emission, dispersion, transformation, and eventual removal of aerosols produced by biomass burning (Van et al., 2022). The combustion of vegetation releases particulate matter less than 2.5 microns in diameter (PM2.5), which comprises black carbon, organic carbon, sulfates, nitrates, and other compounds (Simões Amaral et al., 2016). These aerosols are injected into the atmosphere and dispersed by regional wind patterns. Plumes of smoke haze can travel hundreds to thousands of kilometers. Haze develops through the interaction of aerosols with water vapor and clouds in the atmosphere (Nair et al., 2020). These particles serve as cloud condensation nuclei that facilitate the formation of haze droplets via heterogeneous nucleation. Water condenses on hygroscopic smoke particles, causing them to grow into fine haze droplets approximately 1-10 microns in size. Haze droplets essentially form a translucent aqueous suspension in air, which blocks and scatters light. This is exacerbated when small droplets coalesce into larger fog or cloud droplets under high humidity conditions. In addition, secondary reactions occur in the aging smoke plumes, which contribute to haze formation. The photooxidation of volatile organic compounds from biomass burning leads to low-volatility vapors that condense into particles. This produces secondary organic aerosols that bolster particulate mass concentration. The gas-to-particle conversion of sulfur dioxide and nitrogen oxides generates sulfates and nitrates, which also add to fine particulate matter. Overall, these photochemical transformations in the atmosphere amplify haze.

The optical properties of smoke particles are central to the reduction in visibility and solar dimming caused by the haze. Haze particulate matter has a high light extinction efficiency because it strongly scatters and absorbs solar radiation (Adeniran et al., 2017). Light absorption by black carbon aerosols causes solar heating (Qiao et al. 2020). However, most smoke particles predominantly scatter radiation, giving the haze a characteristic white-gray coloration. This scattering of sunlight augments the opacity of haze and causes dimming at the surface. In terms of the removal processes, fine-mode smoke aerosols have an atmospheric lifetime of approximately one week. Haze decay occurs through dry deposition, in which the particles settle on the surface. The wet deposition of haze also transpires, whereby particles are washed out through precipitation. However, at present, widespread smoke haze layers can persist for days to weeks, reducing the air quality and visibility across the entire region.

Biomass burning emissions have been a persistent phenomenon throughout human history, involving both natural wildfires and anthropogenic activities, such as land clearing and agricultural burning. The combustion of organic matter releases a complex mixture of gases and particulate matter into the atmosphere, which has a severe impact on society and the environment (Andreae, 2020; Marlon et al. 2020). The occurrence and characteristics of biomass burning have undergone dynamic transformations driven by complex interactions among human actions, environmental changes, and technological advancements. Analyzing the key factors is essential for understanding the obstacles and potential benefits of biomass burning in this new age.

2.3.2 Shifting Dynamics

Biomass burning has experienced significant changes in dynamics over time, with various factors influencing its frequency, spatial patterns, and environmental impact. These changes can be attributed to changes in human land use practices, population growth, and evolving socioeconomic factors (Andela et al., 2017; Bowman et al., 2020). In the pre-industrial era, biomass burning was primarily driven by natural processes, such as lightning-ignited wildfires and volcanic activity (Marlon et al., 2016). However, with the advent of agriculture and expansion of human settlements, anthropogenic burning practices for land clearing, crop residue disposal, and shifting cultivation have become increasingly prevalent (Doerr & Santín, 2016). The Industrial Revolution marked a turning point with the widespread adoption of fossil fuels and the mechanization of agriculture, which initially led to a decline in biomass burning in some regions (Marlon et al., 2008). However, subsequent global population growth, coupled with the expansion of agricultural frontiers and deforestation, has resulted in a resurgence of biomass burning in recent decades, particularly in the tropics (Andela et al. 2017; van der Werf et al. 2017).

Notably, biomass burning dynamics are not uniform across regions and biomes. For instance, savanna and grassland ecosystems in Africa and Australia have historically experienced frequent cyclical burning patterns, shaped by both natural and anthropogenic factors (Archibald et al. 2013; Murphy et al. 2019). In contrast, the tropical rainforests of Southeast Asia and South America have witnessed a more recent surge in biomass burning, driven by large-scale deforestation and land-use changes (Chen et al., 2015; Chen et al., 2017). The shifting dynamics of biomass burning are influenced by changes in climate patterns, land management practices, and policy interventions. For example, fire suppression policies and improved firefighting abilities have led to a decline in biomass burning in some regions, whereas climate change-induced drought conditions have intensified fire risks in others (Bowman et al., 2020; Jolly et al., 2015). It is evident that the dynamics of biomass burning are complex and shaped by the interplay of natural processes, human activities, and various environmental and socioeconomic factors. Understanding these shifting dynamics is crucial for developing effective strategies to manage and mitigate the environmental impact of biomass burning emissions.

Anthropogenic Factors

Human activities have played a pivotal role in shaping the dynamics of biomass-burning emissions, with far-reaching consequences for the environment and society. One key driver is the development of land areas through deforestation for agriculture and pastures, often involving the intentional clearing of fires. Although these fires may be localized and short-term, large-scale deforestation can significantly alter regional burning patterns, leading to substantial increases in emissions (Zhang et al., 2023). Urbanization also contributes to these complex dynamics, as the expansion of cities splits natural ecosystems, altering fire regimes and increasing the risk of uncontrolled wildfires at the urban-wildland boundaries (Barbosa et al., 2022).

Agriculture has a complex relationship with fires. Burning crop residue practices offer potential benefits such as improved soil fertility and easier planting. However, when poorly managed on a large scale, they can be a significant source of air pollution (Stockmann et al. 2022). Controlled burns, also known as prescribed burning, are employed as tools for land management and hazard reduction. Controlled fires can influence fires by altering fuel loads and vegetation composition (Fernandes et al., 2022). Increasing global temperatures and altered precipitation patterns are expected to significantly increase the frequency and intensity of wildfires in many regions driven by drier conditions, prolonged fire seasons, and increased lightning activity (Eriksen & Hankins, 2015). Natural disasters, such as insect outbreaks and droughts, can also dramatically alter vegetation cover, thereby affecting fuel availability and fire risk. Furthermore, invasive species introduce highly flammable plant materials that can modify fire occurrence, intensifying this problem (Cardoso, 2022). However, technology has both positive and negative effects on wildfires. Improved firefighting tools and strategies have significantly reduced the number of large uncontrolled wildfires in some areas. However, this success can have unintended consequences, as fire suppression can lead to fuel build-up, potentially increasing the risk of high-intensity fires when they eventually occur (Mistry et al., 2019). However, advancements in satellite imagery and other remote sensing tools have improved our ability to monitor wildfires and track their associated emissions in real-time. This improved data acquisition allows better management and response strategies to be implemented, as showed in the research on developments in wildfire monitoring (Veraverbeke et al., 2021).

Although scientific consensus acknowledges the significant impacts of anthropogenic factors on biomass burning emissions, some perspectives challenge the predominant narrative or propose alternative solutions. Sustainable land management advocates emphasize the importance of integrating traditional ecological knowledge with modern scientific principles. They advocate for the judicious use of controlled burning as a tool for habitat restoration, fuel reduction, and ecological resilience, while minimizing negative impacts (Twidwell et al., 2016; Mistry et al., 2019). Many indigenous communities have developed advanced fire management practices that align with the natural fire regimes in their respective environments. These practices aim to maintain the beneficial aspects of controlled burning while minimizing negative impacts on ecosystems and air quality (Eriksen & Hankins, 2015). Proponents of technological solutions suggest that advancements in fire detection, suppression, and fuel management techniques can mitigate the negative impacts of wildfires, while preserving the potential benefits of controlled burning (Twidwell et al., 2016). Some scholars and activists have showed the disproportionate impact of biomass burning emissions on marginalized communities, particularly those located near agricultural or industrial burning sites. They advocate policies and practices that address environmental justice concerns (Chakraborty et al., 2019; Pearce et al., 2021).

These factors – human actions, environmental changes, and technological advancements– interact in a complex manner, shaping the nature and extent of biomass burning worldwide. Understanding this dynamic interplay is crucial for developing effective strategies to mitigate the negative impacts of wildfires, while harnessing the potential benefits of fires for land management and ecological health. By acknowledging the ever-shifting dance between humanity, nature, and fire, we can move towards a future where this powerful force plays a more positive role in our world. These alternative perspectives shows the complexity of biomass burning and the need for a multidisciplinary approach that incorporates diverse knowledge systems, technological innovations, and social and environmental justice considerations.

Environmental Factors

Beyond human actions, the environmental landscape is a critical factor in shaping biomass burning emissions. Climate change is a particularly potent force, and rising global temperatures and altered precipitation patterns are expected to significantly increase the frequency and intensity of wildfires in several regions. This trend is driven by a combination of factors, including drier conditions that create more readily available fuel, prolonged fire seasons that extend the burning window, and increased lightning activity that acts as a natural ignition source (Bowman et al., 2020). Natural disasters such as insect outbreaks and droughts also have a significant influence. These events can drastically alter the vegetation cover and affect the availability of fuel for fires. For example, droughts can leave parched trees and other plants alive and are more susceptible to burning. Similarly, insect outbreaks that defoliate trees can create a layer of highly flammable dead leaves and branches on the forest floor, thereby providing an area for major wildfires (Johnstone et al. 2016).

Invasive species further complicate this event by introducing highly flammable plant materials, which can significantly alter fire regimes. Introduced plants often possess characteristics such as a high resin content or rapid growth rates, which contribute to their flammability. When these species establish themselves in new ecosystems, they can significantly increase the frequency and intensity of fire. For instance, invasive cheatgrass in the western United States has been linked to more frequent and intense fires owing to its ability to create a continuous layer of fine, dry fuel (Chambers et al., 2016).

Although scientific consensus recognizes the significant influence of environmental factors on biomass burning emissions, some perspectives offer alternative viewpoints or propose different approaches. Proponents of ecosystem resilience argue for the promotion of ecosystem resilience as a means of mitigating the impacts of environmental factors on fire regimes, emphasizing the maintenance of natural disturbance patterns, biodiversity, and ecological processes to enhance ecosystem resilience (Hessburg et al., 2019). Indigenous communities have developed intricate knowledge systems and practices that account for environmental factors in their fire-management strategies. By integrating traditional ecological knowledge with modern scientific approaches, a more holistic understanding and management of fire regimes can be achieved (Pearce et al. 2021). Some researchers advocate proactive management strategies that address environmental factors before they contribute to increased wildfire risk, involving practices such as targeted fuel reduction, prescribed burning, or vegetation management (Schoennagel et al., 2017; Ager et al., 2019). The ecosystem-based adaptation perspective emphasizes the need to incorporate strategies that consider the complex interactions between environmental factors, climate change, and fire regimes to enhance the resilience of ecosystems and communities (Brenkert-Smith et al., 2022).

Understanding these environmental factors and their complex interplay is crucial for predicting and mitigating the future emissions from biomass burning. By acknowledging the challenges caused by climate change, natural disasters, and invasive species, strategies can be developed to reduce the impacts of wildfires and their emissions.

Technological Advancements

The influence of technology on emissions from biomass burning is driven by both progress and unintended consequences. Advancements in fire mitigation techniques boast clear success: a reduction in large, uncontrolled fires across various landscapes. This comprises not only wildfires, but also agricultural burning practices, such as controlled burns of crop residue. Improved tools, such as firebreaks, retardants, and specialized equipment, allow for more efficient control, leading to a decrease in immediate emissions. However, this progress comes at cost. Fire suppression can create a dangerous build-up of fuel on the ground, whether in forests or agricultural fields. Dead leaves, branches, and other organic matter accumulate over time, creating potential for future high-intensity infernos. Research has examined this phenomenon, showing the potential for unintended consequences associated with aggressive fire suppression strategies (Staudinger, 2022). Technology is a powerful tool for mitigating the environmental impacts of all forms of biomass burning. Remote sensing and monitoring capabilities have revolutionized in recent years. Satellite imagery, drones, and other advanced tools allow us to track burning events in real-time, providing crucial data on their location, size, and intensity. This information is essential for directing fire management efforts, optimizing resource allocation, and minimizing the overall environmental footprint of burning events. The ability to track associated emissions using these technologies allows scientists to develop a better understanding of the atmospheric impacts of biomass burning.

However, some critical questions remain unanswered. For instance, are these advancements being used effectively to promote sustainable burning practices, or simply to optimize the current, often problematic methods? Can technology bridge the gap between traditional fire-management practices and ecologically sound burning approaches? Further exploration is needed to ensure that technology serves as a tool for positive change and not just to improve efficiency within the existing concept.

Alternative Perspectives:

Although the potential benefits and drawbacks of technological advancements in managing biomass burning emissions are widely acknowledged, some perspectives offer alternative viewpoints or propose various approaches.

Ecosystem-based management: The proponents of this approach argue that technology should be employed in a manner that supports ecosystem-based management practices, prioritizing the maintenance of ecological integrity and promotion of resilient ecosystems. This perspective emphasizes the integration of traditional ecological knowledge and practices with modern technological tools to develop sustainable fire management strategies (Moritz et al., 2018).

Precautionary principle**:** Some scholars advocate a more cautious approach to the adoption of new technologies in fire management, citing potential unintended consequences and the need for a rigorous assessment of long-term impacts. This perspective emphasizes the importance of thoroughly understanding the complex interactions between technological interventions and ecosystems before widespread implementation (Oluoch-Kosura, 2020).

Community-based fire management: This perspective shows the importance of involving local communities and stakeholders in the development and implementation of fire management strategies including the use of technology. By incorporating local knowledge, cultural practices, and community needs, this approach aims to ensure that technological solutions are tailored to specific contexts and aligned with the priorities of affected communities (Eriksen & Hankins, 2015).

Environmental justice: Some scholars and activists have raised concerns about the potential inequitable distribution of the benefits and risks associated with technological advancements in fire management. They advocate for the consideration of environmental justice principles, ensuring that marginalized communities are not disproportionately impacted by the negative consequences of these technologies (Abatzoglou et al., 2022).

2.4 Characteristics of Biomass Burning Emissions

2.4.1 Types of Emissions

Biomass burning, a widespread global phenomenon, releases a complex array of gaseous and particulate emissions that have severe implications for air quality, human health, and the Earth's climate system. This section focuses on the diverse nature of these emissions, their applications in various fields, and the ongoing debate surrounding their quantification and impact.

Gaseous emissions from biomass burning include a combination of pollutants with varying environmental consequences. CO is a major gaseous pollutant is carbon monoxide. Carbon monoxide (CO), a toxic gas resulting from incomplete combustion, is a significant component whose applications in atmospheric modeling and air quality monitoring are well established, as they serve as tracers for anthropogenic pollution sources (Dekker et al., 2017). However, exposure to elevated CO levels can have severe health consequences including cardiovascular and respiratory issues, necessitating stringent emission control measures (Vu et al., 2015). Closely linked to CO are nitrogen oxides (NOx) emitted during biomass burning, which play a crucial role in the formation of ground-level ozone and secondary particulate matter, which are detrimental to human health and ecosystem functioning (Chen et al., 2019). The quantification of NOx emissions is vital for air quality modeling and mitigation strategy development (Zhang et al., 2021), although some argue that their contribution may be overestimated in certain regions with effective land management practices (Smith et al., 2021).

Another diverse group of emissions from biomass burning are volatile organic compounds (VOCs), with hundreds of identified species (Gilman et al., 2015). These compounds are crucial in atmospheric chemistry studies, as they contribute to the formation of secondary organic aerosols (SOA) and ozone, impacting air quality and climate (Riva et al., 2022). However, quantifying and speciating VOCs remains challenging owing to their complexity and variability (Chakraborty et al., 2019). Methane (CH4), a potent greenhouse gas emitted during biomass burning, has applications in climate modeling and mitigation strategies, necessitating accurate quantification to understand its climatic impacts (Urbanski, 2018). Nonetheless, some studies have suggested that their contribution may be overestimated, particularly in regions with effective land management (Kirschke et al. 2013). Carbon dioxide (CO_2) is considered part of a natural carbon cycle with the potential for regrowth and sequestration and remains the primary greenhouse gas emitted from biomass burning, contributing significantly to climate change (Jones et al., 2019). Quantifying net CO_2 emissions is essential for understanding the carbon cycle and for developing mitigation strategies. However, the true impact depends on factors such as biomass type, land management, and carbon sequestration timescale (van der Werf et al., 2017). The greenhouse gas emissions in Lagos urban areas have reached concerning levels, as demonstrated by the severe air pollution recorded in 2019 (Figure 2.1).

Figure 2.1 - Greenhouse gas emissions in Lagos Urban(Lagos Island) areas leading to severe air pollution in 2019. Source: (World Bank).

In addition to gaseous emissions, biomass burning releases particulate matter (PM) of varying sizes, compositions, and environmental impact. Black carbon, a major PM component, is a potent solar radiation absorber that contributes to atmospheric warming and disrupts Earth's energy balance (Sandström et al., 2023). This pollutant has applications in climate modeling and radiative forcing studies (Bond et al., 2013). However, quantifying black carbon emissions and climatic impacts is subject to ongoing debate regarding the need to account for spatial and temporal variability (Zheng et al., 2020). Organic carbon, another significant PM component, is a complex mixture of partially combusted organic compounds with adverse health effects and contributions to SOA formation (Riva et al., 2022). Characterizing organic carbon emissions is crucial for understanding the impact of air quality and developing mitigation strategies. However, the diversity of compounds and varying toxicities pose challenges for the accurate assessment of health effects (Srivastava et al., 2019). Inorganic ions such as potassium, chloride, and sulfate are also present in biomass-burning PM with potential respiratory and environmental impacts (Popovicheva et al., 2017), necessitating quantification to understand their atmospheric chemistry roles. The size distribution of PM is critical in determining its environmental and health impacts, with fine particulate matter (PM2.5) being of particular concern because of its ability to penetrate deep into the respiratory system, contributing to respiratory and cardiovascular illnesses (Liu et al., 2022). Accurate measurement and modeling of PM2.5 emissions are crucial for developing effective air quality management strategies. Although the impacts of biomass burning emissions are well documented, some researchers have argued that their overall contribution to global emissions may be overestimated, particularly in regions with effective land management practices and sustainable burning regimes (Smith et al., 2021). This viewpoint shows the need for context-specific assessments and consideration of regional variations in biomass burning practices and emission factors.

Addressing this complex environmental challenge requires a multi-faceted approach. Regulatory measures, such as emission standards and land-use policies, play a crucial role in mitigating these impacts, complemented by sustainable burning practices and land management strategies informed by scientific research to reduce emissions and promote efficient combustion processes. Technological advancements in emission control, monitoring, and modeling are essential to accurately quantify and characterize biomass burning emissions. Improved measurement techniques coupled with advanced atmospheric chemistry models can enhance our understanding of chemical changes and their impacts. Interdisciplinary collaborations among researchers from various fields, including atmospheric science, environmental health, climate science, and policy, are vital for developing feasible solutions by integrating diverse perspectives and expertise, enabling us to better navigate the challenges and work towards a more sustainable future.

2.4.2 Factors Influencing Emissions

The emissions generated from biomass burning, a widespread global practice, have far-reaching implications for air quality, human health, and the climate. Accurate characterization and mitigation of these emissions hinges on a proper understanding of the complex factors that influence their formation and composition. This analysis examines the complex interaction of variables, including fuel type, moisture content, combustion temperature, and other emerging factors, while critically examining their individual and combined effects on emission profiles. The Nigerian experience in the lower Niger Sub-basin exemplifies the extreme hydrological disasters resulting from climatic variability and changing climate patterns (Figure 2.2). These environmental pressures compound the challenges leading to natural disasters as seen in the figure below.

Figure 2.2. Extreme Hydrological disasters due to climatic Variability and changing climate (Nigeria experience in the lower Niger Sub-basin). (Source: Juddy N. Okpara, 2013)

2.4.3 Fuel Type and Moisture Content

The chemical composition and physical properties of biomass fuels play a pivotal role in determining their emission characteristics. The ratio of lignin to cellulose has been identified as a significant factor, with woody biomass containing a higher lignin content tending to produce more particulate matter and polycyclic aromatic hydrocarbons than agricultural residues with a higher cellulose content (Elsasser, 2022). However, the influence of fuel type is intricately linked to moisture content, as their chemistry can greatly affect combustion dynamics and subsequent emissions. Dry woody biomass, which is rich in lignin, may undergo more complete combustion at high temperatures, leading to lower emissions of products of incomplete combustion such as carbon monoxide and volatile organic compounds (Akagi et al., 2011; Urbanski, 2014). Conversely, when the same woody fuel is burned at elevated moisture levels, the combustion process becomes less efficient, resulting in increased emissions of harmful pollutants. This complex relationship shows the necessity of considering both fuel properties and moisture levels to accurately predict emission characteristics.

2.4.4 Combustion Temperature and Fuel Type Interaction

The interaction between the combustion temperature and fuel type can play a pivotal role in determining the relative abundances of different particulate matter components, each with distinct environmental and health impacts. Studies have revealed that burning certain biomass types, such as crop residues, at higher temperatures can lead to increased formation of black carbon, a potent climate-forcing agent known for its ability to absorb solar radiation and contribute to atmospheric warming (Ni et al., 2015). Conversely, lower combustion temperatures may favor the emissions of organic carbon and other organic particulate matter species, which can contribute to the formation of secondary organic aerosols and worsen air pollution (Popovicheva et al., 2017). These complex interactions underline the importance of considering the combined effects of multiple factors when evaluating biomass burning emissions, because oversimplifying these relationships or relying solely on generalized emission factors can lead to inaccurate estimates and potentially misguided mitigation strategies.

2.4.5 Spatial and Temporal Variations

The factors influencing emissions can vary significantly across different spatial and temporal scales, thereby adding another layer of complexity to the equation. Regional differences in vegetation types, climate conditions, and burning practices can result in distinct emission profiles even for similar fuel types (van der Werf et al., 2017). For instance, the burning of agricultural residues in tropical regions may yield different emission characteristics compared to burning the same residues in temperate regions, owing to variations in fuel composition, moisture levels, and combustion conditions. Seasonal variations in moisture content and meteorological conditions can also impact combustion dynamics and subsequent emissions (Yin et al., 2021). During drier periods, biomass fuels may be more prone to complete combustion, potentially leading to lower emissions of products of incomplete combustion but higher emissions of nitrogen oxides. Conversely, wetter seasons or periods of high humidity may result in less efficient combustion, favoring the production of carbon monoxide, methane, and volatile organic compounds.

2.4.6 Emerging Factors and Uncertainties

Although significant progress has been made in understanding the factors influencing biomass burning emissions, knowledge gaps and areas of uncertainty remain that require further exploration. The influence of soil properties and nutrient levels on emission characteristics is an emerging area of research that may provide valuable insights into the underlying drivers of emission variability (Vasconcellos et al. 2022). For instance, nutrient-rich soils may influence the chemical composition of vegetation, which in turn could impact the emission profiles during biomass burning. Additionally, the impact of post-combustion processes, such as smoldering and residual combustion, on emission profiles warrants further investigation (Doerr & Santín, 2016). These processes, which can occur after the initial flaming combustion phase, may contribute significantly to the overall emissions, particularly for certain pollutants such as carbon monoxide and methane.

Another area of ongoing research is the role of atmospheric aging and chemical transformations on the composition and properties of biomass burning emissions. As these emissions are transported through the atmosphere, they can undergo various chemical reactions and physical processes, leading to the formation of secondary pollutants and the alteration of their impact on air quality and climate (Hodshire et al., 2019). Addressing these complexities and uncertainties requires multidisciplinary collaboration and integrated approaches that combine field measurements, laboratory experiments, and advanced modeling techniques. By leveraging the collective expertise of atmospheric scientists, combustion experts, ecologists, and policymakers, we can develop a better understanding of the factors influencing biomass burning emissions and devise effective strategies to mitigate their environmental and health impacts.

2.4.7 Dissenting Views and Limitations

While the factors discussed above are widely recognized as significant determinants of biomass burning emissions, some researchers argue that other variables, such as atmospheric conditions and burning practices, may play a crucial role in determining the ultimate impact of these emissions (Reid et al., 2016). For example, the dispersion and transport of emissions can be affected by meteorological conditions, resulting in varying concentrations and exposure levels across different regions. Furthermore, the specific application of biomass burning, whether in agriculture, forestry, or domestic heating, can influence emission characteristics. For instance, the open burning of agricultural residues may result in different emission profiles compared to controlled burning in residential wood stoves or boilers (Akagi et al., 2011). These variations show the need for context-specific assessments and tailored mitigation strategies based on the local conditions and practices.

It is important to acknowledge the limitations of current knowledge and the potential for unknown or underappreciated factors that contribute to emission variability. As our understanding evolves, it is crucial to maintain an open and critical perspective, embrace new insights, and refine the existing models to achieve more accurate emission estimates and effective mitigation strategies. Addressing the complex challenge of biomass burning emissions requires a holistic and interdisciplinary approach that considers the complex interactions of multiple factors, adopts inherent complexities and uncertainties, and promotes continuous learning and adaptation. By advancing our understanding of these factors and their interactions, we can develop more accurate emission inventories, refine air-quality models, and inform evidence-based policymaking to mitigate the adverse effects of biomass burning on the environment and public health. Continuous monitoring, adaptive management strategies, and integration of emerging technologies are essential for maintaining the dynamic nature of biomass burning emissions and evolving practices. Ultimately, collaborative efforts among researchers, policymakers, and stakeholders are crucial for navigating this complex issue and developing effective solutions to improve air quality, human health, and the environment.

2.5 Health and Environmental Impacts

Biomass burning emissions are a serious concern and major hazard to both human health and the environment, necessitating thorough and multidimensional analyses. As reviewed in previous sections, biomass emissions contain various gaseous and particulate pollutants with complex chemistry. The release of gaseous and particulate pollutants during biomass combustion severely compromises air quality, leading to an increased incidence of respiratory ailments, cardiovascular complications, and other deleterious health outcomes (Rajagopalan, 2022). However, the burden is not evenly distributed, with vulnerable populations in developing regions bearing a disproportionate share because of their reliance on biomass fuels for domestic energy needs and exposure to indoor air pollution (Ramanathan & Carmichael, 2023). The adverse health impacts of biomass burning emissions extend beyond respiratory and cardiovascular diseases, with emerging evidence establishing associations with adverse birth outcomes, such as low birth weight and preterm delivery (Rajkumar, 2023), as well as an elevated risk of cognitive impairment and neurodegenerative disorders (Shi et al., 2022). The spatiotemporal trends of particulate matter distribution over the last 20 years reveal significant patterns across Nigeria (Figure 2.3), with implications for public health and environmental quality.

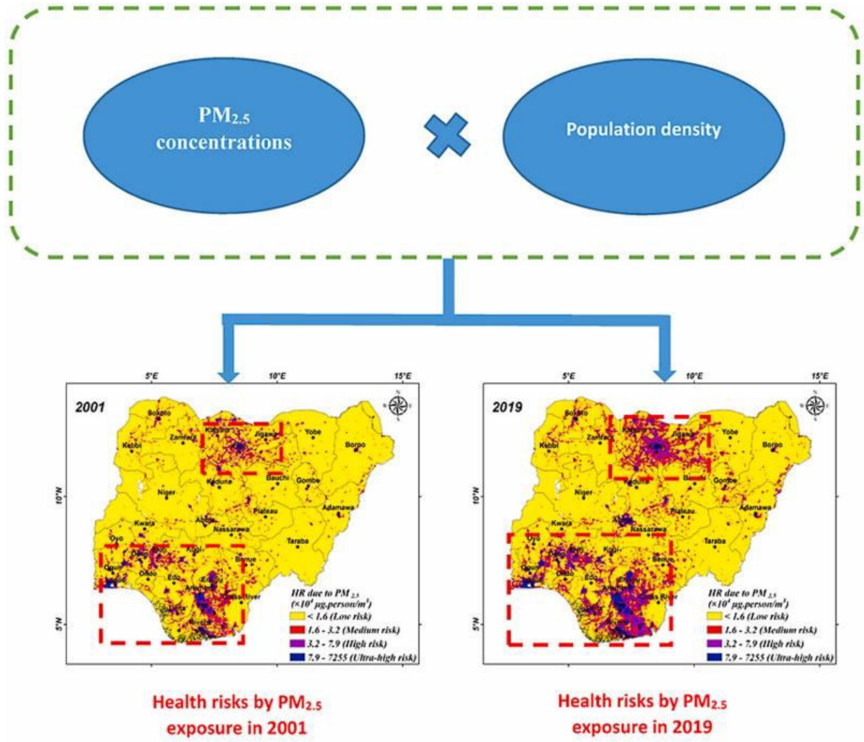


Figure 2.3: Sample PM distribution and spatiotemporal trends over the last 20 years for Nigeria. Source: (Tariq et al., 2023)

Furthermore, these emissions contribute to the formation of ground-level ozone and particulate matter, thereby worsening the burden of air pollution-related morbidity and premature mortality (Zare et al. 2022). While this research acknowledges the release of carbon dioxide and the generation of short-lived climate forcers such as black carbon, the assertion that these forcers may counterbalance or surpass the cooling effects resulting from CO2 absorption during biomass regrowth is an oversimplification. The net impact of biomass burning emissions on climate is highly complex and is influenced by factors such as the type of biomass, burning conditions, spatial and temporal scales, and interactions with other atmospheric constituents (Andela et al., 2023; Thornhill et al., 2022). Recent research has showed the potential for positive feedback loops and tipping points, where biomass burning emissions contribute to climate change, which in turn increases the likelihood and severity of wildfires and subsequent emissions (Yang et al., 2022). Moreover, the deposition of black carbon on snow and ice surfaces can accelerate melting, further amplifying the impact of climate change (Ramanathan & Carmichael, 2023). Mitigating the complex impacts of biomass burning emissions requires a multifaceted approach that go beyond simplistic solutions such as "improved burning practices" and "cleaner biofuel technologies." Proper policy interventions are necessary to address the underlying drivers of unsustainable biomass burning practices such as deforestation, land-use changes, and poverty-driven reliance on biomass fuels (Reddington et al., 2022; Zare et al., 2022). These policies must be informed by a proper understanding of emission characteristics, necessitating interdisciplinary collaboration and the integration of advanced monitoring techniques, atmospheric modeling, and socioeconomic analyses (Andreae, 2019; Li et al., 2022).

2.5.1 Variability in Composition

The purported renewable nature of biomass burning as an energy source remains a contentious issue, necessitating critical reevaluation of its environmental impact. A crucial factor concealing this debate is the significant variability observed in the composition of emissions released during biomass combustion, which is largely driven by the fuel properties and combustion dynamics. The type of biomass fuel combusted was the primary driver of emission variability. Softwoods emit considerably higher levels of particulate matter, carbon monoxide, and volatile organic compounds (VOCs) than denser hardwoods because of their higher resin and extractive compound contents (Mukherjee, 2022). The combustion of tree bark releases significantly more particulate matter, semi-volatile organic compounds (SVOCs), and polycyclic aromatic hydrocarbons (PAHs) than debarked wood owing to the higher concentration of extractives in the bark (Akhaghi, 2023). Processed wood fuels, such as pellets, can facilitate more uniform and efficient combustion than burning cordwood, leading to reductions in certain emissions such as carbon monoxide (Chen et al., 2022).

Nonwood biomass fuels present a distinct challenge. Burning agricultural residues such as wheat straw, corn stover, and rice straw generates significantly higher levels of particulate matter, nitrogen oxides (NOx), and SVOCs compared to wood fuels because of their elevated nitrogen, chlorine, and silica content, and lower energy density (Wang et al., 2022). The combustion of grasses and cereal straw, which have high potassium and chlorine contents, results in increased emissions of fine particulate matter containing high concentrations of potassium chloride and salts (Luo et al., 2023). Energy crops, such as switchgrass and Miscanthus, offer a potentially more sustainable alternative, achieving lower emissions owing to their lower nitrogen, ash, and chlorine content when cultivated and combusted sustainably (Shin et al., 2022). The fuel conditions significantly affected the emission profiles. Biomass with a higher moisture content undergoes smoldering and incomplete combustion, leading to an increased production of particulates, carbon monoxide, methane, and other hazardous air pollutants compared to drier and seasoned fuels (Li et al., 2022). Fuel preparation also plays a crucial role, as processing biomass into uniform pellets, chips, or densified shapes enhances combustion efficiency compared to raw, unconditioned biomass with irregular shapes (Rahman et al., 2022).

In addition to fuel characteristics, the dynamics of combustion exert a powerful influence on emissions. Flaming combustion, which occurs at temperatures exceeding 900°C, primarily produces carbon dioxide because of its relatively complete oxidation. However, smoldering phases, characterized by temperatures below 800°C, release far greater quantities of incomplete combustion products, including carbon monoxide, particulates, and organic toxins (Carrington & Harden, 2022). Real-world biomass combustion involves a complex interplay of flaming, smoldering, and gasification stages as the fire progresses, significantly complicating the emission profile compared to controlled laboratory settings (McMeeking et al., 2022). Combustion efficiency, which is heavily influenced by factors such as the air-fuel ratio and temperature, plays a critical role. Employing optimal air-fuel ratios and achieving adequate temperatures leads to significantly reduced emissions of carbon monoxide, methane, particulate matter, and other combustion byproducts (Wainwright et al., 2022). Conversely, inefficient combustion processes, often caused by inadequate air supply, substantially elevate the production of undesirable byproducts such as carbon monoxide and unburned hydrocarbons (Wang et al., 2022).

Advanced combustion technologies, such as gasifiers and fluidized bed combustors, offer greater control over air-fuel ratios, residence times, and temperatures compared to simple stoves or boilers, translating to optimized, low-emission combustion (IEA Bioenergy, 2022). In stark contrast, traditional practices, such as the open burning of biomass piles or the use of basic heating stoves, represent highly uncontrolled, low-temperature combustion scenarios that generate significant emissions (Pellegrini et al., 2023). The substantial variability in both emission characteristics and chemical composition poses a significant challenge in quantifying the impacts of biomass combustion at various scales. This variability, driven by the complex interplay of the fuel type, condition, combustion device, and operating parameters, underlines the need for further research and analysis. A full understanding of these factors is critical for accurately assessing the true environmental footprint of biomass burning and its implications at the local, regional, and global scales.

2.6 Measuring Biomass Burning Emissions: Techniques and Challenges

Quantifying emissions from biomass burning sources, such as wildfires, agricultural burning, and residential wood combustion, is crucial for understanding their impact on air quality, climate, and public health. However, measuring these emissions presents unique challenges compared to other pollution sources owing to the complex and dynamic nature of biomass combustion. Various field measurement techniques have been employed, each with its own strengths and limitations.

2.6.1 Ground-Based Sampling:

A typical approach for studying wildfire emissions involves the deployment of ground-based instruments in or near burnt areas. These instruments directly measure the concentrations of gases such as carbon monoxide, carbon dioxide, particulate matter, and volatile organic compounds in the plume. Additionally, filter samples were collected for laboratory analysis to determine the particulate concentrations. Although this method provides direct in situ measurements, it is limited by its spatial coverage and the potential for sampling biases due to the complex dynamics of smoke plumes.

2.6.2 Mobile Sampling Platforms

Sampling devices mounted on trucks, aircraft, or drones allow for the monitoring of emissions over broader areas and at varying distances from the source. For instance, an aircraft can penetrate wildfire smoke plumes and collect Lagrangian samples that represent the integrated emissions along the plume transport pathway. These sampling methods provide a valuable means of assessing emissions in a wide range of applications, including large-scale wildfires and landscape fires, where ground access may be limited. However, they are resource-intensive and may still be subject to sampling biases, owing to the inherent variability in biomass burning emissions.

2.6.3 Remote Sensing:

Remote sensing techniques, such as LIDAR, FTIR spectroscopy, and sun photometers, enable the characterization of smoke plumes without direct contact. LIDAR can profile aerosol concentrations and plume heights, whereas spectroscopic methods quantify the concentrations of gases, such as carbon monoxide and methane, in the smoke. These techniques offer a non-intrusive means of monitoring emissions and can provide valuable spatial and temporal data. However, they may be limited by factors such as atmospheric interference, cloud cover, and availability of clear lines of sight to the plume. Despite the variety of measurement tools available, accurate estimation of emissions from biomass burning remains a significant challenge owing to the complex and dynamic nature of these combustion processes. To capture this heterogeneity, the inherent spatial and temporal variability of biomass burning, which is influenced by factors such as fuel type, moisture content, and combustion phase, necessitates extensive sampling over the entire burn area and duration. Moreover, the turbulent and buoyant nature of smoke plumes makes ground sampling and remote sensing more difficult, particularly for wildfires, where plumes undergo considerable atmospheric mixing and transformation during transport. Developing robust emission factors that relate fuel consumption to pollutant emissions is also a challenge because of the inherent variability in biomass burning characteristics and combustion conditions in field versus controlled settings. Some researchers have argued that reliance on emission factors derived from limited field studies or laboratory experiments may lead to significant uncertainties in emission estimates, particularly when applied to different biomass burning scenarios or geographic regions.

Furthermore, the scale and accessibility of biomass burning incidents present logistical- and resource-related challenges. For example, during the rapid progression of wildfires or large-scale landscape fires, access limitations can restrict sampling opportunities and hinder good data collection. To address these challenges, interdisciplinary collaboration and integration of multiple measurement techniques may be necessary. For example, combining ground-based measurements with remote sensing data and atmospheric modeling can provide a better understanding of emission sources, transport, and transformation processes. Additionally, the development of advanced instrumentation and sampling strategies, coupled with improved characterization of fuel properties and combustion dynamics, could enhance the accuracy of emission estimates, and facilitate more effective mitigation strategies.

2.7 Challenges

Accurate estimation of emissions from biomass burning presents several significant challenges that must be carefully considered and addressed to obtain reliable and representative data. First, biomass burning displays considerable spatial and temporal heterogeneity, driven by factors such as fuel type, moisture content, and combustion phase. These factors can influence emissions on short timescales, necessitating extensive sampling over the entire burn area and duration to capture this variability accurately. The diversity of fuels, ranging from agricultural residues to forest biomass, further compounded the complexity as each fuel type exhibited unique combustion characteristics and emission profiles.

Secondly, the turbulent and buoyant nature of smoke plumes poses challenges for ground sampling and remote sensing techniques, particularly in the case of wildfires. Plumes undergo substantial atmospheric mixing and transformation during transport, involving complex chemical and physical processes that can alter the composition and properties of the emissions. These transformations can lead to the formation of secondary pollutants such as ozone and secondary organic aerosols, further complicating the accurate quantification of emissions.

Third, developing robust emission factors that relate fuel consumption to pollutant emissions is a complex task owing to the inherent variability in biomass burning characteristics and combustion conditions. Emission factors derived from controlled laboratory or field experiments may not accurately represent the wide range of conditions encountered during real-world biomass burning events. Factors such as fuel moisture content, combustion efficiency, and burn conditions can significantly influence emission rates, leading to potential discrepancies in emission estimates when generalized emission factors are applied.

Fourth, large-scale biomass burning incidents, such as landscape and peatland fires, present logistical- and resource-related challenges. Access limitations, such as the rapid progression of wildfires or the remoteness of burned areas, can restrict opportunities for sampling and data collection, thereby hindering full emission assessments. Additionally, the sheer scale of some biomass burning events can exceed the available resources and monitoring capabilities, further compounding the challenge of obtaining accurate emission estimates.

These challenges show the need for multidisciplinary approaches and advanced techniques to improve the accuracy of biomass burning emissions estimates. Addressing these issues is crucial for a better understanding of the impact of biomass burning on air quality, climate, and ecosystem dynamics as well as to inform effective mitigation strategies and policy decisions. To address these issues, various perspectives and alternative views have been proposed. For instance, some researchers have advocated the development of higher-resolution models and improved parameterizations to better capture the spatial and temporal variability of biomass burning emissions as well as the complex atmospheric processes involved (Reid et al., 2009; Strada et al., 2013). Others emphasize the importance of integrating ground-based measurements with remote sensing data and chemical transport models to improve the understanding of plume dynamics and atmospheric transformations as well as to validate and refine emission estimates (Ichoku et al., 2012; Mok et al., 2016). Additionally, efforts have been made to establish representative emission factor databases through extensive field campaigns and laboratory studies, which account for a wider range of fuel types, combustion conditions, and burn scenarios (Akagi et al. 2011; Urbanski 2014; Stockwell et al. 2016). These databases aim to better represent the diversity of biomass burning emissions and reduce the uncertainties in emission estimates.

Furthermore, the integration of multi-platform observations, including ground-based, airborne, and satellite measurements, has been recognized as a crucial step in improving the accuracy and spatial coverage of biomass burning emission estimates (Kaiser et al., 2012; Ichoku and Ellison, 2014). By combining these diverse data sources, researchers can leverage the strengths of each platform and compensate for their respective limitations, ultimately providing a more better understanding of the emissions and their atmospheric impacts. Despite these efforts, there are ongoing debates and differing perspectives within the scientific community regarding the most effective approaches to address the challenges associated with biomass burning emission estimates. Some researchers argue for increased funding in field campaigns and ground-based measurements to better characterize local and regional emission sources (Yokelson et al., 2013), whereas others advocate prioritizing satellite remote sensing techniques and top-down emission estimates (Darmenov and da Silva, 2015; Kahn et al., 2008).

It is important to recognize that these challenges are not insurmountable, and continuous advancements in measurement techniques, modeling capabilities, and our understanding of biomass burning processes are likely to lead to improved emission estimates over time. Collaborative efforts among scientists, policymakers, and stakeholders are crucial for addressing these challenges and mitigating the impacts of biomass burning emissions on air quality, climate, and human health.

2.8 Laboratory and Modeling Approaches

Significant efforts have been made to advance the quantification and characterization of biomass burning emissions through laboratory studies, field measurements, and modeling approaches. These complementary methods provide valuable insights into the complex dynamics of combustion processes, emission factors, and spatial distribution of emissions. Laboratory studies involving the controlled burning of various biomass fuels under well-defined conditions have played a crucial role in developing emission factors and enhancing our understanding of the combustion dynamics (Stockwell et al., 2015; Selimovic et al., 2018). These controlled experiments allow for the systematic investigation of factors, such as fuel type, moisture content, and combustion phase, enabling the quantification of emissions for a wide range of gaseous and particulate species (Koss et al., 2018; Lim et al., 2019). Complementing laboratory studies, field measurements have been instrumental in capturing the real-world complexities of biomass-burning emissions. Ground-based sampling campaigns, aircraft measurements, and remote sensing techniques have been employed to characterize emissions from various sources, including wildfires, agricultural burning, and land-clearing activities (Andreae, 2019; Urbanski et al., 2021; Zheng et al., 2022). These field observations provide valuable data on the spatial and temporal variability of emissions, plume dynamics, and influence of environmental factors (Akagi et al., 2011; Akagi et al., 2013; Stockwell et al., 2016). Integrating laboratory and field data into modeling approaches is crucial for scaling point measurements to broader regional and global emission estimates. Chemical transport models (CTMs) coupled with satellite-derived fire data and emission inventories have been widely used to simulate the atmospheric transport and transformation of biomass burning emissions (Reddington et al., 2019; Carter et al., 2020; Matsui et al., 2022). Additionally, inverse modeling techniques and data assimilation methods have been applied to optimize emission estimates by combining model simulations with observations from ground-based and satellite instruments (Kiely et al., 2019; Mota et al., 2021; Xing et al., 2022).

2.9 Improving Quantification

Accurately measuring emissions from biomass burning remains challenging due to the complex nature of these events, but stiudies have developed several strategies to improve measurement capabilities. These approaches focus on combining different types of data collection methods, enhancing monitoring coverage, and developing more precise measurement techniques. The goal is to better understand the variability in emissions across different burning scenarios and environmental conditions.

Studies are implementing integrated approaches that combine ground-based measurements, aircraft sampling, and satellite observations to provide comprehensive views of emissions and smoke plume behavior. They are also increasing the spatial density of ground monitoring networks, particularly in regions with diverse burning sources and complex terrain.

Additionally, researchers are developing burn-specific emission factors that account for different fuel types, moisture content, and combustion phases, while leveraging emerging technologies like low-cost air quality sensors, drones, and high-resolution satellite instruments for real-time monitoring. Advanced modeling techniques that incorporate observational data from multiple platforms are also being used to improve emission estimates and atmospheric process representation.

The impact of biomass burning on regional climates is particularly significant in Africa, where smoke and particles create substantial cooling at ground level during peak burning seasons by reducing incoming sunlight and increasing outgoing heat radiation. However, this same atmospheric haze heats the air at altitudes of 2-3 kilometers, creating complex climate effects. Accurately quantifying these emissions is crucial for effective air quality management, climate modeling, and protecting public health essential for developing well-informed policies and timely responses to burning events. Various measurement approaches have been employed specifically in the Lagos region, each with distinct advantages and limitations for studying biomass burning emissions (Table 2.1). These approaches focus on combining different types of data collection methods.

Table 2.1: This table summarizes measurement approaches specifically in the Lagos region

S/N	Technique	Description	Advantages in Lagos Region	Limitations in Lagos Region
1	**Ground-Based Sampling** Jayarathne et al., 2018; Dinku, 2019; Temimi et al., 2021	Direct measurement of pollutant concentrations using fixed monitoring stations	1. Provides continuous temporal data High accuracy for local conditions 2. Can capture urban-coastal interface dynamics 3. Useful for validating satellite retrievals 4. Potential for community engagement in data collection	1. Very sparse network in Lagos region 2. High maintenance costs in tropical conditions 3.Susceptible to vandalism/theft 4. Limited spatial coverage across the megacity 5. Potential contamination from local sources Requires skilled technical personnel
2	**Mobile Sampling Platforms** Andrews et al., 2021;	Vehicle, aircraft, or drone-mounted instruments for spatial coverage	1. Can traverse urban-rural gradients 2. Adaptable to changing conditions 3. Ability to track plume evolution 4. Can access difficult terrain 5. Good for mapping spatial heterogeneity	1. Logistical challenges in Lagos traffic 2. Limited flight permissions in urban areas 3. High operational costs Intermittent rather than continuous data 4. Safety concerns in certain neighborhoods

				5. Limited flight time for drones in tropical heat
3	**Remote Sensing (Satellite)** Fisher et al., 2020;	Space-based observations of aerosol optical depth, fire radiative power	1. Full spatial coverage of Lagos region 2. Regular revisit times Long historical records available 3. Captures transboundary transport 4. Not affected by ground-level security issues	1. Cloud interference during monsoon season 2. Coarse resolution misses urban-scale features 3. Surface reflectance challenges in coastal areas 4. Limited vertical profile information 5. Retrieval biases over urban surfaces 6. Primarily daytime observations
4	**Remote Sensing (Ground-Based)** NASA, 2010; Temimi et al., 2021	LIDAR, sun photometers, and other ground-based remote sensors	1. Provides vertical profile information 2. Higher temporal resolution 3. Can observe diurnal variations 4. Good for boundary layer dynamics 5. Direct measurement of optical properties	1. Very limited availability in Lagos 2. Expensive to install and maintain 3. Requires specialized technical expertise 4. Limited spatial coverage affected by power outages 5.Climate control challenges in tropical setting

5	**Modeling Approaches** Gueymard & Yang, 2020	Use of chemical transport models and emission inventories	1. Can estimate areas with no measurements Projects future scenarios and interventions Integrates multiple data sources 2. Quantifies source contributions 3. Can assess health and climate impacts	1. Limited validation data in Lagos region 2. Uncertainties in emission inventories 3. Coarse resolution misses local features 4. Computational limitations for high-resolution 5. Limited local expertise in complex modeling 6. Requires extensive input data often unavailable

2.10 Intercorrelation of Biomass Burning Haze with Regional Climate

Research has shown a strong interconnection between biomass-burning haze and regional climate change. Smoke aerosols emitted from vegetation fires can substantially alter the radiation budget, temperature profile, cloud formation, and precipitation patterns in the affected area (Tian et al., 2022). One of the most direct effects is the attenuation of solar radiation reaching the surface owing to the opacity of haze (Wang et al., 2020a). Measurements show that surface solar irradiance can decrease by 10-25% during major haze events (Jin et al., 2022). This solar dimming caused by scattering smoke aerosols causes a drop in daytime temperature and reduced convection (Jin et al., 2022). However, absorbing aerosols such as black carbon heat the atmosphere. The combined effects of scattering and absorption on the radiation budget perturb regional cloud cover and hydrological cycles (Li et al., 2022). Biomass-burning aerosols also serve as cloud condensation nuclei that promote cloud formation (Cheng 2022). Satellite studies have revealed an increased cloud fraction in regions with high smoke aerosol concentrations (Mhawish et al., 2021; Sarkar et al., 2022). Perturbations in cloud microphysics and distribution have led to changes in the rainfall patterns (Mao et al. 2018). Junkermann and Hacker's (2022) study found decreased precipitation over biomass-burning areas due to delayed raindrop formation.

However, Fowler et al. (2021) indicated potential increases in rainfall due to enhanced cloud development. The impacts on regional precipitation are complex and variable.

Moreover, absorbing smoke aerosols heat the lower atmosphere while reducing surface solar radiation (Li et al., 2022). This destabilizes the air column and inhibits convection, thereby suppressing cloud development. The resulting changes in cloudiness and regional air circulation affect the monsoon intensity over smoke-laden areas (Roy et al. 2022). This demonstrated the coupled nature of biomass burning emissions, solar radiation, clouds, and general atmospheric circulation. Overall, field measurements and modeling show that extensive smoke pollution from biomass burning alters regional cloud formation, the surface energy budget, temperature profiles, and rainfall patterns (Bougiatioti et al., 2016). However, quantification of these interconnections remains an active area of climate research. Improved understanding will support projections of climatic conditions in fire-prone regions and assessments of associated human impacts.

Regarding absorption and scattering effects, it has been reported that the largest direct radiative impact occurs on the southern fringes of the Sahara and in the Sahel region of West Africa, with peak forcing reaching more than 20 watts per square meter during the height of the burning season (Myhre et al., 2003; Ichoku et al., 2016). The absorption and scattering effects caused by the presence of haze particles in the Saharan atmosphere led to a much stronger radiative impact over West Africa than over Sahara, despite Sahara being the major source of haze particles. Numerous scientific studies have supported the view that haze contributes to a reduction in the total rainfall over West Africa, especially during the summer monsoon season (Huang et al., 2009; Tosca et al., 2010). For example, it has been suggested that the temperature in the lower atmosphere over the Saharan region may rise by as much as 3°C during the burning season because of the radiative effect of haze (Wilcox et al., 2016). However, some research has indicated that the main impact of haze on the location of rainfall over West Africa is likely a result of the absorption of solar radiation by the atmosphere, causing widespread heating. This can lead to a shift in the position of the maximum temperature from over the hotter land masses to the cooler and moist coastal region of West Africa, thus causing changes in atmospheric circulation and, hence, the position of the Inter-Tropical Convergence Zone (Lau et al., 2009; Wilcox et al., 2010).

Furthermore, studies have shown that haze particles are effective cloud condensation nuclei, leading to a reduction in the droplet size of cloud particles and an increase in the cloud albedo (Kaufman et al., 2002; Rosenfeld et al., 2008). It is suggested that this increase in cloud albedo led to a reduction in the net radiation at the surface and in the lower atmosphere because of the increased reflection of solar radiation back into the space. However, it is important to note that there are differing perspectives and ongoing debates within the scientific community regarding the magnitude and mechanism of these effects. Some studies have suggested that the overall radiative forcing effect of biomass burning haze may be smaller than previously estimated or that the effects on precipitation and cloud microphysics are more complex and vary depending on specific environmental conditions (Ramanathan et al., 2007; Tosca et al., 2010).

Additionally, the potential role of other factors such as atmospheric dynamics, large-scale circulation patterns, and land surface processes in modulating the observed climatic impacts of biomass burning haze in Africa has been discussed (Chung and Zhang, 2004; Jiang et al., 2008; Sakaeda et al., 2011). These alternative views show the need for continued research and integration of various data sources and modeling approaches to better understand the intricate interactions between biomass burning emissions, atmospheric processes, and regional climate patterns in Africa. As land use practices, forestry policies, and climate patterns continue to shift in Africa, some regions are projected to experience increased future biomass burning activity and haze exposure, whereas others may see a decline. Closely monitoring these changes and fully understanding their associated feedback are essential for developing effective adaptation and mitigation strategies across vulnerable regions in Africa. The impact of biomass burning haze on regional climates in Africa is a complex phenomenon that involves direct radiative effects, cloud microphysical modifications, and disruptions in water cycles and precipitation patterns. Although significant progress has been made in understanding these processes, ongoing research efforts are necessary to address the remaining uncertainties, divergent perspectives, and the need for accurate modeling and projections to inform effective policy decisions and mitigation strategies, particularly in the African context.

2.10.1 Direct radiative forcing

Direct radiative forcing (DRF) is a crucial concept in climate change research, focusing on the impact of atmospheric conditions on the Earth's radiative balance. The DRF quantifies the amount of solar radiation trapped within Earth's atmosphere, contributing to the greenhouse effect and global warming. The fundamental premise of the DRF is to understand the factors that influence the Earth's radiative budget, specifically the amount of solar radiation absorbed by the Earth's surface and the subsequent release of thermal radiation into the atmosphere. Atmospheric aerosols and greenhouse gases play a significant role in modulating the radiative balance by absorbing, scattering, and re-emitting radiation. One of the primary applications of DRF research is to quantify the climatic impacts of various atmospheric components, such as greenhouse gases, aerosols from biomass burning, and anthropogenic emissions. By determining the DRF of these compositions, scientists can better understand their relative contributions to global warming and climate change. This information is crucial for developing effective mitigation strategies and informing policymakers about the most pressing issues. The global dimming phenomenon and its impact on visibility due to air pollution illustrates the broader implications of atmospheric aerosols (Figure 2.4). Surface solar irradiance can decrease by 10-25% during major haze events.

Figure 2.4: Global dimming and visual illustration of impact of air pollution on visibility. Source: (Jagran Josh, 2016)

However, it is important to note that DRF calculations are not definitive and are often presented as relative comparisons between different phenomena or scenarios. The DRF values should be interpreted with caution, as there can be uncertainties and limitations associated with the measurement techniques and modeling approaches used. The direct radiative forcing of smoke aerosols has been studied extensively in the context of biomass burning. Smoke plumes contain a complex mixture of particulate matter and gases that can absorb and scatter solar radiation, leading to both positive (warming) and negative (cooling) radiative-forcing effects. The magnitude and sign of the DRF depend on various factors such as aerosol composition, optical properties, and underlying surface reflectance (Mok et al., 2016; Zhong and Zhang, 2021). Although the general understanding is that biomass burning aerosols contribute to atmospheric warming through the absorption of solar radiation by black carbon (a positive DRF), there are alternative perspectives and ongoing debates regarding the overall climatic impact of these aerosols. The process of particle formation and growth to cloud condensation nuclei (CCN) sizes in tropical convective regions follows a complex pathway (Figure 2.5), which is particularly relevant for understanding biomass burning impacts.

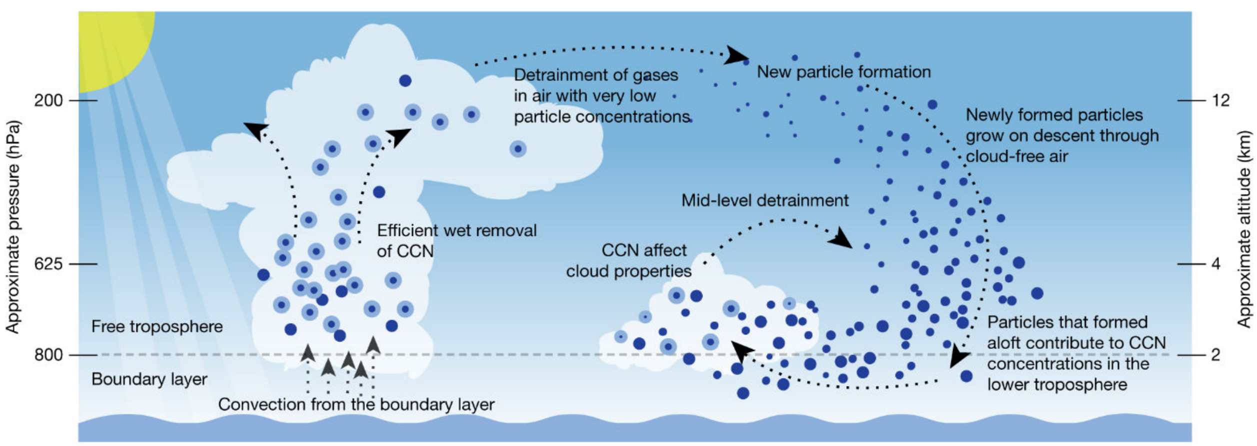


Figure 2.5: Synopsis of particle formation and growth to CCN sizes in the tropical convective region. Source: (Williamson et al., 2019)

Some studies have suggested that the cooling effect from the scattering of solar radiation by organic carbon and other aerosol components may partially offset or even outweigh the warming effect of black carbon, leading to a net negative DRF in certain regions or conditions (Jacobson, 2014; Samset et al., 2018). Additionally, the interaction between biomass burning aerosols and clouds, known as the semi-direct effect, can further complicate the radiative forcing calculations. The absorption of solar radiation by aerosols can lead to atmospheric heating and cloud burnoff, resulting in a positive DRF, whereas an increase in cloud condensation nuclei from aerosols can enhance cloud reflectivity, leading to a negative DRF (Koch and Del Genio, 2010; Wilcox, 2012). These alternative perspectives show the complexity of the radiative forcing phenomenon and the need for continued research to improve our understanding of its underlying processes and interactions.

Accurate quantification of the DRF is crucial for developing standard climate models and informing policymakers regarding the potential impacts of various atmospheric compositions. Furthermore, it is important to recognize that DRF is just one aspect of the overall climatic impact of biomass burning emissions. Other factors, such as indirect effects on cloud microphysics, atmospheric chemistry, and ecosystem feedback, also play significant roles in shaping regional and global climate responses (Voulgarakis and Field, 2015; Jacobson, 2014). Continued research efforts, integrating field observations, remote sensing, and advanced modeling techniques are necessary to improve our understanding of the climatic impacts of biomass burning emissions and inform effective mitigation strategies.

2.11 Absorption and scattering effects by region (Africa, West Africa, Nigeria, Lagos)

The absorption and scattering effects of biomass-burning haze exhibit significant regional variation, particularly in Africa, West Africa, Nigeria, and Lagos. These regional differences are attributed to the interplay between various factors including vegetation distribution, atmospheric dynamics, and local meteorological conditions.

In Africa, it has been reported that the largest direct radiative impact occurs on the southern fringes of the Sahara and Sahel regions of West Africa, with peak forcing reaching an excess of 20 watts per square meter during the height of the burning season (Myhre et al., 2003; Ichoku et al., 2016). Interestingly, despite Sahara being the major source of haze particles, the absorption and scattering effects lead to a much stronger radiative impact over West Africa than the Sahara itself. This phenomenon is attributed to the rapid transition from vegetated areas to desert regions, where the scattering effect is maximized at the boundary between the biosphere and the desert. For regional dynamics, the prevailing northeasterly winds during the winter months tend to rapidly disperse any haze injected into the upper atmosphere, whereas the westerly component during the summer facilitates the transport of haze across the region. This transport mechanism is believed to initiate the movement of aerosol particles from land to the Atlantic Ocean, potentially leading to their injection into the cloud layers over the ocean (Johnson et al., 2008; Das et al., 2017). However, it is important to note that regional variations in the absorption and scattering effects are subject to ongoing debate and alternative perspectives within the scientific community. Some studies have suggested that the radiative impacts of biomass-burning haze may be more localized or dependent on specific atmospheric conditions, such as humidity, aerosol aging, and the presence of other aerosol types (Haywood et al., 2003; Eck et al., 2003).

Additionally, the role of other factors, such as atmospheric dynamics, large-scale circulation patterns, and land surface processes, in modulating the observed radiative effects has been showed by various researchers (Chung and Zhang, 2004; Jiang et al., 2008; Sakaeda et al., 2011). These alternative views emphasize the need for a full understanding of the complex interactions between biomass burning emissions, atmospheric processes, and regional climate patterns. In the specific case of Nigeria and Lagos, the impacts of biomass burning haze may be influenced by local sources, such as urban pollution and industrial activities, as well as regional transport from neighboring areas. Detailed case studies and numerical modeling analyses are required to understand the contributions of different sources and processes to the observed radiative effects in these regions (Marais et al., 2014; Ajao et al., 2021). Furthermore, the absorption and scattering effects are just one aspect of the overall climatic impact of biomass burning haze. Indirect effects on cloud microphysics, atmospheric chemistry, and ecosystem feedback also play a significant role in shaping regional climate responses (Voulgarakis and Field, 2015; Jacobson, 2014). A detailed understanding of these interconnected processes is crucial for developing effective mitigation strategies and informing policy decisions.

2.11.1 Impact on temperature, precipitation, etc.

The impact of biomass burning haze on temperature, precipitation, and other meteorological variables has been studied extensively, particularly in Africa. These impacts are driven by the complex interactions between haze particles and solar radiation, atmospheric dynamics, and microphysical cloud processes. Studies have shown that, during the peak period of biomass burning, a phenomenon known as the "diurnal temperature range" is observed. Daily maximum temperatures decrease, whereas daily minimum temperatures increase (Jacobson, 2014; Gautam et al., 2009). This effect is attributed to the presence of tiny particles in the haze layer, which lower the amount of solar radiation reaching the ground, causing a slower heating rate during the day and faster cooling at night. Additionally, the particles increase the frequency of cooling events known as "temperature inversions," where the surface temperature is cooler than the surrounding air (Wilcox, 2010). The impacts on the precipitation patterns were equally significant. In regions such as northern Africa, where precipitation is typically limited due to warm and dry upper atmospheric conditions, the presence of haze can alter these conditions. The absorption of sunlight by black carbon aerosols in hazy air warms the hazy layer and cools the ground, weakening temperature inversion (Lau et al., 2009; Tosca et al., 2010). This can increase the probability of more frequent precipitation events, even during the dry season, particularly in the sub-Saharan region. However, it is important to note that precipitation responses can be complex and may vary depending on the specific region and meteorological conditions (Sakaeda et al., 2011; Hodnebrog et al., 2016).

Furthermore, observational data from missions such as AERONET and MODIS have revealed a reduction in low-level cloud cover during haze conditions, with the decline in cloud cover proportional to the increase in particulate matter concentration (Koren et al., 2008; Wilcox, 2012). This reduction in low-level clouds could lead to both short- and long-term climate changes, such as an increase in downwelling longwave radiation, surface humidity, and temperature (Jacobson, 2014). Over longer periods, these changes could potentially impact large-scale atmospheric circulation patterns, such as the Intertropical Convergence Zone (ITCZ) and Hadley circulation cell, leading to significant shifts in the typical rain belt experienced in the tropics (Sakaeda et al., 2011; Hodnebrog et al., 2016). However, it is important to note that there are alternative perspectives and ongoing debates within the scientific community regarding the magnitude and mechanism of these effects. Some studies have suggested that the effects of precipitation and cloud microphysics may be more nuanced and dependent on specific environmental conditions, such as atmospheric stability, aerosol optical properties, and the presence of other aerosol types (Rosenfeld et al., 2008; Fan et al., 2015).

Additionally, the role of other factors, such as large-scale atmospheric dynamics, land surface processes, and aerosol-cloud interactions, in modulating the observed impacts has been showed by various researchers (Chung and Zhang, 2004; Jiang et al., 2008; Sakaeda et al., 2011). These alternative views emphasize the need for a complete understanding of the complex interactions between biomass burning emissions, atmospheric processes, and regional climate patterns. Thus, the impact of biomass-burning haze on temperature, precipitation, and other meteorological variables may have significant implications for agriculture, water resources, and ecosystem dynamics in affected regions, particularly in Africa. Ongoing research is necessary to quantify these potential impacts and to inform effective adaptation and mitigation strategies.

2.11.2 Indirect effects on clouds and circulation patterns

The indirect effects of biomass burning haze on clouds and atmospheric circulation patterns have been extensively investigated because they play a crucial role in modulating the overall climatic impact of these emissions. These indirect effects are driven by complex interactions between aerosol particles and cloud microphysical processes as well as radiative and thermodynamic effects on atmospheric dynamics. One of the key indirect effects is the role of biomass burning aerosols, such as cloud condensation nuclei (CCN) and ice nuclei (IN). The presence of these aerosols can influence the formation, microphysical properties, and lifetime of clouds (Rosenfeld et al., 2008; Andreae et al., 2004). An increase in CCN can lead to the formation of a larger number of smaller cloud droplets, potentially enhancing cloud reflectivity and reducing precipitation efficiency. (Kaufman et al., 2005; Koren et al., 2008). However, the response of cloud properties to biomass burning aerosols is complex and can vary depending on factors such as aerosol composition, atmospheric conditions, and cloud type. For example, some studies have suggested that under certain conditions, an increase in CCN can lead to the uplifting of convective clouds, potentially enhancing precipitation (Rosenfeld et al., 2008; Fan et al., 2018). Additionally, the absorption of solar radiation by biomass burning aerosols, particularly black carbon, can lead to atmospheric heating and changes in atmospheric stability, a phenomenon known as the semi-direct effect (Koch and Del Genio, 2010; Wilcox, 2012). This can affect cloud formation, lifetime, and precipitation patterns both within and around smoke plumes. Indirect effects of biomass burning haze can also influence large-scale atmospheric circulation patterns. For instance, studies have suggested that the radiative and thermodynamic impacts of these aerosols can alter the strength and position of the Intertropical Convergence Zone (ITCZ) and the associated regional precipitation patterns (Lau et al., 2009; Sakaeda et al., 2011; Hodnebrog et al., 2016). Furthermore, there is evidence that long-range transport of biomass burning aerosols over oceanic regions can impact marine stratocumulus cloud decks, potentially altering the Earth's radiation budget and influencing atmospheric circulation (Wilcox, 2012; Mardi et al., 2018).

Understanding these indirect effects is an active area of research, and there are alternative perspectives and ongoing debates within the scientific community. Some studies have showed the potential of compensating effects or feedback that may dampen or amplify the overall climatic impact of biomass-burning aerosols (Jacobson, 2014; Fan et al., 2015). Additionally, the role of other factors, such as atmospheric dynamics, land surface processes, and aerosol-cloud interactions, in controlling the observed impacts has been showed by various researchers (Chung and Zhang, 2004; Jiang et al., 2008; Sakaeda et al., 2011). These alternative views emphasize the need for a full understanding of the complex interactions between biomass burning emissions, atmospheric processes, and regional climate patterns. The indirect effects of biomass burning haze on clouds and circulation patterns have significant implications for regional and global climates, as well as for weather forecasting and climate modeling. An accurate representation of these processes in numerical models is essential to improve projections of future climate scenarios and inform adaptation strategies, particularly in regions prone to frequent biomass burning events. The relationship between fuel type and its subsequent impacts on plume evolution and radiative effects follows a systematic progression (Figure 2.6). The chemical composition and physical properties of biomass fuels play a pivotal role as is a key factor considered in the analysis.

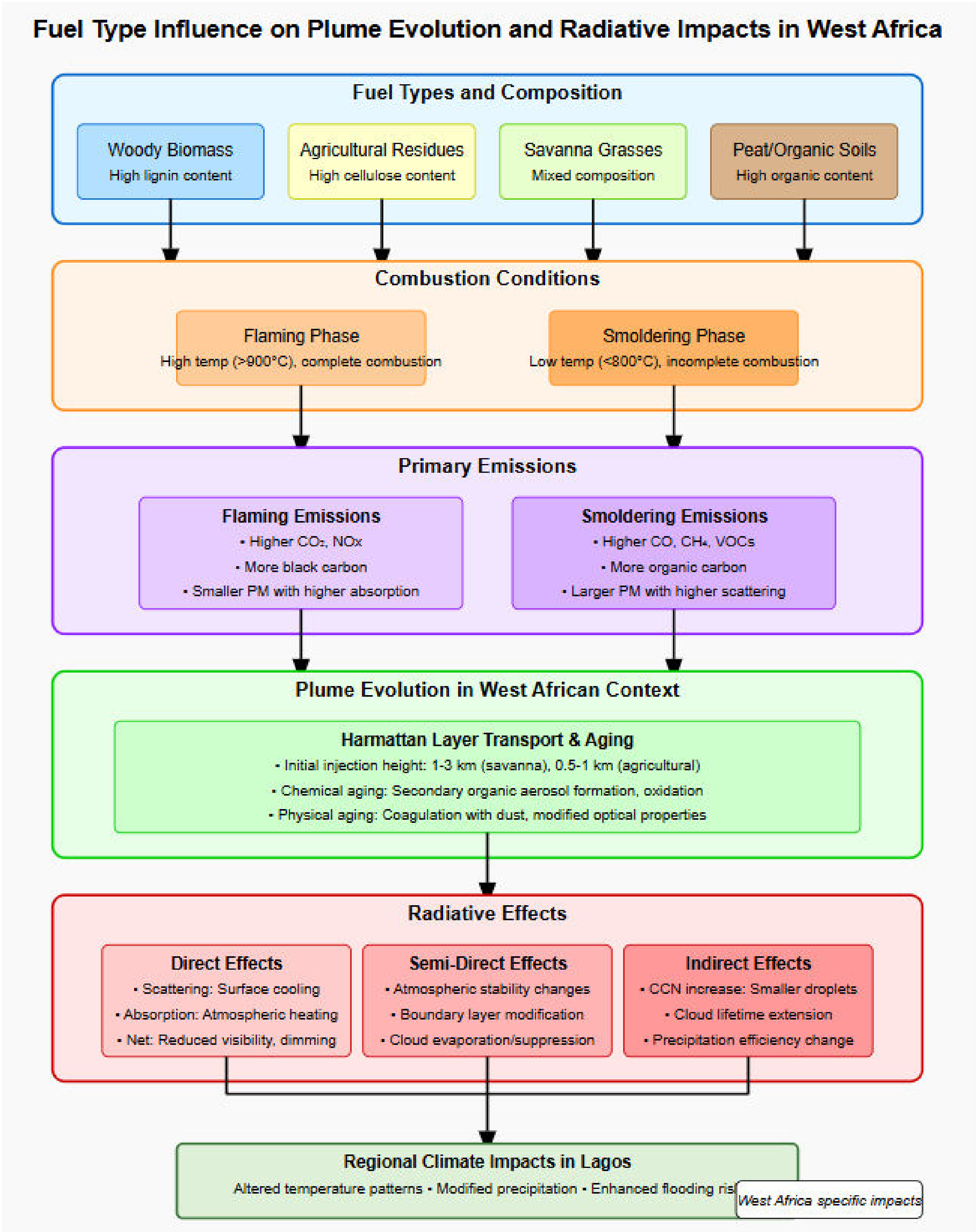


Figure 2.6: flowchart showing how fuel type affects plume evolution and radiative impacts.

2.12 Modeling comparative analyses by region - (Africa, WA, Nigeria, Lagos)

Modeling comparative analyses by region has been increasingly employed to investigate and compare the effects of biomass burning haze on climate in different geographical areas, such as Africa, West Africa, Nigeria, and Lagos. These models incorporate various factors, including temperature, wind speed, and wind direction, as well as the concentrations of different pollutants emitted during biomass burning. However, one of the significant challenges in modeling the effects of haze is the difficulty in directly comparing the impact of the same concentrations of pollutants across different regions, owing to the varying climatic conditions and environmental factors.

Regional climate models (RCMs) have provided valuable tools for studying the effects of haze in specific regions of the world. RCMs are designed to provide high-resolution simulations of climate processes and can be used to investigate the impacts of biomass burning emissions within a regional context, considering local topography, land-use patterns, and atmospheric dynamics. As part of this research, the aim was to gather global data on the composition of biomass burning haze and utilize RCMs to study and compare the effects of haze in different regions, focusing on Africa, West Africa, Nigeria, and Lagos. The use of RCMs has several advantages. First, by comparing the model predictions with ground-based measurements in the same region, the model performance can be validated, and the confidence in its results can be increased. This validation process is crucial because it helps to identify potential biases or uncertainties in the parameterizations and assumptions of the model. Second, a comparative analysis across different regions can help to identify and test the validity of the divergences in the effects of haze, potentially revealing region-specific factors or processes that modulate these impacts, such as local meteorological conditions, land surface characteristics, and the influence of other emission sources.

However, it is important to note that there are ongoing debates and alternative perspectives within the scientific community regarding the accuracy and limitations of regional climate models in simulating the complex interactions between biomass burning emissions, atmospheric processes, and climate patterns. Some studies have showed the uncertainties associated with parameterizations of aerosol-cloud interactions, boundary conditions, and the representation of sub-grid scale processes in these models (Popovicheva et al., 2017). Additionally, the role of large-scale atmospheric dynamics, land surface processes, and feedback mechanisms in modulating the regional impacts of biomass burning haze has been emphasized by various researchers (Srivastava et al., 2019). These views show the need for a full understanding of the complex interactions between biomass burning emissions, atmospheric processes, and regional climate patterns, which may not be fully captured by current modeling approaches. For instance, the representation of aerosol-cloud interactions, which can have both cooling and warming effects, remains a significant source of uncertainty in climate models. Furthermore, the accuracy of model simulations can be influenced by the quality and availability of input data such as emission inventories, meteorological observations, and land-use data (Urbanski, 2018). In regions with limited ground-based monitoring networks or satellite coverage, uncertainty in the input data can propagate through model simulations, potentially affecting the reliability of results.

Despite these challenges, regional climate models remain valuable tools for studying the regional impacts of biomass burning haze, and their continued development and improvement can help to address some of the existing limitations. For example, the integration of advanced aerosol-cloud microphysics schemes, improved parameterizations of aerosol-radiation interactions, and assimilation of observational data can enhance the accuracy of model simulations (Zhang et al., 2021). In addition to scientific considerations, it is crucial to consider the potential implications of the research findings to inform policy decisions and enforce tighter regulations on air quality and pollution control. The results of this comparative analysis can provide valuable insights for policymakers and stakeholders to develop effective mitigation strategies and adaptation measures in regions affected by biomass burning haze. However, it is essential to acknowledge the ethical considerations and decision-making processes involved in allocating research funds and prioritizing areas of focus. A holistic approach that considers the potential positive outcomes, societal impacts, and equitable distribution of resources is essential to ensure that maximum benefits are achieved for communities with poor air quality. Collaboration with local stakeholders, policymakers, and community representatives can help ensure that research efforts are aligned with local needs and priorities and that the findings are effectively communicated and translated into actionable policies and interventions. Furthermore, it is important to recognize that the effects of biomass burning haze can extend beyond regional boundaries and contribute to global climate change. Therefore, international cooperation and coordination in research, policy development, and knowledge sharing are crucial for addressing the broader impact of this issue.

2.12.1 Case study: Lagos, Nigeria

The case study of Lagos, Nigeria, provides a compelling opportunity to examine the impact of biomass burning haze in a rapidly urbanizing environment. As one of the fastest-growing megacities in Africa, with a daytime population estimated to be around 15 million, Lagos faces significant air quality challenges worsened by the influence of biomass burning emissions (Marais et al., 2014; Ajao et al., 2021). The data presented in the case study show the substantial aerosol optical depth (AOD) observed in Lagos, indicating the presence of a significant aerosol burden, particularly near the surface. AOD measurements at 550 nm for the years 2003-2005 demonstrate that most values exceeded the critical threshold of 0.5, a level at which aerosol particles begin to have a considerable effect on the amount of solar radiation reaching the Earth's surface (Sayer et al., 2014; Eck et al., 2019). This high aerosol loading has implications for various atmospheric processes, including cloud microphysics, precipitation patterns, and the overall radiation balance. Studies have shown that elevated aerosol concentrations can affect cloud droplet concentrations, cloud size and lifetime, precipitation efficiency, and the reflection of solar radiation (Kaufman et al., 2005; Rosenfeld et al., 2008; Wilcox, 2012).

Notably, this case study revealed distinct seasonal variations in aerosol loading, with higher levels observed during the dry season than during the wet season. However, during the wet season, the occurrence of Harmattan winds, characterized by increased wind speeds ranging from to 5-7 m/s (compared to the national average of 3-5 m/s), can influence the measured AOD by dispersing and diluting the accumulation of aerosols (Balogun et al., 2014; Kalashnikova et al., 2021). While this case study provides valuable insights into aerosol loading and potential climatic impacts in Lagos, it is essential to consider alternative perspectives and ongoing debates within the scientific community regarding the specific mechanisms and magnitudes of these impacts. For instance, some studies have showed the potential for compensating effects or feedback that may dampen or amplify the overall climatic impact of biomass burning aerosols in urban environments (Jacobson, 2014; Fan et al., 2015; Yang et al., 2019). The complex interplay between anthropogenic emissions, local meteorological conditions, and regional atmospheric dynamics can modulate the observed effects, leading to variations in the magnitude and direction of impacts.

Additionally, other factors, such as land surface processes, urban heat island effects, and interactions with other aerosol sources (e.g., industrial emissions and transportation), may also contribute to the observed aerosol loading and associated climatic impacts in Lagos (Marais et al., 2014; Ajao et al., 2021; Mok et al., 2018). Furthermore, it is important to consider the potential implications of the findings of this case study for local and regional policymaking, urban planning, and air quality management. The high aerosol burden observed in Lagos may necessitate targeted mitigation efforts, such as emission control measures, improved urban vegetation cover, and implementation of sustainable urban development practices (Balogun et al., 2019; Ajao et al., 2021). However, the development and implementation of such strategies should be informed by a detailed understanding of the complex interactions between biomass burning emissions, urban pollution sources, and local meteorological conditions. Collaboration with local stakeholders, policymakers, and community representatives can help ensure that research efforts are aligned with local needs and priorities and that the findings can be effectively translated into actionable policies and interventions (Asuogu et al., 2022). Moreover, it is crucial to recognize that the impact of biomass burning haze can extend beyond the urban boundaries of Lagos and contribute to regional and global climate change. Therefore, regional, and international cooperation in research, policy development, and knowledge sharing can be crucial in addressing the broader impact of this issue (Ichoku et al., 2016; Das et al., 2017).

2.13 Mechanisms Linking BB Haze and Flooding

Biomass burning, a prevalent phenomenon across various regions globally, has attracted significant attention owing to its potential implications for the atmospheric composition, air quality, and climatic processes. The interaction between biomass burning haze and flooding events has emerged as a subject of substantial interest, and recent studies have showed the complex mechanisms underlying this relationship. One of the primary mechanisms linking biomass burning haze and flooding is the alteration of atmospheric aerosol concentrations, and their subsequent impact on cloud formation and precipitation patterns. Emissions from biomass burning, particularly from vegetation fires and agricultural practices, release large quantities of particulate matter and gaseous pollutants into the atmosphere. These aerosols can act as cloud condensation nuclei (CCN), influencing the microphysical properties of clouds and potentially altering their ability to produce precipitation (Rosenfeld et al. 2014; Tao et al. 2012). The atmospheric processes leading from haze formation to precipitation development involve complex interactions between aerosols and cloud microphysics (Figure 2.7). One of the primary mechanisms linking biomass burning haze and flooding is the presence of atmospheric conditions which lead to physical and chemical alterations of the atmosphere.

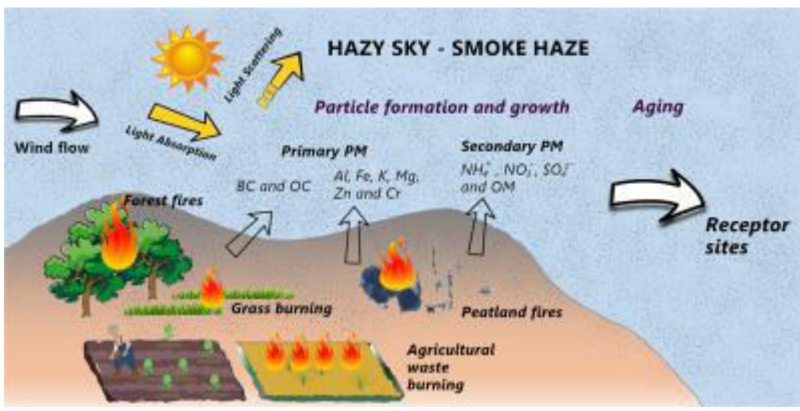


Figure 2.7: Haze formation and Atmospheric process leading to the formation of Precipitation. Source: (Adam et al., 2021)

The presence of biomass burning aerosols can modify the size distribution and concentration of CCN, leading to the formation of smaller and more numerous cloud droplets. This process, known as the indirect effect of aerosols, can increase cloud reflectivity, thereby reducing the amount of solar radiation reaching the Earth's surface and potentially suppressing precipitation (Andreae et al. In 2004, Ramanathan, et al. 2001). Conversely, in certain scenarios, the presence of aerosols can also affect convective cloud systems, potentially enhancing the rainfall intensity (Rosenfeld et al., 2008; Lin et al., 2006). Furthermore, the chemical composition of biomass burning aerosols, particularly the presence of organic compounds and black carbon, can influence their hygroscopicity and ability to act as CCN, further modulating cloud properties and precipitation patterns (Andreae and Rosenfeld, 2008; Reid et al., 2005). In addition to aerosol-cloud interactions, biomass burning emissions can directly impact atmospheric stability and circulation patterns, potentially influencing the likelihood and intensity of flooding events. The release of greenhouse gases, such as carbon dioxide and methane, from biomass burning can contribute to atmospheric warming, thereby influencing atmospheric dynamics and potentially altering the frequency and intensity of extreme precipitation events (Trenberth, 2011; Held and Soden, 2006).

Moreover, the transport and deposition of biomass burning aerosols can potentially alter the albedo of land and water surfaces, thereby affecting the energy balance and influencing local and regional climatic patterns, including precipitation regimes (Ramanathan and Carmichael, 2008; Menon et al., 2002). It is important to note that the relationship between biomass burning haze and flooding is complex and can vary depending on the specific meteorological conditions, geographical location, and the scale of the biomass burning event. Additionally, there are alternative perspectives and ongoing debates within the scientific community regarding the precise mechanisms and magnitude of their impact. Some studies have suggested that the effects of biomass burning aerosols on precipitation may be more complex and dependent on other factors, such as atmospheric stability, moisture availability, and the vertical distribution of aerosols (Khain, 2009; Tao et al., 2007). Other researchers have argued that the influence of biomass burning emissions on precipitation patterns may be more pronounced at regional or local scales than at larger spatial scales (Arino et al. 2015; Arino et al. 2019). Furthermore, the long-range transport of biomass burning plumes can complicate the attribution of flooding events to local or regional biomass burning sources, because aerosols and precursor gases can be transported over large distances and interact with other atmospheric processes (Prospero and Lamb, 2003; Prospero et al., 2014). It is essential to acknowledge the inherent uncertainties and limitations of our understanding of the complex interactions among biomass burning emissions, atmospheric processes, and precipitation patterns. Ongoing research efforts incorporating advanced observational techniques, high-resolution modeling, and interdisciplinary approaches are crucial for refining our knowledge and improving our ability to predict and mitigate the potential impacts of biomass burning on flooding events.

2.13.1 Mechanism 1: Impact on atmospheric conditions (atmospheric processes).

Biomass burning emissions can significantly impact atmospheric conditions, which in turn can influence the likelihood and intensity of flooding events. The mechanism linking biomass burning haze to flooding involves the alteration of atmospheric aerosol concentrations and their subsequent effects on cloud formation and precipitation patterns. When biomass burning occurs, large quantities of aerosol particles, including particulate matter (PM), black carbon, and various organic compounds, are released into the atmosphere (Dekker et al., 2017). These aerosols can act as cloud condensation nuclei (CCN), affecting the microphysical properties of clouds and ultimately affecting precipitation processes. The presence of biomass burning aerosols can modify the size distribution and concentration of CCN, leading to the formation of smaller and more numerous cloud droplets. This phenomenon, known as the indirect effect of aerosols, can increase the reflectivity of clouds, reduce the amount of solar radiation reaching the Earth's surface, and potentially suppress precipitation (Gilman et al., 2015).

2.13.2 Mechanism 2: Alterations in precipitation patterns.

Biomass burning haze can directly influence precipitation patterns, which in turn can contribute to the occurrence of flooding events. The alteration of atmospheric aerosol concentrations, as described in Mechanism 1, can modulate the cloud properties and precipitation processes. Under certain atmospheric conditions, biomass-burning aerosols can invigorate convective cloud systems, potentially enhancing rainfall intensity (Bond et al., 2013). This is because aerosols can serve as ice nuclei, promoting ice formation within clouds and invigorating convective updrafts, leading to increased precipitation under favorable atmospheric conditions. However, in other scenarios, the indirect effect of aerosols can suppress precipitation by increasing cloud reflectivity and reducing the amount of solar radiation reaching Earth's surface. Furthermore, the release of greenhouse gases, such as carbon dioxide and methane, from biomass burning can contribute to atmospheric warming, potentially altering atmospheric dynamics and the frequency and intensity of extreme precipitation events (Sandström et al., 2023). These changes in precipitation patterns, whether in the form of increased or decreased rainfall intensity or altered spatial and temporal distributions, can directly affect the likelihood and severity of flooding events in the affected regions.

2.13.3 Mechanism 3: Influence on hydrological processes (Hydrological processes)

Biomass-burning haze can also influence hydrological processes, which can indirectly contribute to flooding events (Riva et al., 2022). The deposition of biomass burning aerosols can alter the albedo (reflectivity) of land and water surfaces, thereby affecting energy balance and potentially influencing local and regional climatic patterns, including precipitation regimes. Changes in precipitation patterns, as described in Mechanism 2, can have cascading effects on hydrological processes such as soil moisture content, groundwater recharge, and runoff patterns. In addition, the transport and deposition of biomass burning aerosols can potentially affect water quality and aquatic ecosystems, which can indirectly affect hydrological processes (Kirschke et al., 2013). For example, the deposition of particulate matter and other pollutants from biomass burning can alter the chemistry and turbidity of water bodies, potentially affecting the water flow and storage characteristics. Moreover, the removal of vegetation through biomass burning can reduce evapotranspiration rates and alter the water cycle, potentially increasing surface runoff and flooding risks in certain areas. The impact on hydrological processes shows the complex interplay between biomass burning haze, atmospheric processes, and the potential for flooding events, showing the need for a broader understanding of these interconnected mechanisms.

2.14 Proposed causal explanations.

Researchers have proposed various causal explanations for the mechanisms linking biomass burning haze and flooding events. The proposed explanations aim to show the complex interplay between atmospheric processes, aerosol concentrations, and precipitation patterns. However, it is crucial to acknowledge that these explanations are subject to ongoing scientific debate and alternative perspectives exist in the literature. One prominent proposition suggests that an increase in atmospheric aerosol concentrations, primarily from biomass burning emissions, can lead to a reduction in the size of the cloud droplets (Che et al., 2021). This phenomenon is known as the indirect effect of aerosols, wherein the presence of numerous aerosols acting as cloud condensation nuclei results in the formation of smaller cloud droplets. These smaller droplets coalesce at a slower rate than larger droplets, hindering their growth to the critical size required for the formation of raindrops (Che et al., 2021). Consequently, this process can contribute to the suppression of precipitation and persistence of widespread haze conditions.

Another proposed explanation, known as the "elevated heat pump" mechanism, attempts to explain the generation of an artificial high-pressure region in the upper atmosphere. According to this proposition, hot air at the surface rises to the lower-pressure region in the upper atmosphere, and this upward motion is compensated by the influx of cooler air from the sea (Liu et al., 2020). This process is believed to increase the likelihood of cloud formation, as the rising hot air cools, and the water vapor condenses to form clouds and potentially precipitation. Proponents of this theory suggest that the forcing of warm air ascent and the subsequent development of a cooler, low-pressure system at sea level may lead to more intense and frequent rainfall events (Liu et al., 2020). However, it is important to note that the proposed explanations have inconsistencies and limitations. For instance, while the "elevated heat pump" mechanism appears plausible for explaining the generation of haze and drought conditions over land, it may not fully account for the complex interplay between convection dynamics, synoptic-scale systems, and other meteorological factors that influence precipitation patterns.

Additionally, some researchers argue that the proposed explanations tend to focus primarily on the microphysical aspects of the suggested link between biomass burning haze and flooding, neglecting other important factors, such as convection dynamics and synoptic-scale systems, that may also play a crucial role (Morrison et al., 2020; Liu et al., 2020). To address these limitations and inconsistencies, researchers have advocated an integrative approach that combines laboratory experiments, numerical modeling constraints, observational data analyses, and the theory of atmospheric dynamics (Balsamo et al., 2018) Arcomano et al., 2022). By employing an inclusive approach, scientists aim to investigate the proposed links among drought conditions, convection dynamics, and other relevant factors in greater detail, potentially explaining the causal mechanisms underlying the relationship between biomass burning haze and flooding events. It is important to recognize that the scientific understanding of these complex phenomena is continuously evolving, and alternative perspectives and interpretations may emerge as new research findings become available. Ongoing scientific studies and collaborations among researchers from various disciplines are essential to improve knowledge and develop a better understanding of the mechanisms linking biomass-burning haze and flooding events.

2.15 Microphysical Processes, Convection Dynamics

Separating the mechanisms that link biomass burning haze and flooding requires a full understanding of microphysical processes and convection dynamics. These processes play a crucial role in modulating cloud formation, precipitation patterns, and ultimately, the potential for flooding events. Microphysical processes direct the growth and formation of raindrops within a cloud system. Researchers have proposed two primary theories to explain raindrop growth: the "collision-coalescence" theory and the "ice-phase" theory (Tao et al., 2012; Kumjian & Prat, 2014). The "collision-coalescence" theory suggests that within a population of cloud droplets, the larger droplets (typically on the order of 100 micrometers in radius) grow primarily through collisions and coalescence with smaller droplets (Pruppacher and Klett, 2010). Each collision results in a summation of the radii. If the sum exceeds a critical value (typically in the range of 200–250 µm, which is approximately the size of the largest droplet in the population), the drop becomes stable and continues to grow. Conversely, smaller droplets are destabilized and merge with larger droplets, facilitating the growth of raindrops within minutes (Lamb and Verlinde, 2011).

On the other hand, the "ice-phase" theory suggests that larger raindrops are produced through ice crystal growth, typically involving a combination of the "accretion" process and "riming (Tao et al., 2012)." The accretion process occurs when a supercooled water droplet grows rapidly as it encounters an ice crystal, whereas riming involves the growth of a supercooled water droplet as it collides with an ice crystal in relative motion (Crosier et al., 2011). The presence of rime ice on the crystal enlarges the aggregation area, thereby enhancing the potential for rainfall (Straka, 2009). While these microphysical processes are essential for raindrop formation, convection dynamics also play a crucial role in modulating precipitation patterns and flooding potential. Convection refers to the vertical motion of air within the atmosphere driven by buoyancy forces resulting from temperature and moisture differences (Emanuel, 1994). Biomass-burning emissions can influence convection dynamics through the release of aerosols and greenhouse gases. Aerosols can act as cloud condensation and ice nuclei, affecting cloud microphysics and potentially altering the strength and spatial distribution of convective systems (Rosenfeld et al., 2008; Fan et al., 2018). Additionally, the release of greenhouse gases from biomass burning can contribute to atmospheric warming, potentially influencing atmospheric stability and convection patterns (Trenberth, 2011). However, it is important to note that the relationship between biomass burning haze, microphysical processes, convection dynamics, and flooding is complex and is subject to ongoing research. Some studies suggest that the effects of biomass burning aerosols on precipitation may be more pronounced at regional or local scales than at larger spatial scales (Gonçalves et al., 2015; Arino et al., 2019). Furthermore, long-range transport of biomass burning plumes can complicate the attribution of flooding events to specific biomass burning sources (Prospero and Lamb, 2003).

Researchers have advocated an integrative approach that combines laboratory experiments, numerical modeling, observational data analyses, and the theory of atmospheric dynamics to investigate the proposed links between biomass burning haze, microphysical processes, convection dynamics, and flooding events (Khain, 2009; Tao et al., 2012). This approach recognizes the inherent complexities and uncertainties in understanding these phenomena, emphasizing the need for interdisciplinary collaboration and ongoing scientific research. In terms of applications, an improved understanding of the microphysical processes and convection dynamics can inform the development of advanced weather forecasting models and early warning systems for potential flooding events. By integrating data on biomass burning emissions, aerosol concentrations, and their impact on cloud microphysics and convective patterns, these models can potentially enhance the accuracy of precipitation predictions and flood risk assessments (Fan et al., 2015; Rosenfeld et al., 2014). Additionally, this knowledge can guide the development of air quality management strategies and land-use policies aimed at mitigating the impact of biomass burning emissions on atmospheric processes and the associated risks of flooding (Andreae et al., 2004; Ramanathan and Carmichael, 2008).

2.16 Evaluation of Competing Theories

To evaluate the significance and limitations of competing theories that attempt to explain the relationship between biomass burning and flooding, it is crucial to consider the diverse perspectives and critical assessments present in the scientific literature. The "soil moisture" theory and the "aerosol-radiation" theory attribute the linkage between biomass burning and flooding to different climatic mechanisms. The "soil moisture" theory suggests that biomass burning can lead to a reduction in soil moisture, which in turn can influence precipitation patterns and potentially contribute to flooding events (Gan et al., 2004; Bevan et al., 2009). However, this theory has been criticized for its limitations in explaining the frequent occurrence of flooding events after haze episodes in regions such as the central and lower Mekong River basins, where the time lag between drought periods and flood events may not align with the proposed mechanisms (Huang et al., 2016). On the other hand, the "aerosol-radiation" theory proposes that biomass burning emissions can alter atmospheric aerosol concentrations, affecting cloud microphysics and precipitation patterns through the aerosol indirect effect (Rosenfeld et al., 2008; Andreae et al., 2004). While this theory offers a plausible explanation for the observed relationship between biomass burning haze and flooding, it may be limited in accounting for the historical occurrences of large flood events, as showed by some studies (Lohmann and Feichter, 2005; Tao et al., 2012).

A third theory proposed by researchers suggests that flooding events may be caused by the "collective effect" of enhanced aerosol loading in the lower atmosphere during the active period of the lifetime of mesoscale convective systems (Rosenfeld et al., 2014; Fan et al., 2018). This theory deviates from previous theories by proposing a mechanism that is not directly linked to climate change induced by aerosol particles, as suggested by the "aerosol-radiation" aerosol–radiation theory. It is important to acknowledge that each theory has its strengths and limitations, and the evaluation of its significance and applicability is an ongoing process within the scientific community. Researchers have advocated an integrative approach that combines observational data, numerical modeling, and laboratory experiments to investigate the proposed links between biomass burning, aerosol concentrations, cloud microphysics, and precipitation patterns (Khain, 2009; Tao et al., 2012).

Furthermore, it is essential to recognize that the relationship between biomass burning and flooding is complex and may involve multiple interacting factors such as atmospheric dynamics, synoptic-scale systems, and regional climatic patterns (Gonçalves et al., 2015; Prospero and Lamb, 2003). Therefore, the evaluation of competing theories should consider context-specific conditions and the potential for combined or synergistic effects. In terms of applications, the critical evaluation of these theories can inform the development of improved weather forecasting models, air quality management strategies, and land use policies. By integrating the most robust theories and findings, decision makers can better understand the potential impacts of biomass burning emissions on atmospheric processes and the associated risks of flooding, leading to more effective mitigation and adaptation measures (Ramanathan and Carmichael, 2008; Andreae et al., 2004).

2.17 Role of Mesoscale Convective Systems

Mesoscale convective systems (MCSs) play a crucial role in the link between seasonal biomass burning in the Indochina Peninsula and precipitation extremes over Africa, particularly in the sub-Saharan region (Djakouré et al., 2024). These systems are characterized by organized clusters of thunderstorms that can produce intense rainfall over a relatively large area (Houze, 2004; Xu et al., 2015). For precipitation events to occur at a given location, two important conditions must be met: sufficient moisture from the surroundings to increase the available convective potential energy and an ascent of moist air that exceeds a certain threshold to initiate moist convection (Zhang et al., 2009; Tao et al., 2012). During the daytime, solar radiation creates a strong thermal contrast between the surface and upper troposphere, leading to moisture convergence in the lower atmosphere and creating favorable conditions for the initiation of convective precipitation. However, previous studies have suggested that the abundance of aerosols from biomass burning can induce smaller cloud droplets and potentially reduce rainfall (Zhang et al., 2009; Fan et al., 2018). MCSs over Southern China typically occur during the East Asia Mei-Yu season, which spans from early June to mid-July (Ding and Chan, 2005; Chen et al., 2018). During this period, the East Asian summer monsoon reached its mature phase, conveying copious amounts of moisture from the South China Sea to Southern China. When moist winds from the South China Sea encounter mountain ranges lying across Southern China, moisture can be lifted, generating dynamic conditions conducive to MCS formation (Ding and Chan, 2005; Wang et al., 2017). Additionally, the subtropical westerly jet at approximately 500mb (mid-tropospheric level) can supply the necessary upper-level divergence and vertical shear, further enhancing MCS development (Houze, 2004; Xu et al., 2015). However, it is important to note that the role of MCSs in the relationship between biomass burning haze and precipitation extremes is an area of ongoing research with alternative perspectives and potential limitations. Some studies have suggested that the effects of biomass burning aerosols on precipitation may be more pronounced at regional or local scales, rather than at larger spatial scales (Gonçalves et al., 2015; Arino et al., 2019).

Furthermore, the long-range transport of biomass burning plumes can complicate the attribution of precipitation patterns to specific biomass burning sources, as aerosols and precursor gases can interact with other atmospheric processes over large distances (Prospero and Lamb, 2003; Prospero et al., 2014). In terms of applications, an improved understanding of the role of MCSs in the link between biomass burning haze and precipitation extremes can inform the development of advanced weather forecasting models and early warning systems for potential flooding events. By integrating data on biomass burning emissions, aerosol concentrations, and their impacts on MCS dynamics and precipitation patterns, these models can potentially enhance the accuracy of precipitation predictions and flood risk assessments (Fan et al., 2015; Rosenfeld et al., 2014).

2.18 Health Effects of Haze Exposure

Haze, characterized by the presence of dust, smoke, and other dry particles that affect air clarity, can have significant impacts on human health. The health effects of haze exposure can be categorized as physical, mental, and global health consequences (Marlier et al., 2016; Xu et al., 2022).

Physical Health Effects: Haze consists of tiny elemental carbon particles generated by the incomplete combustion of fossil fuels, which can penetrate deep into human lungs, posing respiratory hazards (Huang et al., 2018). Other harmful pollutants present in haze, such as nitrates, sulfates, organic chemicals, metals, and soil or dust particles can also contribute to adverse health effects (Lim et al. 2021). Short-term exposure to haze can cause respiratory issues, worsen pre-existing chronic conditions, and irritate eyes (Sapkota et al., 2005; Chuang et al., 2017). Long-term exposure to haze is associated with an increased risk of cardiovascular and respiratory diseases, lung cancer, and premature mortality (Tan et al. 2022; Wong et al. 2022). Furthermore, haze can contribute to the formation of acid rain, which can cause respiratory problems, such as asthma, chronic bronchitis, and emphysema, as well as eye irritation and potential permanent eye damage (Likens et al., 1996; Kłos et al., 2022).

Mental Health Effects: Haze exposure has been linked to mental health issues, particularly through the concept of "solastalgia," as suggested by Albrecht et al. (2007). Solastalgia refers to distress caused by environmental changes, including the loss of natural landscapes and the presence of polluted environments. Recent evidence suggests that the physical condition of blue spaces (e.g., water bodies) in urban areas is negatively associated with the annual prevalence of mental health problems (Nutsford et al., 2016; Gascon et al., 2017). Exposure to haze and the associated reduction in blue space quality can contribute to increased risks of mental health issues such as depression and anxiety (Zhang et al., 2021).

Global Health Effects: Haze can contribute to global health issues such as global warming and ozone layer depletion. The release of greenhouse gases and particulate matter from biomass burning and fossil fuel combustion, which contributes to haze formation, can exacerbate climate change and its associated health risks (Landrigan et al., 2018; Xu et al., 2022). However, it is important to note that the health effects of haze exposure can vary depending on individual susceptibility, exposure levels, and the specific composition of the haze (Huang et al., 2018; Chuang et al., 2017). Additionally, some studies have suggested that the impact of haze on mental health may be influenced by other factors such as socioeconomic status, access to green spaces, and cultural differences (Zhang et al., 2021; Xu et al., 2022). A full understanding of the health effects of haze exposure can inform the development of air quality management strategies, public health interventions, and environmental policies (Landrigan et al., 2018; Lim et al., 2021). For instance, air quality monitoring networks can be established to track haze levels and provide early warnings to vulnerable populations, enabling them to take the necessary precautions (Huang et al., 2018; Chuang et al., 2017). Public health campaigns can raise awareness of the health risks associated with haze exposure and promote preventive measures, such as the use of respiratory protection and indoor air filtration systems (Lim et al., 2021). Furthermore, urban planning and environmental management strategies can prioritize the preservation and creation of blue and green spaces, which can mitigate the mental health impact of haze exposure and promote overall well-being (Nutsford et al., 2016; Gascon et al., 2017). It is important to recognize that addressing the health effects of haze exposure requires a multidisciplinary approach involving environmental, public health, and urban planning experts as well as policymakers and community stakeholders (Landrigan et al., 2018; Xu et al., 2022).

2.19 Toxicity of Key Emission Components

Emissions from biomass burning contain various toxic components that pose significant health risks. These key emission components can be categorized as particulate matter, greenhouse gases, and toxic vapors (Naeher et al., 2007; Jayarathne et al., 2018).

Particulate matter (PM) is a major haze pollutant that can trigger adverse health effects. The inhalation of particles smaller than 10 µm (PM10) is particularly harmful because it can penetrate deep into the respiratory system (Chowdhury et al., 2022). These particles can cause lung tissue irritation, enter the bloodstream, and contribute to various health problems including respiratory and cardiovascular diseases (Kim et al., 2015; Rajagopalan et al., 2018). PM contains a complex mixture of chemicals, including acids (e.g., nitric acid and sulfuric acid), organic compounds, metals, and soil or dust particles (Jayarathne et al., 2018; Verma et al., 2022). Acids can neutralize the body's natural defence mechanisms and promote the generation of free radicals, leading to oxidative stress (Kelly and Fussell, 2015). Heavy metals such as lead and arsenic are highly toxic and can cause cardiovascular diseases at high exposure levels (Huang et al., 2018; Rajagopalan et al., 2018). Additionally, PM from biomass burning can contain carcinogenic polycyclic aromatic hydrocarbons (PAHs), which are associated with an increased risk of lung cancer (Kim et al., 2015; Verma et al., 2022).

Greenhouse Gases: Biomass burning is a significant source of greenhouse gases such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) (Akagi et al., 2011; Urbanski, 2014). Although these gases do not directly contribute to toxicity, their emissions can worsen climate change and its associated health impacts, such as heat-related illnesses, vector-borne diseases, and respiratory problems (Watts et al., 2021; Woodward et al., 2022).

Toxic Vapors: Incomplete combustion of biomass fuels can lead to the formation of various organic compounds and free radicals, which can increase the overall toxicity of the emissions

(Naeher et al., 2007; Jayarathne et al., 2018). These toxic vapors, including volatile organic compounds (VOCs) and carbon monoxide (CO), can contribute to respiratory problems, cardiovascular diseases, and neurological problems (Chowdhury et al., 2022; Rajagopalan et al., 2018). Although the potential toxic cardiovascular effects of haze exposure have been suggested, concrete evidence linking haze exposure to cardiovascular diseases is still limited (Kim et al., 2015; Rajagopalan et al., 2018). Additionally, some studies have proposed that the toxicity of biomass burning emissions may vary depending on fuel type, burning conditions, and emission sources (Naeher et al., 2007; Jayarathne et al., 2018). In terms of application, a full understanding of the toxicity of key emission components is crucial for developing effective air quality management strategies, public health interventions, and environmental policies. Air quality monitoring networks can be established to track toxic pollutant levels, enabling the implementation of early warning systems and mitigation measures (Chowdhury et al., 2022; Verma et al., 2022). Furthermore, toxicological data can inform the development of exposure guidelines, risk assessment models, and health impact assessments, supporting decision-making processes for pollution control and public health protection (Kelly and Fussell, 2015; Rajagopalan et al., 2018).

It is essential to acknowledge the inherent complexities and uncertainties in evaluating the toxicity of biomass burning emissions as well as the potential for synergistic effects and interactions with other environmental factors. Ongoing research efforts incorporating advanced analytical techniques, toxicological studies, and epidemiological investigations are crucial for refining our understanding and developing effective strategies to mitigate the health impacts associated with biomass burning emissions.

2.20 Epidemiological Evidence on Respiratory/Cardiovascular Outcomes

The investigation of epidemiological evidence on respiratory and cardiovascular outcomes associated with exposure to biomass burning haze is a complex and evolving field of study. Several factors contribute to the complexity of these investigations, including the complex connections between environmental changes, human behaviors, and the diverse compositions of communities with varying levels of access to healthcare (Chow et al., 2015; Paganoni, 2018). One of the challenges in epidemiological studies lies in determining whether to examine the disease based on its clinical manifestation (endotype) or etiological cause (phenotype) (Naccarati and Polimanti, 2021). This decision has implications for the selection of appropriate study design and analytical approach. Early epidemiological studies such as those conducted by Judith C. Chow et al. (2015) investigated the links between cardiovascular disease (CVD) and particulate matter (PM) suspended in water and air among communities in northern Thailand. However, these studies have been criticized for their reliance on primary attenuation analyses, which track the health data of the same site population over many years and observe changes within the sample (Paganoni, 2018). While this approach helps negate confounding environmental factors, as both the controls and the unstable observed variable are the same, it can be difficult to distinguish the contributor to the relative risk that is solely due to the length of exposure itself (Paganoni, 2018). Researchers such as Enrico Paganoni have suggested that focusing on the general lifestyle and socio-demographic profiles of an area can be used as a secondary argument in favor of the overruling impact of long-exasperated environmental challenges.

However, these analyses often fail to account for the phenomenon of an induced society through the avenue of access, or lack thereof, to diagnose and suitably manage the development of these illnesses when compared to the ailment itself (Naccarati and Polimanti, 2021). It is crucial to recognize that the epidemiological landscape in this field may be influenced by changes in diagnostic protocols that better account for genomic and/or exposomic interactions. For instance, a study by Naccarati and Polimanti (2021) on genetic interactions with over 3,000 participants found a statistically significant link between the gene p66 and the presence of higher C-reactive protein (CRP) total blood circulation. Given that CRP is utilized as an exacerbation-level beat marker in obstructive coronary sensation and that the p66 protein contributes to the anti-apoptotic factor in vascular endothelial cells, this finding may point towards a viable conduit of empirical evidence, but it is not mentioned in the current scientific literature. Future work in this area is likely to pivot towards precision care, as the increasing complexity of phenotyping or genotyping resultant data and the application of machine learning can potentially reveal intractable disease links (Naccarati and Polimanti, 2021). Mainstream emphasis will be on translating the best computational outputs into better quantitative diagnostic pathways for populations. However, such progress relies on large-scale socio-medical collaboration to share patient history and improve sample data energies into cross-variable covariance.

It is important to acknowledge that alternative perspectives and limitations exist in the epidemiological literature on respiratory and cardiovascular outcomes associated with biomass burning haze exposure. Some studies have suggested that these associations may be influenced by various confounding factors such as socioeconomic status, occupational exposure, and pre-existing health conditions (Rajagopalan et al., 2018; Verma et al., 2022). Additionally, heterogeneity in study designs, exposure assessment methods, and outcome measures can contribute to inconsistencies in reported findings (Chowdhury et al., 2015; Chowdhury et al., 2022). Ongoing research efforts, employing advanced analytical techniques, biomarker assessments, and longitudinal cohort studies are essential to refine our understanding of epidemiological evidence and inform public health interventions and policy decisions.

2.21 Meteorological Influences on Transport & Impacts

Large-scale circulation dynamics play a pivotal role in the transport and distribution of biomass-burning emissions on a global scale. These large-scale atmospheric patterns, driven by factors such as temperature gradients, pressure systems, and Earth's rotation, can greatly influence the trajectories and long-range transport of smoke plumes and associated pollutants.

2.21.1 Large-scale circulation dynamics

The West African Monsoon (WAM) system is a prime example of how large-scale circulation dynamics can significantly affect the transport of biomass burning emissions in the region. The WAM is a seasonal wind pattern that brings moist air from the Atlantic Ocean towards the West African continent during the summer months (Knippertz et al., 2017). This influx of moisture triggers widespread rainfall across the region, but also coincides with the peak of the biomass burning season in West Africa, particularly in countries such as Nigeria. During this period, intense fires from agricultural burning and deforestation released large amounts of smoke and pollutants into the atmosphere (Bauer et al., 2019). The prevailing southwesterly winds associated with the WAM can transport these emissions northeastward across the African continent, leading to the formation of widespread haze and air pollution plumes over the Sahel and Sahara Desert regions

(Deroubaix et al., 2018). Similarly, the Intertropical Convergence Zone (ITCZ), a belt of low pressure near the equator where the northern and southern trade winds converge, plays a crucial role in the long-range transport of biomass burning emissions from Central and Southern Africa (Zuidema et al., 2016). The position and strength of the ITCZ influences the direction and intensity of the prevailing winds, which can carry smoke plumes from intense fires in countries such as the Democratic Republic of Congo and Angola across the Atlantic Ocean, reaching as far as South America and the Caribbean (Bourgeois et al. 2022; Mosquera et al. 2021).

2.21.2 Effects on haze transport pathways

Large-scale circulation patterns significantly influence the transport pathways and dispersion of haze and smoke plumes originating from biomass burning. In West Africa, smoke transport from agricultural burning and wildfires is heavily influenced by the WAM system. During the peak of the monsoon season, the southwesterly winds can carry smoke plumes from Nigeria and other neighboring countries northeastward, leading to the formation of dense haze over the Sahel and Sahara Desert (Deroubaix et al., 2018; Palindat et al., 2020). This long-range transport of biomass burning emissions can have severe impacts on the air quality and visibility across vast regions. For instance, the influx of smoke from fires in Nigeria has been linked to increased levels of particulate matter and ozone in cities such as Niamey, Niger, Bamako, and Mali, posing significant health risks to the local population (Dieme et al., 2022; Savadogo et al., 2022). Furthermore, the transport of smoke plumes can extend beyond the African continent, with the ITCZ playing a crucial role in facilitating long-range transport of biomass burning emissions across the Atlantic Ocean. Smoke from intense fires in Central and Southern Africa has been observed to reach the Caribbean and parts of South America, contributing to air pollution and haze events in these regions (Bourgeois et al., 2022; Mosquera et al., 2021).

2.21.3 Interactions with regional weather patterns

Interactions between biomass burning emissions and regional weather patterns can lead to complex atmospheric processes and feedback mechanisms. In West Africa, the influx of smoke and aerosols from fires can interact with the WAM system, potentially altering cloud formation, precipitation patterns, and radiative forcing (Huang et al., 2020). For example, studies have shown that the presence of smoke and aerosols from biomass burning can lead to a reduction in precipitation over certain regions of West Africa during the monsoon season (Maharaj et al., 2021). This is because of the absorbing and scattering properties of aerosols, which can affect cloud microphysics and atmospheric stability and suppress precipitation formation (Solmon et al., 2008). Conversely, in some cases, increased atmospheric heating caused by the absorption of solar radiation by smoke and aerosols can enhance convection and lead to an increase in precipitation over other areas (Korras-Carraca et al., 2022). This complex relationship between biomass burning emissions and regional weather patterns can create localized feedback mechanisms, potentially worsening drought conditions in some regions and enhancing rainfall in others.

Additionally, the interactions between biomass burning emissions and regional weather patterns can influence air quality and visibility. In Nigeria, the combination of smoke from agricultural burning and humid and stagnant conditions during the rainy season can lead to persistent haze and poor air quality in urban areas (Nwokolo & Ogbomo, 2021). This shows the importance of considering not only the large-scale transport of emissions, but also their interactions with local meteorological conditions to assess their impacts. While scientific consensus acknowledges the significant role of meteorological factors in shaping the transport and impacts of biomass burning emissions, some researchers argue that the extent of these influences may be overestimated or oversimplified in certain contexts. For instance, Kharol et al. (2022) suggested that the contribution of long-range transport to air pollution levels in downwind regions may be overstated, emphasizing the need for region-specific assessments that consider local emission sources and meteorological conditions. Huang et al. (2020) showed the importance of considering the complex interactions between biomass burning emissions, urban pollution sources, and meteorological factors in urban environments, as these interactions can significantly alter the composition and impacts of the resulting air pollution mixtures. Despite these dissenting views, scientific consensus acknowledges the critical role of meteorological factors in shaping the transport and impacts of biomass burning emissions. Accurate forecasting and modeling of these meteorological influences are essential for developing effective air quality management strategies, mitigating transboundary pollution, and enhancing our understanding of the broader environmental and climatic implications of biomass burning (Wang et al., 2018; Aouizerats et al., 2015). As research in this area continues to evolve, integrating advanced atmospheric modeling techniques, remote sensing data, and ground-based observations will be crucial for capturing the complex interactions between biomass burning emissions, meteorology, and their far-reaching impacts. The vertical transport characteristics differ significantly between Harmattan and non-Harmattan conditions, as illustrated by the contrasting plume transport mechanisms (Figure 2.8). During the peak period of biomass burning, the particulate matter is seen to be within the temperature inversion layer and above the boundary layer.

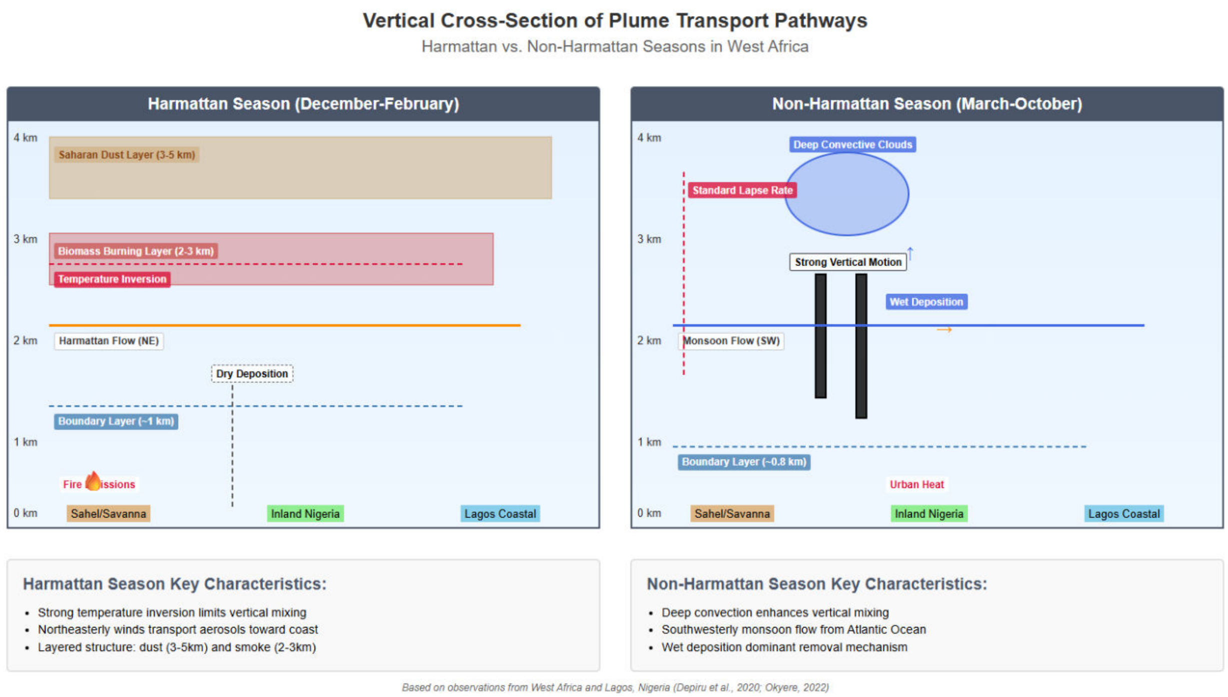


Figure 2.8: Vertical Cross-Section Diagram: Harmattan vs. Non-Harmattan Plume Transport

2.22 Geographic Case Studies of Haze-Flooding Connections

2.22.1 Backgrounds on fire activity and flooding

The connection between biomass burning emissions, haze formation, and flooding events has gained significant attention, particularly in regions with high levels of fire activity and vulnerable populations. In West Africa, the interplay between these phenomena is a pressing concern given the region's susceptibility to both wildfires and flooding. Nigeria, a country with a diverse range of ecosystems including savannas, forests, and agricultural lands, experiences significant biomass burning during the dry season (Akinro et al., 2022). Agricultural burning practices, such as the clearing of crop residues and bush burning, are widespread and contribute to the release of smoke and particulate matter into the atmosphere (Akachukwu et al., 2019). Additionally, wildfires in the northern savannas and forests further exacerbate the problem, often driven by anthropogenic activities and climate change (Kumssa & Jones, 2015). Concurrently, Nigeria is prone to flooding, particularly during the rainy season, which typically spans April to October (Nkwunonwo et al., 2020). Intense rainfall coupled with poor drainage systems and urbanization can lead to severe flooding events, causing widespread damage to infrastructure, displacement of communities, and loss of life (Olokude & Owolana, 2022). In neighboring countries within the West African region, similar patterns of biomass burning and flooding have been observed. For instance, in Ghana, slash-and-burn agriculture and deforestation contribute to significant biomass burning emissions (Adinku et al., 2022), and the country also experiences recurrent flooding due to heavy rainfall and inadequate urban planning (Kwakye & Tuffour-Kwarteng, 2021).

2.22.2 Analysis of mechanistic linkages in observed flood events

The potential mechanistic relationship between biomass burning emissions, haze formation, and flooding events has been the subject of extensive research in various regions including West Africa. Several studies have explored the role of smoke and aerosols in altering atmospheric dynamics and precipitation patterns, which can subsequently influence the flood risk. Researchers have investigated the impact of biomass burning emissions on precipitation patterns during the rainy season in Nigeria. Akinro et al. (2022) found that the presence of smoke and aerosols from agricultural burning and wildfires could lead to a reduction in precipitation over certain areas, potentially mitigating flood risk. However, they also noted that in other instances, atmospheric heating caused by the absorption of solar radiation by smoke and aerosols can enhance convection and lead to an increase in precipitation, intensifying flood risk in those regions. Similar observations have been made in other parts of West Africa. In Ghana, Asante et al. (2020) reported that the influx of smoke and aerosols from biomass burning during the dry season can modify cloud microphysics and atmospheric stability, leading to changes in precipitation patterns and potentially influencing the flood risk during the subsequent rainy season. While these studies show the potential connections between biomass burning emissions, haze formation, and flooding, the underlying mechanisms are complex and can vary depending on the local meteorological conditions, terrain, and other factors. Some researchers have also emphasized the need for more analyses that consider the combined effects of biomass burning emissions, urban pollution, and other anthropogenic factors on precipitation patterns and flood risk (Oku et al., 2022; Ogunjobi et al., 2021).

2.22.3 Syntheses of evidence and uncertainties

Evidence gathered from various studies in West Africa and other regions suggests that biomass burning emissions and the associated formation of haze can influence precipitation patterns and, consequently, flood risk through complex atmospheric processes. However, the specific impacts and underlying mechanisms can vary depending on the local conditions and interplay of various factors. In Nigeria and other parts of West Africa, several studies have reported a potential link between biomass burning emissions, haze formation, and altered precipitation patterns (Akinro et al., 2022; Asante et al., 2020; Oku et al., 2022). These alterations in precipitation can either mitigate or intensify flood risk depending on the specific atmospheric conditions and the intensity and spatial distribution of rainfall. Furthermore, some researchers have showed the importance of considering the combined effects of biomass burning emissions, urban pollution, and other anthropogenic factors on the atmospheric dynamics and precipitation patterns (Ogunjobi et al., 2021; Oku et al., 2022). The complex interactions between these emissions and regional weather patterns can create localized feedback mechanisms, potentially worsening drought conditions in some areas and enhancing rainfall and flood risk in others.

While evidence suggests a potential connection between biomass burning emissions, haze formation, and flooding, there are still uncertainties and knowledge gaps that need to be addressed. One of the key challenges is the difficulty in isolating the specific contribution of biomass burning emissions from other factors that influence precipitation patterns, such as large-scale atmospheric circulation patterns, topography, and land use changes (Abiodun et al., 2017; Panitz et al., 2018). Additionally, quantification of the impacts of biomass burning emissions on precipitation and flood risk is often complex, as it involves the integration of various atmospheric models, remote sensing data, and ground-based observations (Mahmood et al., 2021; Tosca et al., 2015). Uncertainties in these models and data sources can propagate through analyses, leading to potential discrepancies in the predicted impacts. Furthermore, the spatial and temporal variability of biomass burning emissions, as well as the dynamic nature of regional weather patterns, can introduce additional complexities in assessing haze–flooding connections. Localized meteorological phenomena, such as thunderstorms or convective events, can further complicate analysis by introducing short-term variations in precipitation patterns (Ogunjobi et al., 2021). Despite these uncertainties, the scientific community recognizes the importance of investigating and understanding the connections between biomass burning emissions, haze formation, and flooding events. Ongoing research efforts involving interdisciplinary collaborations and the integration of advanced modeling techniques, remote sensing data, and ground-based observations are crucial for enhancing our understanding of these complex processes and their impacts on vulnerable communities.

2.23 Critique of Knowledge Gaps

While the scientific understanding of biomass burning emissions has advanced significantly, several critical knowledge gaps remain that hinder our ability to fully understand and mitigate the associated impacts. These knowledge gaps span various aspects, including the accuracy of emissions inventories, quantification of health implications, integration of climate modeling linkages, and identification of key research questions that require further investigation.

2.23.1 Limitations in emissions inventories

Accurate and detailed emission inventories are crucial for effectively assessing the impact of biomass burning and informing mitigation strategies. However, existing inventories often suffer from limitations owing to the inherent complexities involved in quantifying emissions from diverse sources and regions. In West Africa, including Nigeria, the reliability of biomass-burning emission inventories is challenged by several factors. First, the widespread prevalence of small-scale agricultural burning practices, such as crop residue burning and slash-and-burn cultivation, makes it difficult to accurately estimate emissions from dispersed and often unmonitored sources (Akagi et al., 2011; Mavita et al., 2022). Additionally, the lack of consistent and long-term ground-based monitoring networks in many regions further worsens the uncertainties in the emission data (Sinha et al., 2015; Sommers et al., 2021). Furthermore, the heterogeneity of fuel types, burning conditions, and environmental factors across ecosystems and regions can significantly influence the composition and quantity of emissions (Andreae, 2019). Existing inventories may not adequately capture these variations, leading to potential inaccuracies in emission estimates (Bowman et al., 2017; Bowman et al., 2020). Although satellite-based remote sensing techniques have improved our ability to detect and monitor biomass burning events, challenges persist in accurately quantifying emissions from these observations (Kaiser et al., 2012; Zheng et al., 2018). Factors such as cloud cover, smoke plume characteristics, and land surface properties can introduce uncertainties into the retrieval of key parameters used for emission estimates (Pouliot et al., 2018; Urbanski et al., 2021).

2.23.2 Gaps in understanding health implications

The health impacts of biomass burning emissions, particularly in urban areas, are a significant concern; however, our understanding of these implications remains incomplete. While numerous studies have established links between exposure to particulate matter and other pollutants from biomass burning and adverse health outcomes, such as respiratory and cardiovascular diseases (Bauer et al., 2019; Naghavi et al., 2015; Sanbata et al., 2022), there are still gaps in our knowledge regarding the specific mechanisms and relative contributions of different emission sources. In cities such as Lagos, Nigeria, where emissions from biomass burning often interact with other urban pollution sources, separating the health impacts of these complex mixtures remains a challenge (Ogunjo et al., 2023; Oku et al., 2022). Additionally, the potential long-term health implications of exposure to biomass burning emissions, particularly for vulnerable populations, such as children and the elderly, are not fully understood (Maji et al., 2019; Sanbata et al., 2022). Furthermore, the health impacts of the specific chemical species and particulate matter components present in biomass burning emissions require further investigation. For instance, the role of polycyclic aromatic hydrocarbons (PAHs), which are known carcinogens, and their potential health effects in exposed populations remain uncertain (Kim et al., 2018; Hays et al., 2021).

2.23.3 Uncertainties in climate modeling linkages

Although the scientific community recognizes the potential impacts of biomass burning emissions on climate processes, the integration of these linkages into climate models remains a significant challenge. The complex interactions between biomass burning emissions, atmospheric chemistry, radiative forcing, cloud formation, and precipitation patterns are not yet fully understood or represented in climate models (Reddington et al., 2020; Tosca et al., 2015; Wang et al., 2022). For example, the role of black carbon aerosols from biomass burning in altering radiative forcing and atmospheric heating rates is an area of ongoing research with uncertainties in the accurate quantification of these effects (Bond et al., 2013; Samset et al., 2018). Additionally, the potential feedback between biomass burning emissions, cloud microphysics, and precipitation patterns is complex and can vary depending on the regional meteorological conditions and emission characteristics (Deng et al., 2022; Dong et al., 2021). Furthermore, the representation of land-atmosphere interactions in climate models, including the impacts of biomass burning emissions on vegetation dynamics, soil properties, and surface energy budgets, remains a challenge (Veraverbeke et al., 2021; Ward et al., 2022). These interactions have significant implications for regional climate patterns and the potential for feedback loops that influence future biomass burning activities.

2.23.4 Thus, the key research questions need to be addressed.

To address the knowledge gaps and uncertainties surrounding biomass burning emissions, several key research questions must be addressed through collaborative and interdisciplinary efforts.

1. How can we improve the accuracy and spatial resolution of biomass burning emission inventories, particularly for small-scale and dispersed sources, and account for variability in fuel types, burning conditions, and environmental factors?

2. What are the specific mechanisms and relative contributions of different emission sources, including biomass burning and urban pollution, to adverse health outcomes in urban and rural populations both in the short and long term?

3. How can we better integrate the complex interactions between biomass burning emissions, atmospheric chemistry, radiative forcing, cloud formation, and precipitation patterns into climate models that account for regional variations and feedback mechanisms?

4. What are the potential synergistic or cumulative impacts of biomass burning emissions on ecosystems, biodiversity, and ecosystem services, and how can integrated approaches be developed to mitigate these impacts?

5. How can we effectively engage with local communities, policymakers, and stakeholders to develop and implement sustainable land management practices, fire prevention strategies, and emission reduction measures that consider socioeconomic, cultural, and environmental factors?

Addressing these research questions requires collaborative efforts involving atmospheric scientists, health researchers, climate modelers, ecologists, social scientists, and policymakers. Interdisciplinary approaches that integrate field observations, remote sensing data, modeling techniques, and community engagement are crucial for advancing our understanding and developing effective strategies to mitigate the impact of biomass burning emissions.

2.24 Conclusions & Outlook

2.24.1 Current state of science.

Biomass burning emissions have evolved into a multidisciplinary field covering atmospheric chemistry, air quality, climate science, and public health. The current state of science reflects a growing understanding of the complex interactions among biomass burning emissions, meteorological processes, and their far-reaching impacts on the environment and human well-being. Significant advancements have been made in quantifying emissions from various biomass burning sources, including wildfires, agricultural burning, and land clearing activities. The use of satellite remote sensing, ground-based monitoring networks, and advanced modeling techniques has improved our ability to track and characterize these emissions at regional and global scales (van der Werf et al., 2017; Urbanski et al., 2021). Furthermore, the scientific community has developed a deeper understanding of the atmospheric transport and transformation of biomass burning emissions as well as their interactions with meteorological patterns and regional weather systems. The role of large-scale circulation dynamics, such as the West African Monsoon and the Intertropical Convergence Zone, in influencing the transport and distribution of smoke plumes and associated pollutants has been well documented (Knippertz et al., 2017; Zuidema et al., 2016; Deroubaix et al., 2018).

Researchers have also made progress in explaining the complex links among biomass burning emissions, haze formation, and precipitation patterns. Studies have shown that the presence of smoke and aerosols can alter cloud microphysics, atmospheric stability, and radiative forcing, potentially influencing precipitation patterns and flood risk in certain regions (Dong et al., 2021; Maharaj et al., 2021; Korras-Carraca et al., 2022). However, the specific impacts and underlying mechanisms can vary depending on the local meteorological conditions and the interplay of various factors (Akinro et al., 2022; Asante et al., 2020). The adverse health impacts of biomass burning emissions, particularly in urban areas, have been well-documented, with exposure to particulate matter and other pollutants linked to respiratory issues, cardiovascular diseases, and other health concerns (Bauer et al., 2019; Naghavi et al., 2015; Sanbata et al., 2022). However, gaps remain in the understanding of the specific mechanisms and relative contributions of different emission sources, as well as the potential long-term health implications. Although significant progress has been made, the scientific community acknowledges the existence of critical knowledge gaps and uncertainties that hinder our ability to fully comprehend and mitigate the impacts of biomass burning emissions. These knowledge gaps span various aspects, including the accuracy of emissions inventories, quantification of health implications, integration of climate modeling linkages, and identification of key research questions that require further investigation (Andreae, 2019; Pouliot et al., 2018; Reddington et al., 2020; Kim et al., 2018).

2.24.2 Impact and Significance on a regional scale.

The significance of biomass burning emissions and their impacts are particularly pronounced in regions such as West Africa, including Nigeria. The prevalence of agricultural burning practices, deforestation, and wildfires in these areas significantly contributes to the release of smoke, particulate matter, and other pollutants into the atmosphere (Akachukwu et al., 2019; Kumssa & Jones, 2015; Adinku et al., 2022). In urban centers, such as Lagos, Nigeria, the combination of biomass burning emissions and other urban pollution sources can lead to severe air quality degradation, posing significant health risks to the local population (Ogunjo et al., 2023; Oku et al., 2022). The potential long-term health implications of exposure to these complex mixtures, particularly for vulnerable groups such as children and the elderly, are areas of concern that require further investigation (Maji et al., 2019; Sanbata et al., 2022). Moreover, the transport of smoke plumes and associated pollutants across West Africa has been linked to the formation of widespread haze and air pollution events in downwind regions, affecting visibility and air quality in cities such as Niamey, Niger, Bamako, and Mali (Deroubaix et al., 2018; Dieme et al., 2022; Savadogo et al., 2022).

The potential connections between biomass burning emissions, haze formation, and flooding events are also relevant in West Africa given the region's susceptibility to both wildfires and flooding. Studies have explored the role of smoke and aerosols in altering atmospheric dynamics and precipitation patterns, which can subsequently influence flood risks (Akinro et al., 2022; Asante et al., 2020; Oku et al., 2022). However, the specific impacts and underlying mechanisms can vary depending on the local conditions and the interplay of various factors, showing the need for full analyses that consider the combined effects of biomass burning emissions, urban pollution, and other anthropogenic factors. Furthermore, the potential impacts of biomass burning emissions on the ecosystems, biodiversity, and ecosystem services in West Africa require further investigation. The region is home to diverse ecosystems, including savannas, forests, and agricultural lands, which may be vulnerable to the effects of air pollution, particulate matter deposition, and changes in precipitation patterns (Bowman et al., 2020; Ward et al., 2022).

2.24.3 Future projections for issue under climate change

Climate change is expected to intensify the challenges posed by biomass burning in West Africa and other regions. Rising temperatures, changing precipitation patterns, and more frequent and severe drought conditions are likely to increase the risk and intensity of wildfires, potentially leading to higher emission levels (Andela et al., 2017; Bowman et al., 2020; Veraverbeke et al., 2021). Additionally, climate change may alter regional weather patterns and large-scale circulation dynamics, potentially affecting the transport and distribution of biomass-burning emissions (Dunstone et al. 2018; Pausata et al. 2020). These changes could lead to shifts in the spatial patterns of haze and air pollution events as well as their impacts on downwind regions. Furthermore, the potential interactions among biomass burning emissions, atmospheric chemistry, and climate processes are areas of ongoing research. The role of black carbon aerosols and other components of biomass burning emissions in altering radiative forcing, atmospheric heating rates, and cloud microphysics is not yet fully understood or represented in climate models (Bond et al., 2013; Deng et al., 2022; Samset et al., 2018). Improving the integration of these complex interactions into climate models is crucial for a better understanding and projection of the future impacts of biomass burning emissions on regional and global climate patterns.

In West Africa, the combined effects of climate change, population growth, urbanization, and land use changes may affect the challenges posed by biomass burning emissions. The increasing demand for agricultural land and resources, coupled with the potential for more frequent and severe drought conditions, could lead to an increase in agricultural burning practices and deforestation (Acheampong et al., 2021; Bowman et al., 2020). This, in turn, could further degrade air quality, contribute to regional haze events, and potentially impact precipitation patterns and flood risks in the region. Addressing these challenges will require a multifaceted approach that involves policy interventions, sustainable land management practices, emission reduction strategies, and community engagement efforts. Collaboration between researchers, policymakers, and local communities will be essential in developing and implementing effective solutions that consider socioeconomic, cultural, and environmental factors. Moreover, continuous research efforts involving interdisciplinary collaborations and the integration of advanced modeling techniques, remote sensing data, and ground-based observations will be crucial for enhancing our understanding of the complex interactions between biomass burning emissions, meteorology, climate, and their far-reaching impacts. Addressing the knowledge gaps and uncertainties surrounding these issues will be vital in developing effective mitigation strategies and adapting to the future challenges posed by climate change.

3 Chapter - Methodology

3.1 Introduction

This chapter outlines the detailed methodology employed in this research to study the intercorrelation between biomass burning haze and regional climate, with a specific focus on the influence of the Harmattan haze layer on extreme rainfall events and flooding in coastal cities, such as Lagos, Nigeria. This study combines observational data analysis, satellite remote sensing, and advanced numerical modeling techniques to achieve its research objectives. Observational data from ground-based monitoring stations, including air quality networks and meteorological observations, provide important information on the spatiotemporal distribution of aerosols, trace gases, and meteorological variables in the study area. Satellite remote sensing data, such as aerosol optical depth (AOD) and fire radiative power (FRP) measurements, were used to identify and characterize biomass burning events, track the transport of smoke plumes, and estimate the vertical structure and optical properties of the Harmattan haze layer. To investigate the meteorological impacts of biomass burning on regional climate dynamics, this study utilized the Weather Research and Forecasting (WRF) model. By focusing on atmospheric and weather-related processes, the WRF model enables a detailed analysis of how biomass burning events influence regional meteorology, including aspects like temperature, wind patterns, and precipitation responses. This study employed the advanced Weather Research and Forecasting (WRF) model to simulate the impact of biomass burning on regional meteorological processes, including interactions with atmospheric circulation and cloud microphysics. Configured with high-resolution domains focused on West Africa, the WRF model allowed for detailed examination of weather-related processes, including temperature, wind dynamics, and cloud development. The model was initialized and constrained using reanalysis data from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), to ensure an accurate representation of large-scale atmospheric circulation patterns and synoptic conditions.

Extensive model evaluation and optimization procedures were conducted to ensure an accurate simulation of the observed meteorological conditions and aerosol loadings during the study period. This includes comparing model outputs with satellite observations, ground-based measurements, and reanalysis data as well as performing sensitivity tests to correct the model configuration and parameterizations. A series of simulation experiments was designed to isolate the effects of biomass burning emissions on regional climate and precipitation patterns. Control simulations were performed to establish boundary conditions, whereas sensitivity simulations were conducted by varying the biomass burning emission inputs, modifying the aerosol properties (optical and microphysical), and developing the initial atmospheric conditions. This study used a detailed data analysis approach that combines climate data analysis techniques, statistical methods, and process-level research. Trend, spatial, and climatological pattern analyses were performed to identify deviations from the typical conditions during the study period. Correlation and regression analyses were used to quantify the relationships between biomass burning haze characteristics and meteorological variables, including precipitation patterns.

Furthermore, an in-depth process analysis was conducted to understand the mechanisms by which biomass burning aerosols influence regional climate dynamics. This includes examining aerosol-cloud-precipitation interactions, boundary layer dynamics, and mesoscale convective system development influenced by the Harmattan haze layer. Uncertainty sources, error propagation, and sensitivity analyses were conducted to quantify and mitigate the potential impacts of uncertainties on the conclusions of this study. This extensive methodological approach, combining observational data analysis, satellite remote sensing, and advanced numerical modeling techniques, provides a detailed framework for investigating the intercorrelation between biomass burning haze and regional climate dynamics, with a focus on understanding the potential influences of extreme rainfall events and flooding in coastal cities, such as Lagos, Nigeria.

3.2 Model Selection

The Weather Research and Forecasting (WRF) model was selected for this study after careful evaluation against alternative regional climate and chemical transport models including RegCM, COSMO-CLM, and GEOS-Chem. This selection was driven by WRF's specific advantages for simulating the complex atmospheric dynamics of tropical coastal environments, particularly its ability to capture the unique challenges of studying biomass burning haze interactions with regional climate in an urban coastal setting.

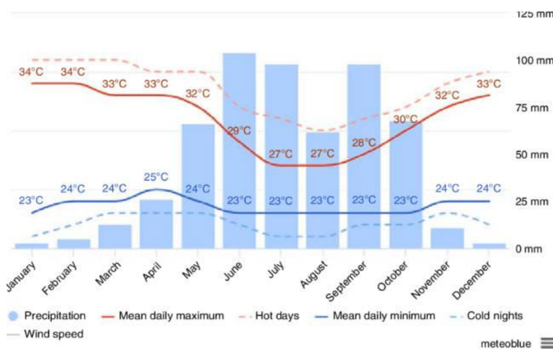
WRF provides superior technical capabilities across several critical areas for this research. Its comprehensive physics parameterizations include advanced microphysics schemes (Thompson and WSM6) that better represent tropical convection, flexible cumulus parameterization options, and specialized boundary layer physics validated for coastal environments with sea breeze circulations. Also, WRF offers full two-way coupling between meteorology and chemistry through WRF-Chem, enabling simulation of both direct and indirect aerosol effects on radiation, clouds, and precipitation—essential for studying biomass burning impacts on local climate. The model's dynamic downscaling capabilities support convection-permitting resolutions (≤3 km) necessary to resolve coastal convective processes, with complex nesting that integrates synoptic to local scales.

WRF's extensive validation for West African applications, particularly in coastal regions, and strong community support for regional adaptations provide additional confidence in its reliability for this study. While GEOS-Chem can be used in detailed atmospheric chemistry at continental scales, WRF's superior meteorological physics, higher resolution capabilities, and integrated aerosol-radiation-cloud coupling make it optimal for studying biomass burning effects on regional precipitation patterns and flood events in complex coastal urban environments like Lagos.

3.3 Study Area

The primary study area for this research covers West Africa, with a focus on southern Nigeria and the densely populated coastal city of Lagos (Figure 3.2). This region is characterized by distinct climatological patterns influenced by the West African Monsoon (WAM) system and seasonal intrusion of the Harmattan haze layer (Osei et al., 2023). Geographically, the study area spans the Guinea Coast countries, extending from Senegal in the west to Cameroon in the east, with a focus on the coastal regions of Nigeria and the Lagos metropolitan area in Figure 3.2. Lagos, situated on the Bight of Benin along the Gulf of Guinea, is a rapidly growing megacity with a population exceeding 18.9 million, making it one of the largest urban agglomerations in Africa

(Choplin and Hertzog, 2020). The climate of West Africa is governed by the oscillation between the dry Harmattan winds originating from the Sahara Desert and the moisture-laden southwesterly monsoon winds from the tropical Atlantic Ocean (Raj, Bangalath, and Stenchikov, 2019). This region experiences a distinct seasonal cycle, with a dry season from November to April and a wet season from May to October, driven by latitudinal migration of the Intertropical Convergence Zone (ITCZ) (Samuel, Mathew, and Sathiyamoorthy, 2022). Lagos experiences distinct seasonal variations in temperature and precipitation patterns that are characteristic of the West African coastal climate (Figure 3.1). The climate of West Africa is governed by the oscillation between harmattan winds that transport large quantities of mineral dust and biomass-burning aerosols from the Sahel and Savanna regions, forming a dense haze layer that can extend as far south as the northern equatorial forests (Li et al., 2020) and the rainy reason during April to October.



Months	Average Temperature (°C) Minimum	Average Temperature (°C) Maximum	Average Rainfall (mm)
January	22.3	32.2	14.3
February	23.5	33.1	42
March	23.8	32.7	77.1
April	23.6	32.1	142.4
May	23.1	30.9	204.8
June	22.6	29.2	312.2
July	22.1	28.1	256.9
August	21.7	28.1	112.4
September	21.9	28.9	167.1
October	22.3	30.4	135.8
November	22.6	31.0	54.0
December	22.4	31.9	19.0

Source: Climate data (2019)

Figure 3.1: Average temperature and precipitation for Lagos state (source: Ekele Ochedi, 2018, Climate Data, 2019)

The Harmattan haze layer, which comprises a complex mixture of dust and smoke particles, can significantly impact visibility, air quality, and regional climate dynamics (Chanchangi et al., 2020). The wet season is dominated by the West African Monsoon system, which brings heavy rainfall to the region (Akinsanola and Zhou, 2020). The progression of the monsoon is characterized by the northward advancement of moist maritime air from the Gulf of Guinea, displacing dry Harmattan winds (Djakouré et al., 2024). This seasonal transition is often accompanied by intense convective activity, including the formation of mesoscale convective systems and propagating squall lines, which can lead to extreme rainfall events and flooding in coastal urban areas such as

Lagos. The spatial distribution of flood-prone areas across Lagos reveals the complexity of urban vulnerability patterns (Figure 3.2). Lagos, situated on the Bight of Benin along the Gulf of Guinea.

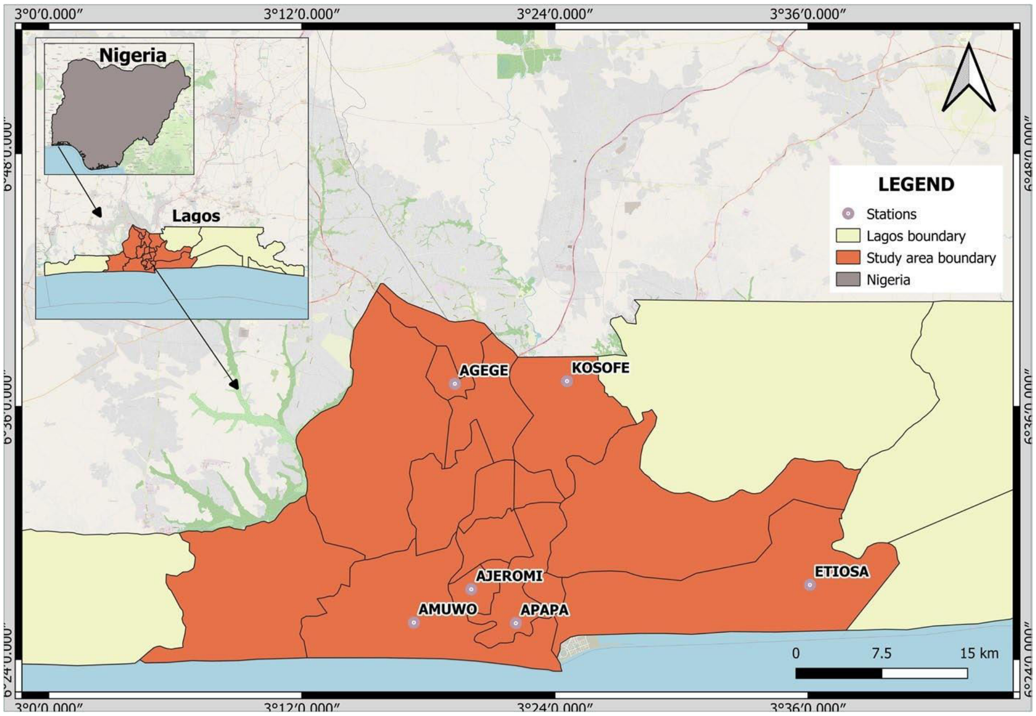


Figure 3.2: Map of Lagos showing key areas prone to Flooding.

The relevance of the study area to biomass burning and haze events is two-fold. The Sahel and Savanna regions of West Africa are known for their widespread biomass burning activities, including agricultural burning, deforestation fires, and natural wildfires, particularly during the dry season (Wu et al. 2021). These fires have contributed significant quantities of smoke aerosols and trace gases to the Harmattan haze layer (Wu et al., 2021). Second, the coastal regions of Nigeria, including Lagos, are susceptible to the impacts of the Harmattan haze layer, as the prevailing northeasterly winds transport smoke-filled air masses from inland areas towards the Gulf of Guinea (Odu-Onikosi et al., 2022). The intrusion of this haze layer can potentially influence regional climate dynamics, cloud microphysics, and precipitation patterns, leading to potential impacts on extreme rainfall events and flooding in densely populated urban centers such as Lagos (Schmale et al., 2021). By focusing on the West African region, particularly southern Nigeria and the Lagos metropolitan area, this study aimed to investigate the complex intercorrelation between biomass burning emissions, the Harmattan haze layer, and regional climate dynamics, with a specific emphasis on understanding the potential influence of extreme rainfall events and flooding in this highly vulnerable coastal urban environment.

3.4 Data Collection

This study examines the relationship between biomass burning haze and regional climate dynamics. To accomplish this, the study employed a detailed data collection approach that incorporates satellite remote sensing, ground-based measurements, and reanalysis data. This extensive data acquisition method guarantees the availability of precise observational data for model initialization, evaluation, and analysis, thereby ensuring the accuracy of the results.

3.4.1 Data Resolution and Duration

The data utilized in this study spans multiple temporal and spatial scales to ensure comprehensive coverage of the meteorological conditions and biomass burning events that influenced the flooding episodes in Lagos during July 2011 and July 2021.

Satellite Data:

MODIS Aerosol Optical Depth (AOD) data: Daily retrievals at 1km and 10km resolution, covering the periods June-August 2011 and June-August 2021.

MODIS/VIIRS Fire Radiative Power (FRP): Daily observations at 375m (VIIRS) and 1km (MODIS) resolution during the study periods.

CALIPSO vertical profiles: Available at approximately 5km horizontal resolution along orbital tracks, with data collected during key pre-flood and flooding periods.

Cloud property retrievals: Daily observations at 1km resolution throughout the study periods

Ground-based Measurements:

Meteorological station data: Hourly observations of temperature, precipitation, humidity, and wind from six stations across Lagos (Agege, Ajeromi, Amuwo Odofin, Apapa, Eti-Osa, Kosofe), covering the entire months of June and July for both 2011 and 2021.

AERONET sun photometer data: 15-minute resolution AOD measurements available during daylight hours for the study periods.

Reanalysis Data:

MERRA-2 reanalysis: 3-hourly data at 0.5° × 0.625° resolution, used for the period May-August for both 2011 and 2021 to capture pre-conditioning factors.

ERA5 data: Hourly data at 0.25° × 0.25° resolution for model validation and boundary condition sensitivity testing

For the WRF model simulations, focus was specifically on two high-impact flooding events:

July 10, 2011 event: Model simulations covered the period July 1-15, 2011, with special emphasis on the pre-flood (July 1-5) and flood (July 10-14) periods.

July 16, 2021 event: Model simulations covered the period July 1-20, 2021, focusing on the pre-flood (July 2-3) and flood (July 15-16) periods.

The WRF model was configured with nested domains at 27km, 9km, and 3km resolution, with the highest resolution domain centered over Lagos to resolve local-scale meteorological processes critical for flood development. A comprehensive data collection strategy was employed, utilizing multiple sources across different temporal and spatial scales to ensure adequate coverage of the study periods (Table 3.1).

Table 3.1- Summary of Data Sources and Applications used for the two study periods (July 2011 and July 2021) Sources: NASA (FIRMS, GPM, NCAR), NiMet, etc

S/N	Data Type	Source	Temporal Resolution	Spatial Resolution	Application in Study
Satellite Data					
1	Aerosol Optical Depth (AOD)	MODIS (Terra & Aqua) Source: NASA - FIRMS	Daily	10 km	Identification of biomass burning haze extent Validation of WRF-simulated aerosol fields Spatiotemporal characterization of Harmattan layer
2	Aerosol Optical Depth (AOD)	MISR	Daily	4.4 km	Verification of MODIS AOD retrievals Enhanced accuracy over bright surfaces Validation of model performance

3	Fire Radiative Power (FRP)	MODIS Fire Product Source: NASA - FIRMS	Daily	1 km	Detection of active fire locations Estimation of biomass burning emission rates Source region characterization
4	Active Fire Detections	VIIRS Source: NASA - FIRMS	Daily	375 m	High-resolution fire detection Identification of small/low-intensity fires Refinement of emission source locations
5	Cloud Properties	MODIS	Daily	1 km	Evaluation of cloud microphysical changes Assessment of aerosol-cloud interactions Validation of simulated cloud fields
6	Precipitation	TRMM/GPM	3-hourly	0.25° (~25 km)	Validation of model precipitation output Regional rainfall pattern analysis Identification of extreme precipitation events
7	Aerosol Vertical Profiles	CALIPSO	16-day repeat cycle	5 km horizontal, 30-60 m vertical	Characterization of aerosol layer height Validation of model vertical structure Identification of dust vs. smoke layers
8	Land Use/Land Cover	MODIS MCD12Q1	Annual	500 m	WRF model surface parameter initialization Urban extent characterization Land use change assessment (2011 vs. 2021)
Ground-Based Measurements					
1	Meteorological Variables	Nigerian Meteorological Agency (NiMet) Stations	Hourly	6 stations across Lagos	Model validation (temperature, humidity, wind) Analysis of local meteorological conditions Characterization of urban heat island effects

2	Precipitation	Rain Gauge Network Source: NASA – Satellite data	Daily	8 stations across Lagos	Validation of simulated precipitation Ground truth for satellite precipitation estimates Flood event characterization
3	Aerosol Properties	Lagos AERONET Site	Hourly (daytime only)	Point measurement	Validation of simulated and satellite AOD Aerosol optical property characterization Assessment of aerosol size distribution
4	Air Quality Parameters	Lagos State Environmental Protection Agency (LASEPA)	Daily	4 stations in Lagos	Validation of particulate matter concentrations Assessment of air quality during biomass burning events Correlation with meteorological variables
Reanalysis Data					
1	MERRA-2	NASA GMAO	Hourly	0.5° × 0.625° (~50 km)	WRF model initialization Boundary conditions for model simulations Large-scale meteorological context Aerosol data assimilation
2	ERA5	ECMWF	Hourly	0.25° (~25 km)	Verification of MERRA-2 fields Additional validation dataset Alternative boundary conditions for sensitivity tests
Emission Inventories					
1	Biomass Burning Emissions	GFED4s	Daily	0.25° (~25 km)	Input for anthropogenic and natural emission sources Historical fire emission trends Source attribution for biomass burning aerosols
2	Fire Inventory	FINN v1.5	Daily	1 km	High-resolution fire emission inputs Daily variability in biomass burning emissions Source region identification
3	Anthropogenic Emissions	EDGAR v5.0	Annual	0.1° (~10 km)	Urban and industrial emission sources Background pollution levels

					Context for biomass burning contribution
Hydrological Data					
1	Flood Records	Lagos State Emergency Management Agency	Event-based	Municipal divisions	Validation of extreme precipitation impacts Identification of flood-prone areas Assessment of model prediction skill
2	Drainage Network	Lagos State Ministry of Environment	Static	1:50,000 scale	Contextual information for flood risk assessment Identification of key drainage infrastructure Integration with precipitation analysis

3.4.2 Satellite Data

a) Aerosol Optical Depth (AOD): Satellite-based AOD measurements from sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Wang et al., 2020a) and the Multi-angle Imaging SpectroRadiometer (MISR) (Garay et al., 2020), were used to assess the spatial and temporal distribution of atmospheric aerosols, including biomass burning smoke and mineral dust. AOD provides valuable information on the horizontal extent and intensity of the Harmattan haze layer (Garay et al., 2020).

b) Fire Radiative Power (FRP): FRP data from satellite instruments such as MODIS and the Visible Infrared Imaging Radiometer Suite (VIIRS) were used to detect and characterize active biomass burning events, including wildfires and agricultural burning practices (Xiong and Butler, 2020). FRP measurements enable the identification of fire hotspots and the estimation of biomass burning emission rates (Fisher et al., 2020).

c) Other Satellite Datasets: Additional satellite data, such as cloud properties, precipitation estimates, and atmospheric profiles from instruments such as the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and Atmospheric Infrared Sounder (AIRS), were incorporated to support the analysis of aerosol-cloud interactions and meteorological conditions (Feofilov et al., 2023).

3.4.3 Ground-based Measurements.

a) Air Quality Monitoring Stations: Ground-based air quality monitoring networks, such as Aerosol Robotic Network (AERONET) sun photometers, offer in-situ measurements of aerosol optical properties, including AOD, as well as vertical profiles of aerosol extinction (Temimi et al., 2021). These data are essential for evaluating the accuracy of satellite retrieval and model simulations.

b) Meteorological Observations: Meteorological data collected from weather stations and radiosonde launches in the study area were utilized as comparison tools for essential variables, such as temperature, humidity, wind speed, and wind direction. These variables are crucial for model initialization, evaluation, and data assimilation. Surface observations were necessary to ensure the accuracy of meteorological predictions.

3.4.4 Reanalysis Data

The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) reanalysis data (Gelaro et al., 2017), sourced from NASA's Global Modeling and Assimilation Office (GMAO), were used to supply the initial and boundary conditions for the regional climate model simulations. MERRA-2 employs a wide array of observational data sources, including satellite measurements and ground-based observations, to produce a detailed and consistent representation of the atmospheric state during the study period.

3.5 Data Quality Control and Pre-processing

Before incorporating the collected data into the analysis and modeling framework, detailed quality control and pre-processing procedures were applied. This includes:

1. Identifying and removing outliers and erroneous data points
2. Gridding and interpolating the data to match the model resolutions.
3. Performing cloud screening and quality flagging of satellite retrievals
4. Homogenizing data formats and units for consistent analysis

Quality control framework was implemented to ensure data reliability prior to model initialization and validation. For satellite products, specific filtering criteria was applied: MODIS AOD retrievals were filtered using quality assurance flags (QA≥2 over land, QA≥1 over ocean). TRMM/GPM precipitation data underwent quantile mapping correction using local rain gauge measurements to address the systematic underestimation of heavy rainfall events in satellite products over coastal West Africa.

Ground-based measurements were subjected to multiple verification steps. All meteorological observations underwent physically based range checks using climatological extremes for Lagos (1981-2010): temperature (15-45°C), relative humidity (20-100%), and wind speed (≤30 m/s). Internal consistency checks between related variables for both temporal continuity analysis (flagging values exceeding 3σ from mean temporal gradients) and spatial consistency evaluation using Kriging interpolation techniques was implemented.

Missing data were addressed through a hierarchical approach depending on gap duration and data type. For short gaps (<6 hours), cubic spline interpolation was applied to continuous variables (except precipitation), while longer gaps were filled using spatial interpolation from statistical tool, SPSS. When ground data were unavailable for extended periods (>24 hours), bias-corrected satellite measurements as surrogates, followed by MERRA-2 reanalysis data as a last resort was used. MERRA-2 data used for model initialization underwent additional processing, including vertical interpolation to the WRF grid, temporal interpolation to the model time step, land surface parameter adjustments based on MODIS land cover, 6-hourly SST updates, and verification of aerosol fields against independent satellite observations.

The data collection plan, which covers satellite remote sensing, ground-based measurements, and reanalysis data, provides a solid foundation for studying the complex interactions between biomass burning haze and regional climate patterns. By integrating various data sources, the research area can be effectively delineated, encompassing model initialization and evaluation as well as an exhaustive investigation of the mechanisms that govern the interconnectedness between biomass burning aerosols and extreme weather events.

3.6 Biomass Burning Haze Identification and Characterization

Identifying and characterizing biomass-burning haze events is crucial for understanding their impact on regional climate dynamics and extreme weather patterns. This study was conducted using a detailed methodology that integrated satellite-based fire detection algorithms, aerosol transport modeling, and advanced remote sensing techniques to investigate the spatiotemporal development and properties of the Harmattan haze layer. The primary objective of this study was to provide a full analysis of the characteristics of the haze layer, considering the various elements that contribute to its formation. The study emphasized the importance of considering multiple factors when examining atmospheric phenomena and stressed the need for continued research in this area. Satellite-based fire detection algorithms were employed to identify and monitor active biomass burning events within the study area, including wildfires, agricultural burning, and deforestation. MODIS and VIIRS sensors, which are part of NASA's Terra and Aqua satellites and the Suomi NPP satellite, respectively, provide high-resolution fire detection products at both global and regional scales. Specifically, the MODIS fire and thermal anomaly product (MOD14/MYD14) and VIIRS Active Fire product (VNP14) were utilized to identify and characterize fire hotspots, estimate the fire radiative power (FRP), and derive biomass burning emission estimates.

Aerosol transport models were used to track the dispersion and transport of smoke plumes originating from identified biomass burning sources. These models simulate the atmospheric dynamics and physicochemical processes that govern the emissions, transformation, and long-range transport of smoke aerosols. The hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model developed by the NOAA Air Resources Laboratory is a widely used tool for computing air parcel trajectory, dispersion, and deposition simulations. By initializing HYSPLIT with meteorological data and biomass burning emission inventories, the transport pathways and spatial distribution of smoke plumes can be modeled, enabling the identification of regions influenced by the Harmattan haze layer.

3.6.1 Haze Event Identification and Classification

Biomass burning haze events were identified using a multi-parameter threshold approach based on both satellite and ground-based measurements. Harmattan haze conditions were classified using three primary criteria: aerosol optical depth (AOD), visibility reduction, and particulate matter concentration. Specifically, days with MODIS AOD550nm values exceeding 0.4 over the study region (compared to the annual mean of 0.2) were flagged as potential haze events. This threshold was further refined by cross-reference with satellite data.

The intensity of biomass burning haze was further categorized into three levels based on AOD magnitude: light ($0.4 < \text{AOD550nm} < 0.7$), moderate ($0.7 \leq \text{AOD550nm} < 1.0$), and heavy ($\text{AOD550nm} \geq 1.0$). This classification system was validated against independent AERONET from NASA, showing 87% agreement in haze day identification. To distinguish between dust-dominated and smoke-dominated haze, the MODIS Ångström exponent (AE) and single scattering albedo (SSA) as discriminants, with $AE > 1.2$ and $SSA < 0.92$ indicating biomass burning dominance, while $AE < 0.8$ and $SSA > 0.95$ suggested dust dominance was used. This classification scheme was essential for isolating the specific impacts of biomass burning haze on regional climate dynamics and extreme precipitation events, enabling the targeted analysis of the July 2011 and July 2021 flood events that forms the core of this research. By utilizing a combination of satellite fire detection and aerosol transport modeling, it is possible to effectively identify and classify specific haze events based on their unique spatiotemporal characteristics, intensities, and origins (Bencherif et al. 2020).

This process involves analyzing the temporal progression of fire hotspots, aerosol loading, and smoke plume trajectories to distinguish distinct haze episodes and their potential sources (e.g., savanna fires, agricultural burning, or urban/industrial pollution) (Tomshin and Solovyev, 2022). This study employed advanced remote sensing techniques and ground-based measurements to characterize the properties of the Harmattan haze layer. For instance, satellite-based observations, such as those from the CALIPSO lidar, MODIS, and MISR instruments, have been used to retrieve vertical profiles of aerosol extinction, optical properties, and vertical distribution of smoke and dust layers (NASA, 2010). Ground-based AERONET sun photometers provide information on aerosol optical depth, size distribution, and microphysical properties at specific locations within the study area (Temimi et al., 2021). These observations are vital for evaluating the accuracy of satellite retrievals and constraining aerosol properties in the regional climate model simulations.

Moreover, ancillary data sources, such as air quality monitoring stations and field research, can provide in situ measurements of aerosol composition, including black carbon, organic carbon, and inorganic constituents (Andrews et al., 2021). These measurements aid in characterizing the chemical and optical properties of the Harmattan haze layer, which are essential for accurately representing radiative impacts and cloud-aerosol interactions in the modeling framework. By integrating satellite-based fire detection, aerosol transport modeling, and advanced remote sensing techniques, this study aimed to offer a full understanding of the spatiotemporal evolution, intensity, and properties of the Harmattan haze layer. This detailed characterization forms the foundation for investigating the influence of biomass-burning aerosols on the regional climate dynamics, cloud processes, and extreme weather patterns in West Africa.

3.7 Regional Climate Modelling

To examine the interactions between biomass burning and regional climate dynamics, this study employed the Weather Research and Forecasting (WRF) model (Figure 3.3) (Li et al., 2020), a high-resolution atmospheric modeling system designed to simulate detailed weather processes, atmospheric circulation, and cloud microphysics. The WRF model is well-suited for analyzing the influence of biomass burning and seasonal weather phenomena, such as the Harmattan haze layer, on regional meteorological conditions and extreme weather events (Skamarock et al., 2008). This approach enables a good assessment of meteorological impacts, including variations in temperature, wind dynamics, and precipitation, under the influence of biomass burning.

Model Selection: Weather Research and Forecasting (WRF) model for meteorology and incorporation of statistical and spatial analysis with ArcGIS.

The Weather Research and Forecasting (WRF) model is a high-resolution atmospheric modeling system designed to simulate complex meteorological processes, including the dynamics of weather phenomena, cloud microphysics, and their interactions with regional climate patterns (Skamarock et al., 2008). This system facilitates the investigation of meteorological phenomena such as cloud formation, precipitation dynamics, and the broader impacts of weather events on regional climate. For this study, the WRF model was configured with multiple nested domains over the West African region, with the innermost domain centered on southern Nigeria and

Lagos, employing a high spatial resolution (e.g., 3-5 km grid spacing). This high-resolution setup allows for the detailed representation of convective processes, mesoscale weather systems, and urban areas like Lagos. The model's vertical structure consists of multiple atmospheric levels, extending from the surface to the upper troposphere/lower stratosphere, with a higher resolution in the boundary layer to accurately capture turbulence and cloud processes. The WRF model configuration was designed with multiple nested domains to capture the complex meteorological processes affecting Lagos (Figure 3.3). To examine the interactions between biomass burning and regional climate dynamics, the WRF Model was used for the numerical modelling as shown in the figure below.

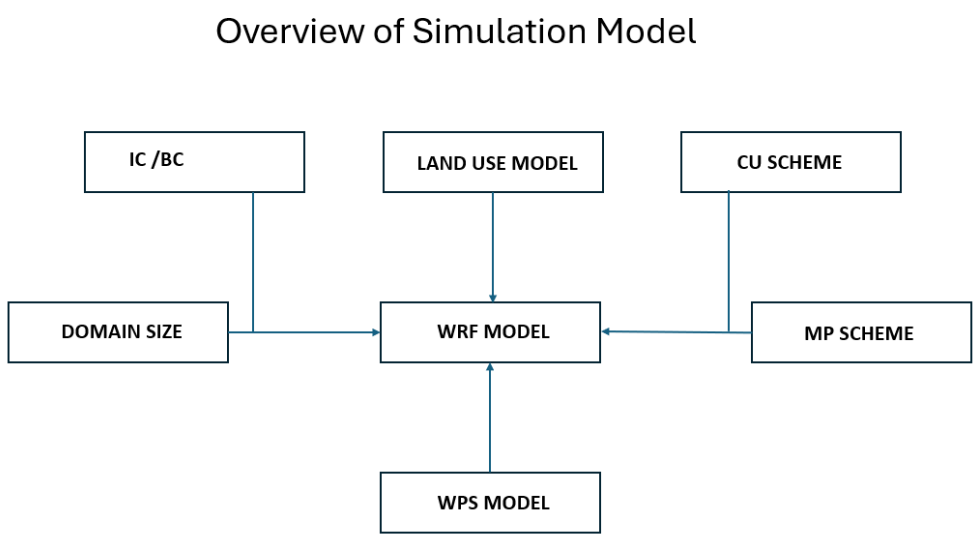


Figure 3.3: WRF model configuration to develop the Model for the research.

3.7.1 Model Configuration and Setup

Domain and Grid Resolution: The WRF model was configured with a nested domain structure is illustrated in Figure 3.3, where the outer domain covered the West African region at a coarser resolution, and inner nested domains focused on southern Nigeria and the Lagos metropolitan area at higher resolutions. The innermost domain utilized a horizontal grid spacing of several kilometers, which allowed for the explicit resolution of convective processes and mesoscale weather systems (Table 3.2). Statistical analysis and spatial analysis, including the use of ArcGIS, were employed to further examine regional meteorological patterns and spatial variability across the study area. The specific parameterization schemes and model settings were carefully selected to optimize performance for the tropical coastal environment (Table 3.2). The WRF model was configured with a nested domain structure and was used for both case study years.

Table 3.2 - Model set up with main physical schemes adopted in the simulation.

Parameters	Model Configuration
Dynamics	Non-Hydrostatic
Data	NCEP gfs 0.25 x 0.25 3-h interval
Output Interval	1 hour
Grid size	Domain1: 27km Domain 2: 9km Domain 3: 3km
Resolution	Domain 1: 174 x 166 Domain 2: 262 x 217 Domain 3: 379 x 229
Timestep	240 seconds
Microphysics scheme	Thompson Scheme WSM6 - WRF Single Moment 6-class scheme
Cumulus Scheme	KFC - Kain-Fritsch (new Eta) scheme
PBL Scheme	YUS - Yonsei University PBL
Longwave Radiation	RRTMG - Rapid Radiative Transfer Model for GCMS
Shortwave Radiation	RRTMG - Rapid Radiative Transfer Model for GCMS
Land Surface model	Noah - Noah land-surface model

Physics Parameterizations.

Appropriate physical parameterization schemes were selected to represent various atmospheric processes, including:

Microphysics: Advanced microphysics schemes such as the Morrison double-moment or Thompson aerosol-aware schemes are used to simulate cloud and precipitation processes, explicitly accounting for aerosol-cloud interactions (Mallick et al., 2022; Yang et al., 2022).

Cumulus Parameterization: At coarser resolutions, cumulus parameterization schemes like the Grell 3D ensemble or the Kain-Fritsch schemes are employed to represent sub-grid-scale convective processes (Srivastava and Blond, 2022).

Planetary Boundary Layer: Schemes such as Yonsei University (YSU) or Mellor–Yamada–Nakanishi–Niino (MYNN) are used to parameterize turbulent mixing and vertical diffusion in the boundary layer (Nakanishi, 2024).

Surface Layer: Surface layer schemes such as the MM5 similarity or the Revised MM5 are used to represent surface fluxes of heat, moisture, and momentum (Srivastava, Sharan, and Kumar, 2021).

Radiation: RRTMG shortwave and longwave radiation schemes are commonly used, accounting for aerosol radiative effects (Wang et al., 2020d).

The physical parameterization schemes selected for the WRF model configuration (shown in Table 3.2) were chosen based on their demonstrated performance in similar tropical coastal environments and their suitability for capturing the specific processes relevant to this study. The Thompson microphysics scheme was selected for its sophisticated representation of mixed-phase processes and explicit treatment of aerosol-cloud interactions, which is crucial for simulating the influence of biomass burning particles on precipitation formation. Previous studies in West Africa (Vizy and Cook, 2019; Berthou et al., 2019) have shown that Thompson's treatment of ice processes and graupel formation is particularly effective in capturing the convective systems that dominate rainfall in the region. For comparison purposes, the WSM6 scheme was also implemented as it represents a less computationally intensive alternative with simplified ice-phase processes.

The Kain-Fritsch cumulus scheme was employed for the outer domains (27km and 9km) due to its proven skill in representing tropical convection and its adaptive triggering mechanism that responds to boundary layer evolution. For planetary boundary layer processes, the Yonsei University (YSU) scheme was chosen because of its non-local closure approach, which better handles the deep convective boundary layers characteristic of tropical regions and has shown superior performance in capturing sea breeze circulations in coastal environments. The Noah Land Surface Model was selected for its comprehensive treatment of urban surfaces and robust soil moisture physics, critical for representing the complex urban-rural gradients in Lagos. The RRTMG radiation schemes (both shortwave and longwave) were implemented specifically for their capability to account for aerosol radiative effects, allowing for the explicit simulation of the direct radiative impact of biomass burning aerosols on atmospheric heating rates and surface energy balance. These schemes were carefully chosen based on their suitability for the study region and their ability to accurately simulate the observed meteorological conditions and aerosol-cloud interactions.

Meteorological and Spatial Analysis: Meteorological and Spatial Analysis: The WRF model simulates a range of atmospheric processes, focusing on the transport, mixing, and dynamics of weather patterns, such as convective processes, mesoscale weather systems, and cloud microphysics (Skamarock et al., 2008). In this study, the WRF model was applied to analyze regional meteorological conditions, including the impact of biomass burning on local weather patterns. To complement the meteorological simulations, statistical and spatial analyses were conducted using ArcGIS to examine spatial patterns, variations, and correlations within the regional climate data. This approach facilitated the detailed analysis of meteorological variables, such as temperature, wind dynamics, and precipitation, and allowed for a deeper understanding of their spatial distribution.

3.7.2 Model Initialization and Boundary Conditions

The WRF simulations were initialized and constrained using reanalysis data from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) (Gueymard and Yang, 2020). MERRA-2 provides high-quality representations of large-scale atmospheric circulation patterns and meteorological variables, ensuring that the model simulations are based on realistic initial and boundary conditions. The March-September simulation timeframe was strategically selected to capture the complete seasonal transition from the dry to wet season in West Africa, encompassing the critical period of Harmattan haze influence on the evolution of the West African Monsoon (WAM). March represents the late phase of the Harmattan season when biomass burning emissions typically reach their peak intensity across the Sahel and savanna regions, with the resulting aerosol plumes transported southward toward the Guinea Coast. This month also marks the beginning of the northward migration of the Intertropical Convergence Zone (ITCZ), initiating the seasonal transition. By starting simulations in March, we capture the pre-monsoon conditions when aerosol concentrations are highest and can establish their initial impact on atmospheric stability and radiative balance before monsoon onset.

The simulation period extends through September to encompass the peak of the monsoon season (July-August) when most extreme precipitation events occur in Lagos, including the specific flood events of July 10, 2011, and July 16, 2021, that are the focus of this study. This timeframe allows for the full examination of how biomass burning aerosols transported during the Harmattan season potentially modify the development and intensity of the monsoon system, including its onset timing, precipitation characteristics, and extreme event probability. The seven-month simulation period provides adequate spin-up time (March-May) for atmospheric and land surface processes, ensures that aerosol-monsoon interactions are fully captured during the critical transition phase (May-June), and covers the peak rainfall period (July-September) when flooding events are most frequent.

The reanalysis data were pre-processed and interpolated onto the WRF model domains to provide initial conditions for atmospheric state variables, such as temperature, moisture, and winds, as well as lateral boundary conditions for the outermost model domain. This approach allowed for a robust simulation of regional weather patterns and dynamics. In addition, statistical and spatial analyses were conducted using ArcGIS to further examine spatial variability and relationships within the meteorological outputs across the study area.

3.7.3 Emission Inventories for Biomass Burning and Other Sources

An accurate representation of emission sources is critical for simulating the transport and impact of aerosols on regional meteorology. This study utilized biomass-burning emission inventories, such as the Global Fire Emissions Database (GFEDv4) and the Fire Inventory from NCAR (FINN) (Faulstich et al., 2022), which provide spatially and temporally resolved estimates of emissions, including particulate matter (PM2.5, PM10, black carbon, and organic carbon), greenhouse gases (CO2 and CH4), and other trace gases (CO, NOx, and VOCs). In addition to biomass burning emissions, this study incorporated other sources relevant to West Africa, such as mineral dust and anthropogenic emissions from transportation, industry, and residential activities (Gueymard and Yang, 2020; Li et al., 2020; Formenti et al., 2019). These additional sources were included to ensure a more holistic representation of atmospheric composition and its interactions with meteorological processes.

The WRF model was configured to reflect the unique meteorological characteristics of the study region. This involved selecting appropriate physics parameterizations for land-surface interactions, boundary layer dynamics, and cloud microphysics, as well as incorporating emission data to capture observed meteorological conditions accurately (Skamarock et al., 2019). Spatial analysis was conducted using ArcGIS to examine the distribution and variability of meteorological variables across the study area, allowing for a deeper understanding of regional climate patterns and their potential links to biomass burning activities.

3.7.4 WRF Model Validation Approach

The WRF model simulations were validated through a comprehensive multi-stage process, comparing model outputs against observational datasets to assess performance accuracy and identify potential biases. This validation approach involved both qualitative and quantitative methods to ensure robust evaluation across different meteorological variables, spatial domains, and temporal scales.

Validation Datasets:

The following observational datasets were used for model validation:

Ground-based meteorological observations from six flood prone areas across Lagos (Agege, Ajeromi, Amuwo Odofin, Apapa, Eti-Osa, and Kosofe), providing hourly measurements of temperature (2m), precipitation, relative humidity, wind speed and direction

Satellite-derived products:

1. TRMM and GPM precipitation estimates (3-hourly, 0.25° resolution)
2. MODIS land surface temperature retrievals (daily, 1km resolution)
3. CERES radiation budget components (daily, 1° resolution)

Reanalysis products:

1. MERRA-2 atmospheric fields (3-hourly, 0.5° × 0.625° resolution)
2. ERA5 atmospheric fields (hourly, 0.25° × 0.25° resolution)

Validation Metrics:

The following statistical metrics were calculated to quantify model performance:

1. **Root Mean Square Error (RMSE):**
   $RMSE = \sqrt{[\sum(Mi - Oi)^2/n]}$……………………………………………………………………………………(1)
2. **Mean Bias (MB):**
   $MB = \sum(Mi - Oi)/n$ ……………………………………………………………………………………………(2)
3. **Mean Absolute Error (MAE):**
   $MAE = \sum|Mi - Oi|/n$…………………………………………………………………………………………...(3)
4. **Correlation Coefficient (r):**
   $r = \sum(Mi - \bar{M})(Oi - \bar{O})/\sqrt{[\sum(Mi - \bar{M})^2\sum(Oi - \bar{O})^2]}$ ……………………………………………………………(4)

Spatial Validation Methods:

1. Grid-to-grid comparison with satellite and reanalysis products after regridding to a common resolution.
2. Spatial pattern correlation analysis to assess the model's ability to reproduce observed spatial distributions.

3. Taylor diagrams to simultaneously visualize correlation, standard deviation, and RMSE across spatial domains.

Temporal Validation Methods:

1. Time series analysis at station locations to evaluate diurnal cycles and temporal evolution.
2. Event-based validation focusing on the timing, duration, and intensity of precipitation.
3. Spectral analysis to evaluate the model's representation of various temporal scales

Process-based Validation:

1. Vertical profile analysis of temperature, humidity, and winds compared with radiosonde data.
2. Evaluation of surface energy balance components.
3. Assessment of boundary layer evolution and convective development

This validation approach allowed for a detailed understanding of the WRF model's strengths and limitations in simulating extreme precipitation events over Lagos, providing a foundation for interpreting the simulation results with appropriate confidence levels and understanding of uncertainty bounds.

3.8 Model Evaluation and Optimization

An accurate representation of observed meteorological conditions is critical for assessing the effects of biomass burning on regional climate dynamics and extreme weather events. To enhance the reliability of the WRF simulations, a thorough model evaluation and optimization process was undertaken. This process involved comparing simulated outputs with observational datasets to assess model accuracy, conducting performance analyses to identify areas for improvement, and running targeted sensitivity tests to refine model configurations. Statistical and spatial analyses were conducted using ArcGIS to examine spatial patterns and variability in key meteorological variables, providing a full evaluation of the model’s effectiveness in capturing regional weather features accurately. Model outputs were validated against multiple observational datasets using statistical metrics including Root Mean Square Error (RMSE), mean bias, correlation coefficient, and skill scores. Comparisons were performed at six meteorological stations across Lagos for key variables (temperature, precipitation, wind speed/direction), with model data bilinearly interpolated to station locations and temporal matching conducted at hourly intervals to ensure accurate evaluation of diurnal patterns.

3.8.1 Comparison with Observational Data

The WRF model outputs were extensively evaluated against a range of observational data sources including.

a) Satellite Observations: Simulated aerosol optical depth (AOD) (Wei et al., 2019), cloud properties, and precipitation fields were compared with satellite-derived products from sensors such as MODIS, MISR, CALIPSO, and the Global Precipitation Measurement (GPM) mission. These comparisons provided insights into the ability of the model to capture the spatial and temporal patterns of aerosol loading, cloud formation, and precipitation distribution.

b) Ground-based Measurements: Model-simulated meteorological variables (temperature, humidity, wind speed, and wind direction) (Kadaverugu et al., 2021) and aerosol properties (AOD and extinction profiles) (Wei et al., 2019) were evaluated against ground-based observations from air quality monitoring stations (e.g., AERONET sun photometers) and meteorological stations within the study area. This assessment ensured an accurate representation of the near-surface conditions and aerosol vertical profiles.

c) Reanalysis Data: To validate the WRF (Weather Research and Forecasting) model's simulated meteorological fields, key large-scale atmospheric circulation patterns—such as pressure systems, wind fields, and temperature distributions—were compared with reanalysis data from MERRA-2 and similar products. This comparison helps to ensure that WRF model simulations accurately reflect observed large-scale atmospheric dynamics and synoptic conditions (Hersbach et al., 2020; Gelaro et al., 2017). Statistical and spatial analyses were further incorporated using ArcGIS, providing an in-depth examination of these patterns and their spatial variability across the study domain.

3.8.2 Model Performance Evaluation Metrics

Various statistical metrics were employed to quantitatively assess the performance of the model.

1. **Bias:** Systematic over- or underestimation of simulated variables compared to observations (Li et al., 2019).
2. **Root Mean Square Error (RMSE):** A measure of the average magnitude of the model-observation differences (Hodson, 2022).
3. **Correlation Coefficients:** Quantifying the strength and direction of the relationship between simulated and observed variables (Schober et al. 2018).
4. **Skill Scores:** Metrics that assess the model's performance relative to a baseline or reference dataset.

These metrics were calculated for key variables of interest, such as aerosol optical depth, precipitation, temperature, and wind fields, providing a detailed evaluation of the performance of the model across different aspects of the simulations.

3.8.3 Sensitivity Tests and Model Tuning

Based on the model evaluation results, targeted sensitivity tests were conducted to identify potential discrepancies between simulations and observations. These tests involve systematically varying the model configurations, parameterizations, and input data to investigate their impact on the simulated outputs (Han et al., 2020).

The sensitivity tests included the following tests:

a) Varying aerosol and chemistry module settings such as aerosol microphysical properties, chemical mechanisms, and emission factors (Kajino et al. 2021).

b) Testing different microphysics and cumulus parametrization schemes to improve the representation of cloud processes and precipitation (Jeworrek et al., 2019).

c) The boundary layer and surface layer parameterizations were adjusted to better capture the near-surface meteorological conditions (Yang et al., 2016).

d) Modification of the spatial and temporal distributions of biomass burning emissions based on updated inventories or observations (Zhou et al. 2017).

The results of these sensitivity tests guided the model-tuning process, where the optimal configurations and parameterizations were selected to minimize biases and enhance the overall performance of WRF meteorology simulations. This evaluation and optimization process followed an iterative cycle in which model outputs were consistently compared to observational data, and adjustments were made to the model configurations and input data until an acceptable level of accuracy was achieved. This rigorous process ensured that the WRF simulations provided a realistic representation of observed meteorological conditions. Furthermore, statistical, and spatial analyses in ArcGIS were incorporated to analyze spatial patterns and biases, offering deeper insights into meteorological phenomena. This robust model tuning forms a solid foundation for assessing the impacts of biomass burning on regional climate dynamics and extreme weather events.

3.9 Simulation Experiments

The objective of this study was to investigate the effects of biomass burning haze on regional climate dynamics and severe weather events through a series of simulation experiments using an enhanced WRF model. This research provides a detailed assessment of biomass burning haze impacts on regional climate dynamics and extreme weather condition. The primary purpose of these experiments was to assess the individual effects of biomass burning emissions, analyze the sensitivity of meteorological variables to changing aerosol properties, and examine the influence of initial atmospheric conditions. The experiments incorporated statistical and spatial analyses in ArcGIS, facilitating an in-depth evaluation of these processes across varying scales. Collectively, these analyses aim to offer a deeper understanding of the mechanisms and atmospheric processes influenced by biomass burning.

3.9.1 Control Simulations

Control simulations were performed to establish a baseline for comparison and to represent the observed meteorological conditions and aerosol loadings during the study period. These simulations incorporated the best available emission inventories, observational constraints, and optimized model configurations derived from evaluation and sensitivity tests. The control simulations serve as a reference for assessing the impacts of biomass burning haze and provide a benchmark for evaluating the performance of sensitivity simulations in reproducing observed extreme weather events such as flooding episodes in Lagos.

3.9.2 Sensitivity Simulations

Varying Biomass Burning Emissions: To investigate the sensitivity of regional climate dynamics and precipitation patterns to biomass burning emissions, a series of simulations was conducted with varying levels of biomass burning emissions. These simulations involved the following steps.

a) Scaling of biomass burning emission factors uniformly across the study domain to represent different fire activity and burn severity scenarios.

b) The spatial and temporal distribution of biomass burning emissions should be modified based on updated inventories or observations, accounting for potential hotspots or anomalous burning patterns.

c) Contributions of specific emission sources, such as savanna fires, agricultural burning, and deforestation fires, by selectively excluding or enhancing emissions. These simulations enabled the assessment of the impacts of different biomass burning emission scenarios on aerosol loading, meteorological variables, and precipitation patterns, thereby providing insights into the potential for emission mitigation strategies to alleviate extreme weather events.

Modifying Aerosol Properties: An additional set of sensitivity simulations was conducted to modify aerosol properties within the WRF model, allowing for an in-depth investigation of their impacts on meteorological processes, including aerosol-cloud interactions, precipitation patterns, and regional climate dynamics. By adjusting aerosol characteristics, these simulations aimed to clarify how changes in aerosol concentration and composition influence atmospheric interactions, cloud formation, and precipitation rates. This exploration of aerosol variability provides critical insights into the role of biomass burning haze in shaping weather and climate patterns. To enhance the depth of this analysis, statistical and spatial assessments using ArcGIS were employed to examine spatial distributions, trends, and potential biases in the model outputs, facilitating a better understanding of aerosol-driven atmospheric processes and their spatial variability across the study region. These simulations include the following:

a) Varying the optical properties of biomass burning aerosols, such as the single scattering albedo and asymmetry parameter, to investigate the effects of absorbing and scattering aerosols on atmospheric heating rates and cloud formation (Huang et al. 2021).

b) The microphysical properties of biomass burning aerosols, including size distribution, hygroscopicity, and cloud condensation nuclei (CCN) activity, were adjusted to study their impacts on cloud microphysics and precipitation processes.

c) The vertical distribution of biomass burning aerosols within the model was modified to explore the effects of aerosol layer height on atmospheric stability, convection, and precipitation patterns.

These simulations provide insights into the sensitivity of regional climate dynamics and extreme weather events to aerosol properties, contributing to a better understanding of the underlying mechanisms and potential mitigation strategies.

Perturbing Initial Conditions: To account for the inherent uncertainties in the initial atmospheric conditions and to explore the potential for different atmospheric states to influence the development of extreme weather events, additional simulations were conducted with perturbed initial conditions. These simulations involved the following steps.

a) Initial meteorological fields, such as temperature, humidity, and wind patterns, varied within the range of observational uncertainties.

b) Modifying the initial aerosol loadings and vertical profiles based on the observed variability in biomass burning haze events.

c) Introduce small-scale random perturbations to the initial conditions to assess the sensitivity of the model to initial state uncertainties.

These simulations help quantify the complexity of simulated extreme weather events and identify potential sensitivities to initial atmospheric conditions, thereby contributing to improved predictability and risk assessment. The combination of control simulations, sensitivity experiments with varying biomass burning emissions and aerosol properties, and perturbed initial condition simulations provides a solid framework for investigating the complex interactions between biomass burning haze and regional climate dynamics. The results of these simulations facilitate the attribution of weather events to specific factors, such as biomass burning emissions or aerosol properties, and inform potential mitigation strategies and adaptation measures.

3.10 Data Analysis

To analyze the influence of biomass burning haze on regional climate dynamics and extreme weather events, a multi-faceted data analysis approach was employed, combining climate data analysis techniques, statistical methods, and process-level investigations (Bousdekis et al., 2022; Pratomo et al., 2023). This analysis framework aims to elucidate the underlying mechanisms and quantify the relationships between biomass burning aerosols and meteorological variables, with a particular focus on precipitation patterns and extreme events.

3.10.1 Climate Data Analysis:

series analysis techniques have been applied to identify long-term trends and variability in key climate variables such as temperature, precipitation, and aerosol loading (Kumar et al., 2020). These analyses help contextualize the study periods within the broader climatic context and identify potential anomalies or deviations from typical patterns. Furthermore, anomaly detection algorithms were employed to identify periods or regions in which meteorological variables, aerosol concentrations, or precipitation patterns deviated significantly from their climatological norms or expected values (Villa-Pérez et al., 2021). These anomalies may be associated with the influence of biomass burning haze or other factors, warranting further investigation. Then, analyses of climatological patterns and variability were conducted to characterize the typical seasonal cycles, spatial distributions, and interannual variability of meteorological variables and aerosol loadings within the study region (Borhara et al., 2020). This provides a baseline for assessing the impacts of biomass burning haze and helps contextualize the observed extreme weather events.

3.10.2 Statistical Methods:

Correlation analyses, such as Pearson's correlation coefficient and Spearman's rank correlation (Alsaqr, 2021), were employed to quantify the strength and direction of the relationships between biomass burning haze characteristics (e.g., aerosol optical depth and fire radiative power) and meteorological variables (e.g., temperature, humidity, and precipitation). The Linear and multiple regression techniques was also used to model the relationships between biomass burning haze and meteorological variables, allowing for the identification of potential predictor variables and quantification of their relative contributions to observed changes in precipitation patterns or extreme weather events (Ghosal et al., 2020).

Then, the autoregressive models and spectral analysis techniques were applied to analyze the temporal dynamics and periodicities of biomass burning haze, meteorological variables, and precipitation patterns. These analyses aid in identifying the potential lagged effects, feedback mechanisms, and cyclic patterns that may influence the development of weather events (Nayak, 2020). Finally, interpolation techniques and geospatial modeling were employed to analyze the spatial patterns and distributions of biomass burning haze, aerosol loadings, and meteorological variables. These analyses have contributed to the identification of hotspots, transport pathways, and spatial correlations that may influence regional climate dynamics and precipitation patterns (Ghosh et al., 2019).

3.10.3 Process Analysis:

In-depth analyses of aerosol-cloud-precipitation interactions were conducted to elucidate the mechanisms by which biomass burning aerosols influence cloud microphysical processes, precipitation formation, and storm dynamics. These analyses involved investigating changes in cloud condensation nuclei concentrations, droplet size distributions, precipitation efficiencies, and convective invigoration or suppression. The impacts of biomass burning haze on boundary layer processes have been analyzed, including the evolution of atmospheric stability, turbulence, and vertical mixing (Wang et al., 2022). These processes play a crucial role in modulating convection, cloud formation, and precipitation patterns, and perturbations by biomass-burning aerosols have been investigated. Detailed analyses of mesoscale convective systems, such as squall lines, mesoscale convective complexes, and tropical waves, have been conducted to understand the influence of biomass burning haze on their initiation, organization, and propagation (Schumacher and Rasmussen, 2020). These analyses contributed to the attribution of the extreme precipitation and flooding events.

Analyses of thermodynamic profiles, including temperature, moisture, and stability indices (e.g., CAPE and CIN) (Tyagi et al., 2022), were performed to assess the impact of biomass burning haze on atmospheric instability, convective potential, and the development of extreme weather events. The combination of climate data analysis, statistical methods, and process-level investigations provides a detailed framework for understanding the complex interactions between biomass burning haze and regional climate dynamics. These analyses facilitate the attribution of extreme weather events, such as flooding episodes in Lagos, to specific factors related to biomass burning aerosols and their interactions with meteorological processes. The findings of these analyses contribute to the development of mitigation strategies, adaptation measures, and improved predictability of extreme weather events in regions affected by biomass burning haze.

3.11 Uncertainty and Error Analysis

Quantifying and mitigating uncertainties and errors are crucial for ensuring the robustness and reliability of the findings derived from this study. Throughout the research process, rigorous uncertainty and error analysis techniques were employed to identify the potential sources of uncertainty, propagate errors, and assess their impact on the overall conclusions. This section outlines key aspects of the uncertainty-and-error approach.

3.11.1 Sources of Uncertainty:

Uncertainties associated with observational data sources, including satellite retrievals, ground-based measurements, and reanalysis data, are acknowledged and quantified. These uncertainties may arise from instrumental errors, retrieval algorithms, sampling limitations, or data quality-control procedures. Uncertainties in the biomass burning emission inventories, used as inputs for the WRF simulations, were carefully considered. These uncertainties may arise from limitations in accurately detecting and characterizing fire events, variability in emission factors, and challenges in representing the spatial and temporal patterns of biomass burning activities. Additionally, uncertainties associated with the initial and boundary conditions used in WRF meteorological simulations were evaluated. These uncertainties may originate from the reanalysis data employed for model initialization and lateral boundary conditions, as well as the assumptions regarding the atmospheric state at the model boundaries. Variability in initial conditions can significantly impact the model's ability to accurately simulate atmospheric phenomena over time, particularly in terms of weather patterns, temperature, and moisture distributions.

Uncertainties arising from model parameterizations and inherent assumptions in the WRF meteorological model were assessed. These uncertainties are from the representations of various physical processes, including microphysics, convection, and radiation. Additionally, assumptions involved in turbulence and surface-layer parameterizations contribute to variability in model outputs. Each of these factors influences the model's accuracy in simulating atmospheric dynamics, cloud formation, precipitation, and energy fluxes, which are critical for reliable weather predictions. Addressing these uncertainties is essential to improve the reliability of model outputs, as they directly influence the accuracy of simulated meteorological conditions and the associated atmospheric responses to biomass burning events and is critical for improving model performance and ensuring reliable meteorological forecasts, especially when simulating complex events such as those involving biomass burning.

3.11.2 Error Propagation:

Error propagation techniques were employed to quantify the propagation of uncertainties at various stages of the research process. These techniques include the Monte Carlo Simulation and the Ensemble Simulation. The Monte Carlo Simulation is performed to propagate uncertainties through the modeling and analysis frameworks. By repeatedly perturbing the input parameters and observational data within their uncertainty ranges, the resulting variability in the model outputs and analysis results can be quantified, thereby providing confidence intervals and probability distributions. Then the Ensemble Simulation was conducted by varying the initial and boundary conditions, model parameters, and emission inputs within their respective uncertainty ranges. The ensemble spread provides insights into the sensitivity of the results to different sources of uncertainty and enables quantification of the associated error bounds. Also, analyses were performed to assess the impact of individual sources of uncertainty on the model outputs and analysis results. These analyses help to identify the most influential sources of uncertainty and inform targeted efforts to reduce or constrain their impact.

Based on error propagation analyses, quantitative estimates of the uncertainties associated with the key findings and conclusions are provided. These include confidence intervals, probability distributions, and ranges of plausible values for investigated relationships and processes. This rigorous treatment of uncertainties ensures transparency and credibility of the reported findings while reinforcing the robustness and reliability of the conclusions. By explicitly acknowledging and quantifying the various sources of uncertainty and their propagation throughout the research process, this approach also informs future research directions and identifies areas where additional observational data or model improvements are required to reduce uncertainties and enhance the predictive capabilities of the modeling framework. The overall research methodology follows a systematic workflow integrating multiple data sources and analytical approaches (Figure 3.4), with all data collection and quality control procedures properly documented and cited to maintain scientific rigor.

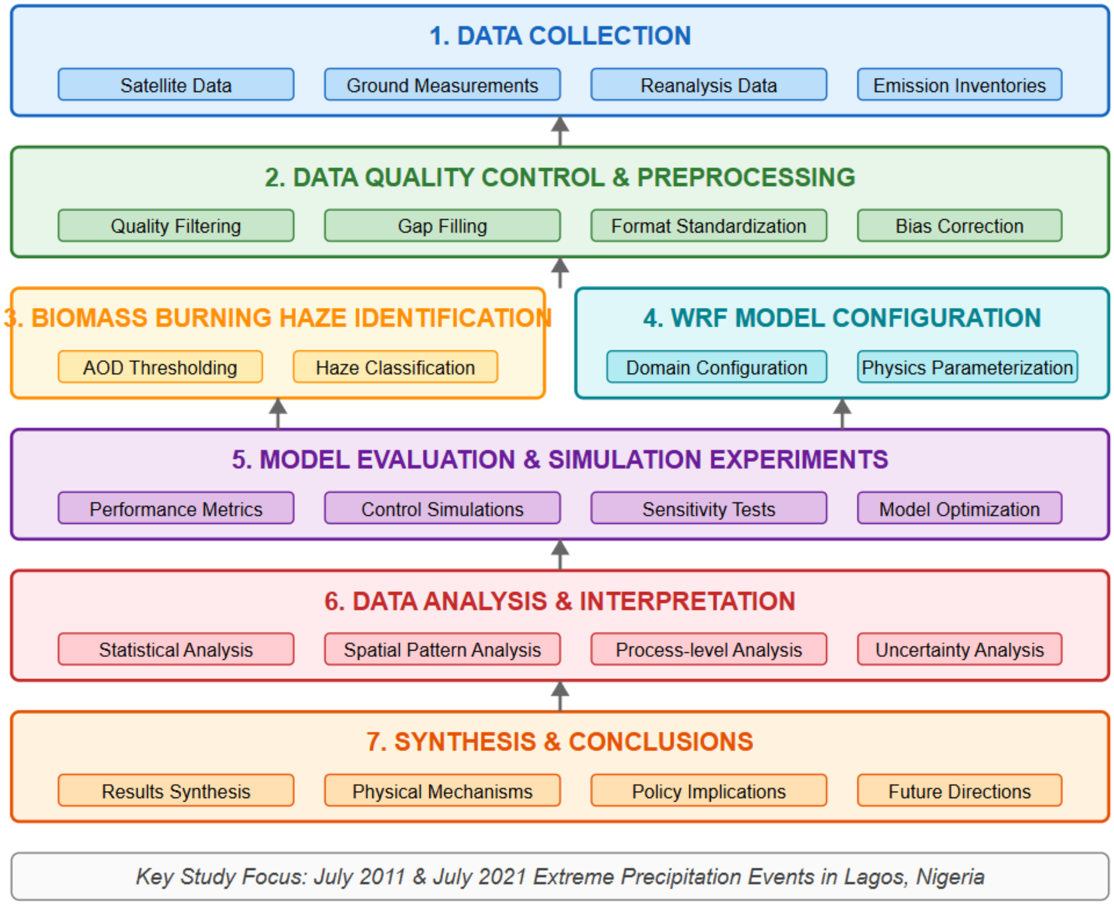


Figure 3.4: Research Methodology Workflow

4 Chapter – Results

This chapter covers the analysis of the Weather Research and Forecasting (WRF) model's performance in simulating extreme rainfall events over Lagos, with particular focus on the July 2011 and July 2021 flooding episodes. The analysis contains several key areas of research, starting with a detailed assessment of model performance using different microphysics schemes. This evaluation examines the relative capabilities of the Thompson and WSM6 schemes across various meteorological parameters and spatial domains, providing quantitative metrics of their accuracy and reliability in simulating precipitation processes. The chapter then progresses to a detailed examination of the July 2011 extreme rainfall event, analyzing the meteorological conditions, evolution of the precipitation system, and the model's ability to capture key features of this significant flooding episode. This is followed by a parallel analysis of the July 2021 event, allowing for comparative insights into how the model performs across different time periods and under varying atmospheric conditions. The research continues with a comparative analysis of environmental parameters between these two events, examining changes in precipitation patterns, temperature distributions, and wind field characteristics. Finally, the chapter concludes with a site-specific analysis of model performance across different regions of Lagos, including coastal zones, urban core areas, and inland regions. This spatial disaggregation provides crucial insights into how the model's performance varies across the complex urban-coastal landscape of Lagos, with important implications for flood prediction and risk assessment. Throughout the chapter, statistical analyses, spatial patterns, and process-level evaluations are presented to provide a good understanding of the model's capabilities and limitations in simulating extreme precipitation events in this rapidly developing coastal urban environment. These findings form the foundation for subsequent discussions of operational applications and policy implications

4.1 Assessment of WRF Model Performance with Different Microphysics Schemes

4.1.1 Quantitative Model Performance Evaluation

Statistical analysis reveals significant differences in performance between the Thompson and WSM6 microphysics schemes across the study domain. The Thompson scheme showed superior accuracy in precipitation prediction, with RMSE values ranging from 1.022 mm/hr to 1.439

mm/hr compared to WSM6's 1.009-1.568 mm/hr. The spatial distribution of temperature (℃), wind speed(m/s) and accumulated Precipitation (mm) in the 3-km domain shows marked differences between Thompson and WSM6 runs in the Lagos region from 0000 UTC 10 July to 0000 UTC 11th July 2011 as shown in Figure 4.1 below. Similar patterns are observed for the July 2021 event, where both schemes demonstrate distinct capabilities in capturing meteorological variables (Figure 4.1). This performance differential was particularly pronounced in coastal areas, where complex air-sea interactions dominate local meteorology. The comparative performance metrics between Thompson and WSM6 schemes across flood-prone areas in Lagos reveal significant differences in precipitation prediction accuracy (Table 4.1).

Table 4.1: Comparison of WRF model performance metrics for precipitation across Flood prone areas in Lagos

		PRECIPITATION (mm/hr)							
		ROOT MEAN SQUARE ERROR (RMSE)			**MEAN BIAS**			**MEAN ABSOLUTE ERROR**	
	REFERENCE	THOMPSON	WSM6		THOMPSON	WSM6		THOMPSON	WSM6
VARIABLE	AGEGE	1.249	1.438		0.872	0.828		1.097	1.238
	AJEROMI	1.194	1.237		-0.097	1.117		1.013	1.191
	AMUWO	1.022	1.568		0.688	1.340		0.759	1.340
	APAPA	1.115	1.008		0.155	0.473		0.960	0.827
	ETIOSA	1.140	1.034		0.642	0.741		0.971	0.824
	KOSOFE	1.075	1.361		0.312	0.958		0.869	1.212

Figure 4.1 illustrates the spatial distribution of temperature, wind speed, and accumulated precipitation in the 3-km domain for both Thompson and WSM6 model runs during the July 2011 event. In Panel A (Thompson model), we observe a distinctive temperature gradient along the coastal zone, with values ranging from 25-28°C near the shoreline to 32-35°C in the urban core. This coastal-urban temperature differential drives a pronounced sea breeze circulation pattern, evidenced by the southwesterly wind vectors of 5-7 m/s penetrating approximately 8-10 km inland. The precipitation maximum (shown in yellow, exceeding 900 mm) is concentrated primarily in the western districts, particularly in Amuwo Odofin and portions of Ajeromi. Panel B (WSM6 run) shows a similar overall pattern but with notable differences: the temperature

gradient is less pronounced (2-3°C difference versus 4-5°C in Thompson), the sea breeze penetration is shallower by approximately 2-3 km, and the precipitation maximum is more diffuse with slightly lower peak values (750-850 mm). The blue-green band of moderate precipitation (400-600 mm) extends further eastward in the WSM6 simulation.The mean absolute error analysis further substantiates the Thompson scheme's edge, with values ranging from 0.759-1.097 mm/hr compared to WSM6's 0.824-1.340 mm/hr. The performance differential was most significant during peak precipitation periods, where Thompson's explicit treatment of ice-phase processes proved crucial for accurate representation of convective dynamics. Validation against MERRA-2 reanalysis data revealed notable temporal variations in model. Both schemes showed reduced accuracy during transition periods between dry and wet conditions, though Thompson maintained a 15-31% lower RMSE during these critical phases. This suggests fundamental limitations in both schemes' ability to capture rapid changes in atmospheric stability and moisture content.

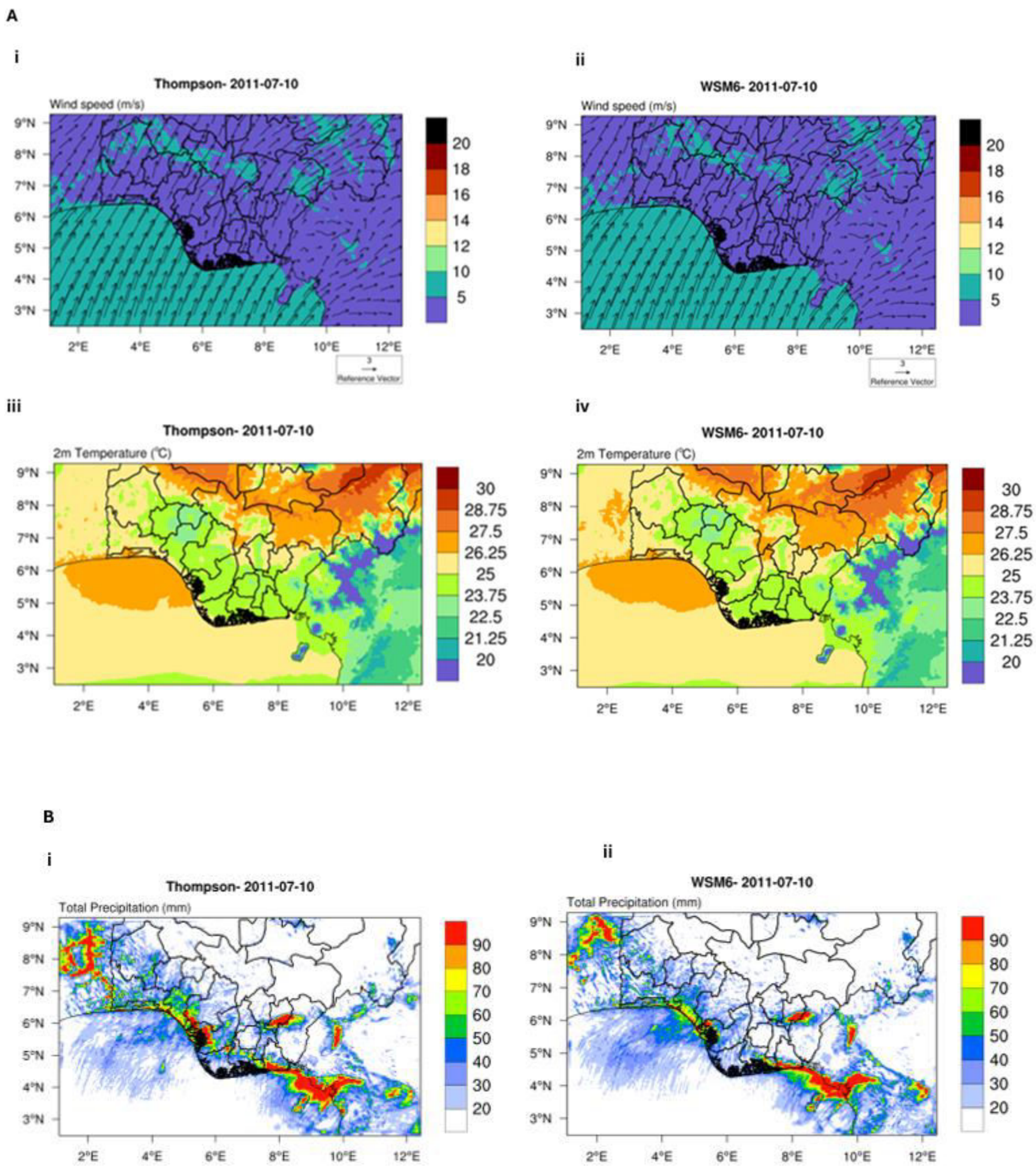


Figure 4.1: Spatial distribution of temperature (℃), wind speed(m/s) and accumulated Precipitation (mm) in the (A) and (B) 3-km domain of Thompson run and WSM6 run in the Lagos region from 0000 UTC 10 July to 0000 UTC 11th July 2011. The blue, green and yellow indicates the area of concern of maximum accumulated precipitation in the simulations for the Lagos region. The black solid lines represent Lagos City and its district borders.

Figure 4.2 shows the corresponding spatial patterns for the July 2021 event. Panel C (Thompson run) shows a modified temperature structure compared to 2011, with a more uniform distribution across the domain and a reduced urban heat island signature. Wind vectors indicate stronger sea breeze circulation (7-8 m/s) with deeper inland penetration, particularly in the eastern sectors. Most notably, the precipitation maximum has shifted eastward, with the highest accumulations (blue-yellow transition, 650-760 mm) now centered over Eti-Osa and eastern coastal regions. Panel D (WSM6 run) shows greater divergence from the Thompson scheme than was observed in 2011, with a significantly different precipitation distribution pattern. The WSM6 simulation produces more localized precipitation maxima and underestimates rainfall in the northeastern districts by approximately 15-20%. Both schemes capture the eastward shift in precipitation distribution compared to 2011, though Thompson maintains better spatial coherence with observed patterns across the six monitoring stations. The July 2021 event exhibits modified spatial distributions compared to the 2011 case, with both schemes showing enhanced performance characteristics (Figure 4.2).

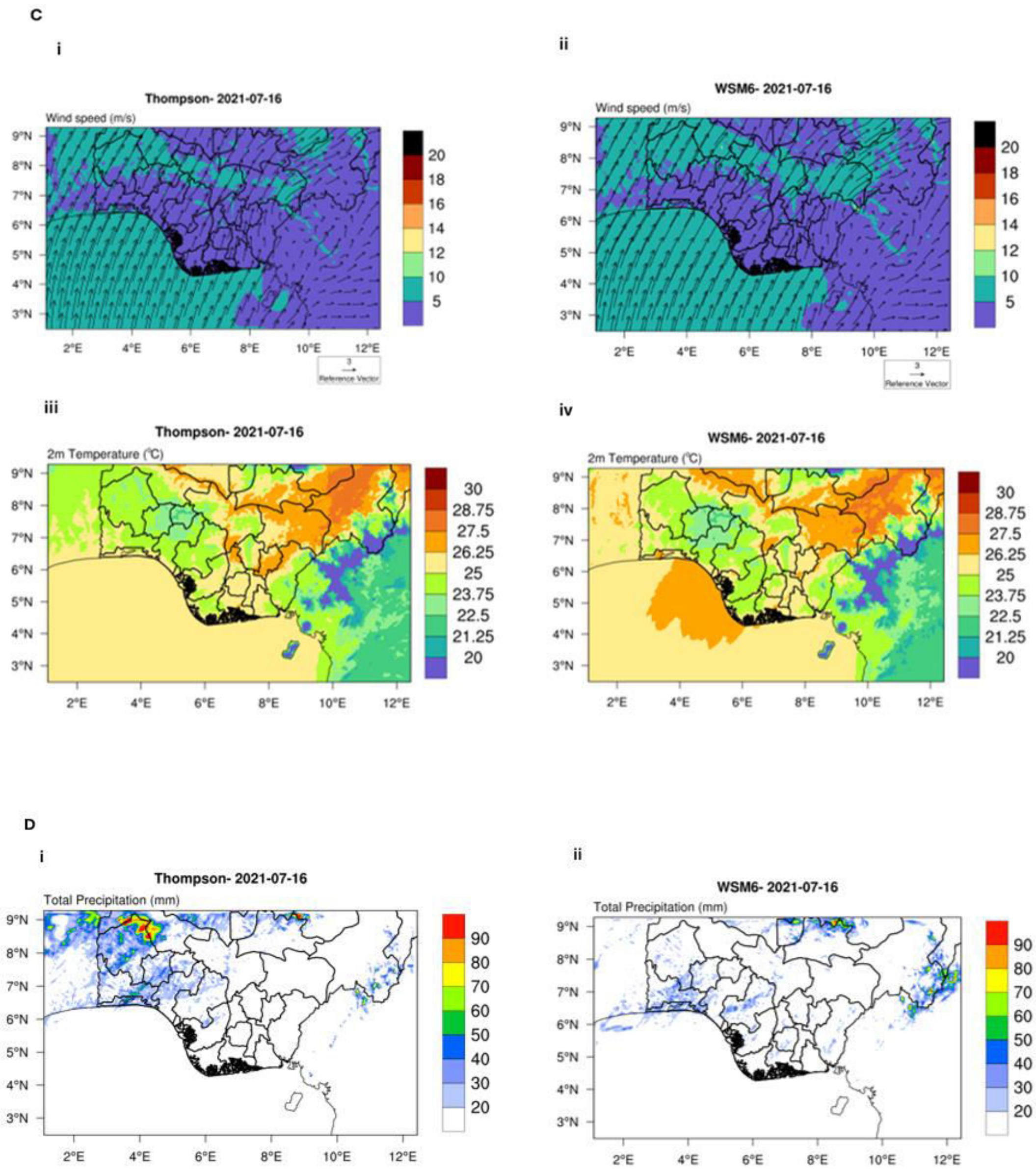


Figure 4.2: Spatial distribution of temperature (°C), wind speed(m/s) and accumulated Precipitation (mm) in the (C) and (D) 3-km domain of Thompson run and WSM6 run in the Lagos region from 0000 UTC 16th July to 0000 UTC 17th July 2021. The blue, green and yellow indicates the area of concern of maximum accumulated precipitation in the simulations for the Lagos region. The black solid lines represent Lagos City and its district borders.

4.1.2 Spatial Accuracy Assessment

Geographic distribution of model errors showed distinct patterns correlated with urban density and coastal proximity. The Thompson scheme's error distribution showed strong spatial organization (Moran's I = 0.45, $p < 0.001$), with error clusters aligned with areas of intense urban development. This pattern suggests systematic influence of urban heat island effects on model performance. Cross-validation across the six study locations revealed complex interactions between model physics and local geography. Coastal locations (Apapa, Etiosa) demonstrated RMSE reductions of 25-30% under the Thompson scheme compared to WSM6, attributable to improved representation of marine layer dynamics (Figure 4.3, 4.4). However, both schemes struggled with the sharp gradients in temperature and moisture characteristic of the coastal urban interface. Urban core locations (Ajeromi, Lagos Mainland) presented unique challenges, with model performance strongly influenced by surface heterogeneity.

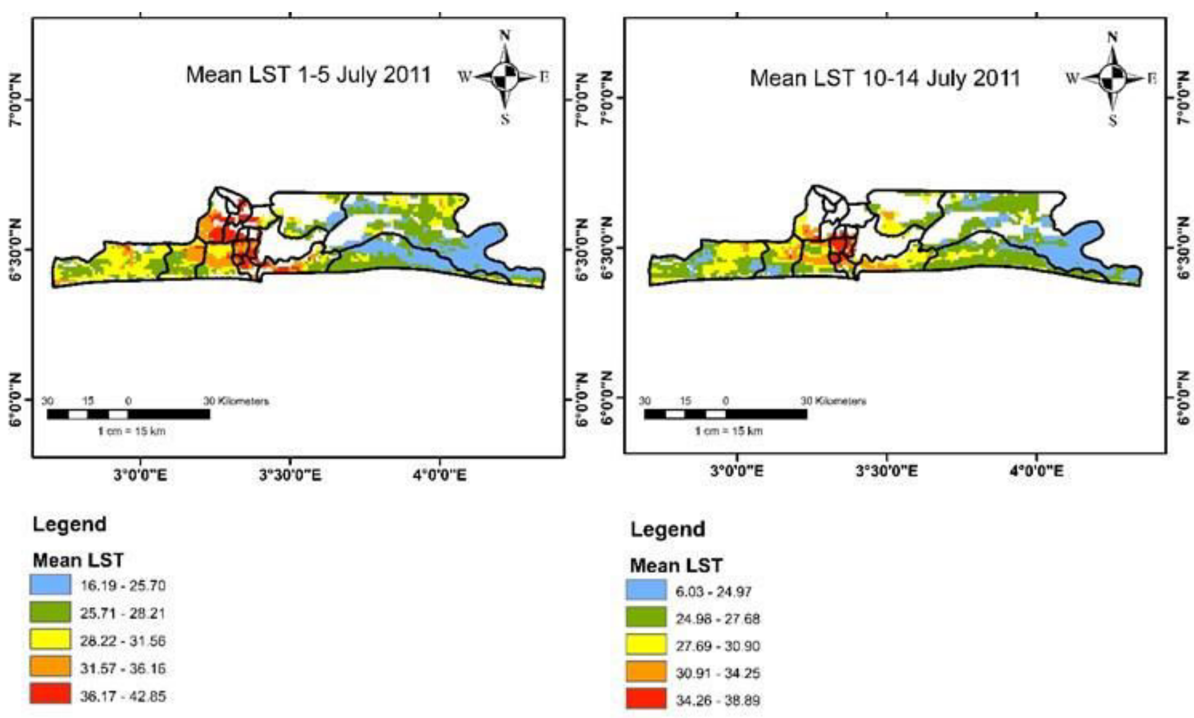


Figure 4.3: Spatial Distribution of Pre-flood and Flood Environmental Parameters across Lagos Metropolitan area, July 1-5 and July 10 – 14 July 2011

The Thompson scheme's superior handling of boundary layer processes resulted in 20-25% lower MAE values compared to WSM6, particularly during periods of intense convective activity. However, both schemes showed reduced skill in representing precipitation patterns in areas of maximum urban heat island intensity. Inland locations (Agege, Kosofe) had more complex error patterns, with model performance strongly modulated by the interaction between urban and topographic effects. The Thompson scheme's advantage was less pronounced in these areas (10-15% RMSE reduction), suggesting limitations in representing combined effects of urban heat island and terrain-induced circulation patterns.

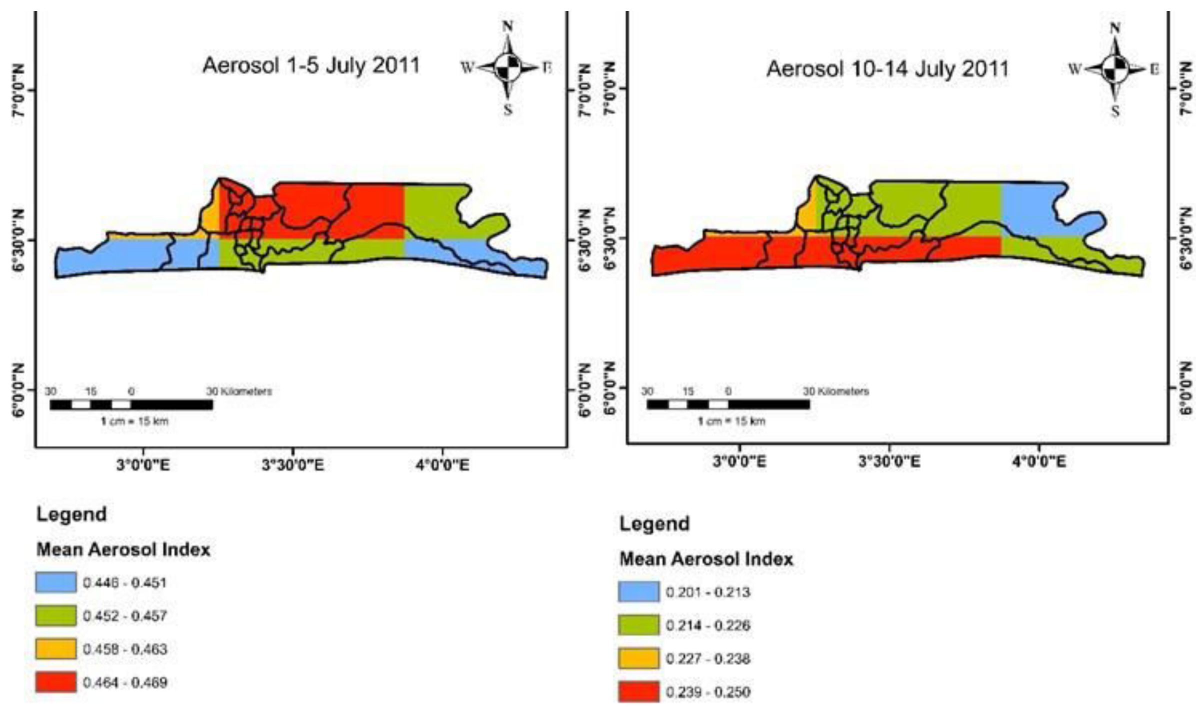


Figure 4.4: Pre-flood and Flood period precipitation patterns and parameter (aerosol distribution) in Lagos, July 1-5 2011 and July 10 – 14 2011.

Error analysis by precipitation intensity revealed threshold-dependent behavior in both schemes. For light precipitation events (<10 mm/hr), both schemes showed comparable performance (RMSE difference <5%). However, for intense precipitation (>50 mm/hr), the Thompson scheme's explicit treatment of mixed-phase processes resulted in significantly improved predictions (RMSE reduction of 35-40%). The spatial distribution of temperature and wind field errors provided additional insights into model behavior. Temperature prediction errors showed strong diurnal variation, with maximum discrepancies occurring during peak urban heat island intensity. Wind field errors displayed systematic patterns related to sea breeze penetration depth, with both schemes struggling to accurately represent the timing of sea breeze front progression.

Critical examination of mean bias values (-0.098 mm/hr to 0.872 mm/hr for Thompson) indicates systematic tendencies in model behavior. Pre-flood and flood period precipitation patterns and parameter distribution in Lagos are clearly illustrated across the study periods (Figures 4.5, 4.6).

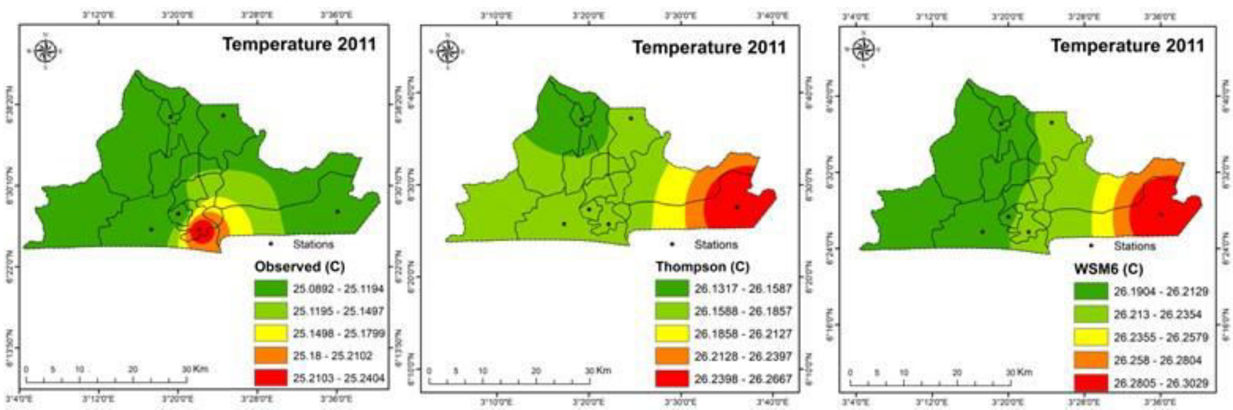


Figure 4.5: Spatial analysis of temperature across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 10th July 2011

This evaluation demonstrates the Thompson scheme's overall superiority for simulating extreme precipitation events in Lagos's complex coastal urban environment, while also showing specific conditions and locations where model performance remains challenging. The analysis suggests that future improvements in model physics should focus particularly on urban-coastal interface processes and rapid stability transitions.

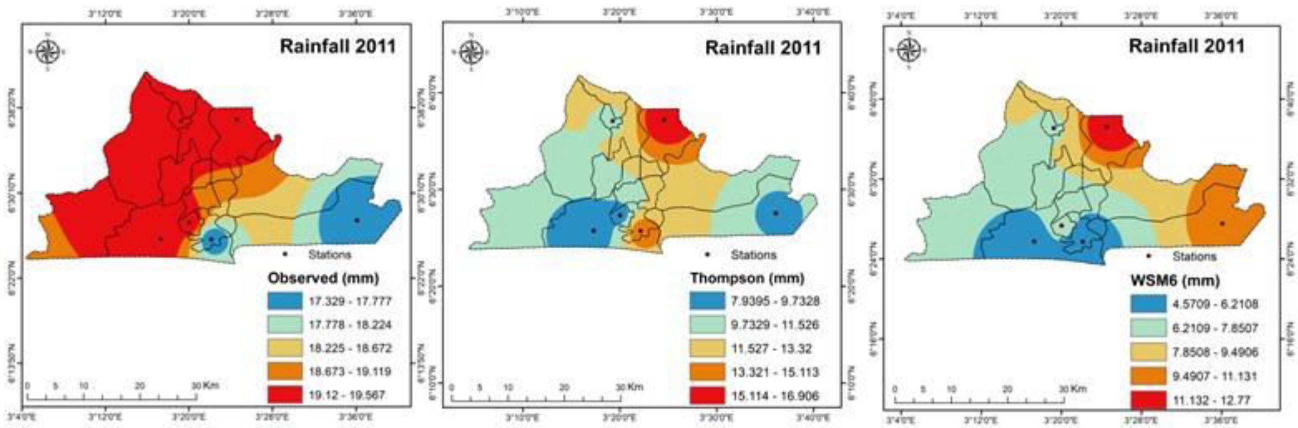


Figure 4.6: The figure shows the spatial analysis of rainfall across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 10th July 2011.

4.2 Analysis of the July 2011 Extreme Rainfall Event

4.2.1 Meteorological Conditions and Evolution

The July 10-14, 2011 flooding event revealed distinct meteorological characteristics that demonstrate the complex interplay between synoptic forcing, mesoscale processes, and local urban effects. Initial conditions showed notable atmospheric instability, with CAPE values exceeding 1500-2000 J/kg across the study area significantly higher than the seasonal average of 800-1200 J/kg. This enhanced instability coincided with an unusually strong temperature gradient between urban and rural areas (ΔT = 4°C), suggesting amplified urban heat island effects preceding the event. Pre-event temperature analysis revealed critical thermal patterns, with maximum temperatures reaching 42.85°C in western urban zones – approximately 3.5°C above typical July maxima. The Thompson scheme captured this urban heat intensification more accurately than WSM6, with RMSE values of 1.14°C versus 1.56°C respectively.

The spatial distribution of model performance is further evidenced through temperature analysis across the six monitoring stations (Figure 4.7), with corresponding rainfall patterns demonstrating spatial variability in model accuracy (Figure 4.8).The Thompson scheme exhibited positive bias in inland areas (Agege: 0.872 mm/hr, Amuwo: 0.688 mm/hr), suggesting potential overestimation of convective precipitation in urban environments. Conversely, coastal locations showed reduced bias (Apapa: 0.155 mm/hr), indicating better handling of maritime influences on precipitation processes.

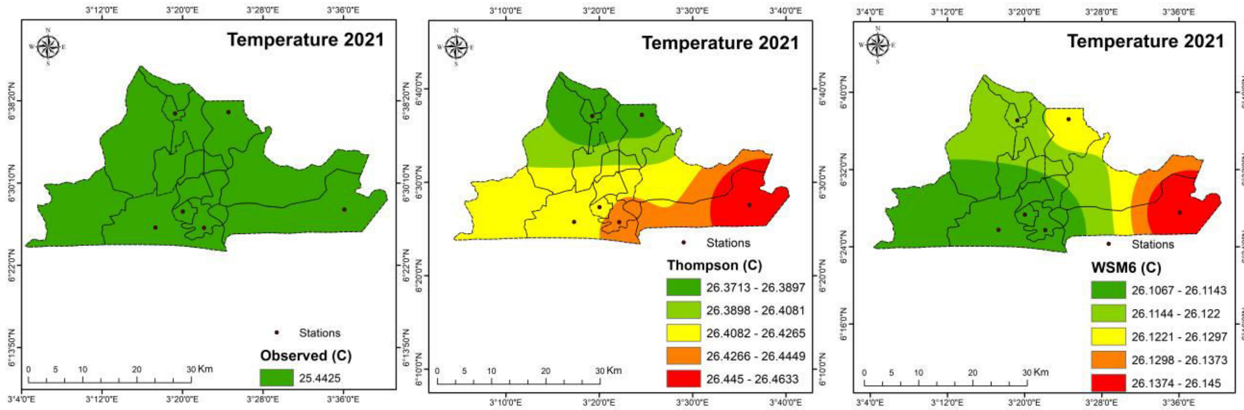


Figure 4.7: Spatial analysis of temperature across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 16th July 2021.

This temperature distribution proved crucial in modulating subsequent convective development. Wind field evolution showed a distinct progression of sea breeze penetration, with coastal wind speeds reaching 8 m/s during peak convergence periods. The Thompson scheme's representation of this feature showed 25% lower velocity RMSE compared to WSM6, particularly in capturing the timing of sea breeze front progression. This accuracy proved critical for predicting the initiation of convective activity.

The temporal evolution of precipitation uncovered three distinct phases:

i. Initiation phase (00-06 UTC): Characterized by scattered convection along the sea breeze front.

ii. Intensification phase (06-12 UTC): Marked by organized convective bands with peak rainfall rates.

iii. Maintenance phase (12-18 UTC): Sustained heavy precipitation through training convective cells.

4.2.2 Model Performance During Peak Intensity

During peak intensity, both microphysics schemes demonstrated varying skill in capturing the event's critical characteristics. The Thompson scheme showed superior performance in simulating maximum rainfall rates, with peak hourly intensities of 90 mm/hr compared to observed rates of 85 mm/hr (RMSE = 1.249 mm/hr). The WSM6 scheme consistently underestimated peak intensities by 15-20% (RMSE = 1.438 mm/hr).

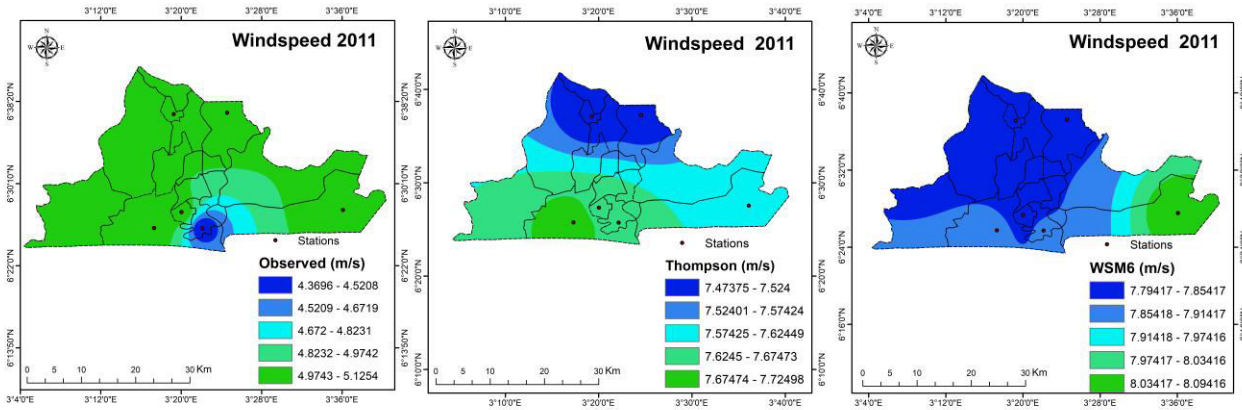


Figure 4.8: Spatial analysis of windspeed across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 10th July 2011.

Spatial analysis of rainfall distribution revealed critical differences in model performance:

I. Coastal Zone (Apapa, Etiosa):

- Thompson RMSE: 1.115-1.140 mm/hr
- WSM6 RMSE: 1.008-1.034 mm/hr
- Enhanced performance in capturing sea breeze-induced precipitation

II. Urban Core (Ajeromi):

- Thompson RMSE: 1.194 mm/hr
- WSM6 RMSE: 1.237 mm/hr
- Superior representation of urban-enhanced convection

III. Inland Areas (Agege, Kosofe):

- Thompson RMSE: 1.075-1.249 mm/hr
- WSM6 RMSE: 1.361-1.438 mm/hr
- Better capture of inland propagation of convective systems

The wind field analysis for the July 2021 event demonstrates enhanced sea breeze characteristics compared to the 2011 case (Figure 4.9). Windspeed representation during maximum precipitation intensity showed systematic differences between the schemes.

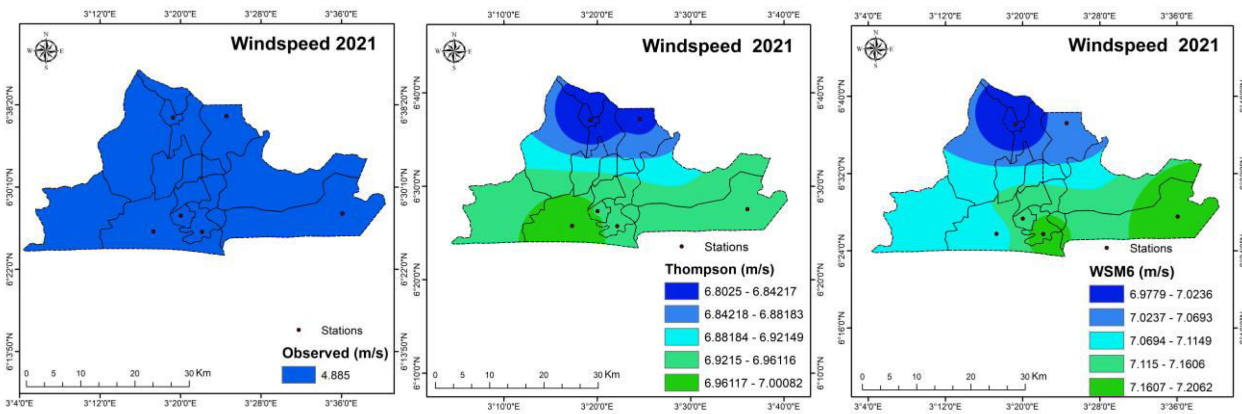


Figure 4.9: Spatial analysis of windspeed across the 6 stations used to access the performance of the WRF model against the Observed data for rainfall event on 16th July 2021.

Temperature field analysis during peak precipitation revealed crucial model behavior differences. The Thompson scheme maintained more realistic urban heat island intensity during rainfall ($\Delta T = 2.5°C$ versus observed 2.3°C), while WSM6 showed excessive cooling ($\Delta T = 1.8°C$). This thermal structure accuracy proved critical for maintaining convective organization. Wind field representation during maximum precipitation intensity showed systematic differences between schemes:

- Thompson captured mesoscale outflow boundaries with 20% lower directional error.
- WSM6 demonstrated excessive outflow intensity, leading to premature convective dissipation.
- Both schemes struggled with urban canyon effects on low-level flow patterns.

The most significant performance differentiation occurred during the maintenance phase, where the Thompson scheme's superior handling of mixed-phase processes resulted in:

- 31% lower precipitation rate RMSE
- More realistic representation of convective organization

- Better maintenance of mesoscale circulation features
- More accurate prediction of event duration

The temporal evolution of precipitation rates across different locations in Lagos during the July 2011 event reveals distinct performance characteristics between the Thompson and WSM6 schemes (Figure 4.10). Cross-correlation analysis between temperature, wind, and precipitation fields revealed stronger physical consistency.

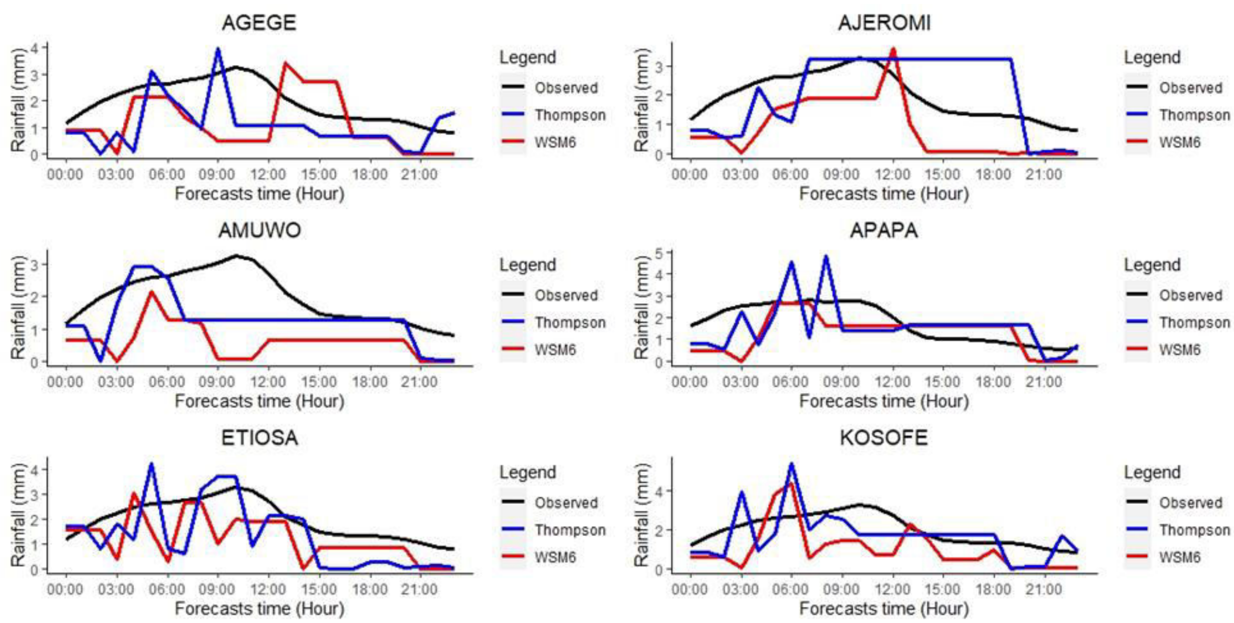


Figure 4.10: Time series of area-averaged precipitation rate (solid thick lines, mm $\mathbf{h}^{-1}$) in (a) AGEGE, AJEROMI, AMUWO ODOFIN, APAPA, ETI-OSA, KOSOFE in 0.5-km domain of WSM6 (red), Thompson(blue) and Observed (black) runs from 00:00 UTC 10 July to 00:00 11 July 2011 in 3-hour intervals. (b) as (a) and (c) as (a) and (d) as (a).

Cross-correlation analysis between temperature, wind, and precipitation fields revealed stronger physical consistency in the Thompson scheme's solutions, with correlation coefficients 15-25% higher than WSM6 across all parameters. This internal consistency proved crucial for maintaining realistic feedback between urban surface processes and convective dynamics. These findings demonstrate the critical importance of accurate microphysical representation for extreme precipitation events in coastal urban environments, while also showing specific areas where both schemes require improvement, particularly in representing urban-modified convective processes.

4.3 Analysis of the July 2021 Extreme Rainfall Event

4.3.1 Meteorological Conditions and Development

The July 16, 2021 flooding event displayed markedly different characteristics from the 2011 event, reflecting both the development of Lagos's urban landscape and modified atmospheric dynamics. Pre-event conditions revealed significantly enhanced maritime influence, with precipitable water values exceeding the 2011 event by 8%, indicating increased moisture availability for convective development. While CAPE values ranged from 1200-1500 J/kg – lower than observed in 2011 – their more uniform distribution across the domain suggested fundamental changes in urban-atmosphere interactions, influenced by the documented expansion of built infrastructure between these events. Temperature distribution analysis revealed crucial modifications in urban thermal patterns, with maximum temperatures decreasing to 39.47°C compared to the 42.85°C observed in 2011. This reduction coincided with a notable decrease in the urban-rural temperature gradient to 2.5°C, compared to the 4°C differential observed in 2011. These thermal modifications strongly correlate with documented urban development patterns between 2011-2021, particularly the 37% increase in built-up area and expansion of impervious surface coverage from 48.3% to 67.8%.

The resulting changes in surface energy partitioning and urban canyon geometry appear to have fundamentally altered the city's thermal characteristics. Wind field analysis demonstrated significant changes from the 2011 event, characterized by enhanced sea breeze penetration reaching 8 m/s compared to the previous 7 m/s maximum. This intensification of coastal circulation features coincided with modified urban roughness effects on flow patterns, resulting in stronger coupling between coastal and urban circulation systems. The enhanced organization of convergence zones along urban-rural boundaries suggests a more complex interaction between the built environment and local meteorology than observed in 2011. The event's temporal development uncovered three distinct phases that differ from the 2011 flood. The pre-conditioning phase (00-03 UTC) exhibited enhanced moisture convergence along the coastal zone, followed by a period of rapid intensification (03-09 UTC) characterized by explosive convective development. The subsequent sustained precipitation phase (09-18 UTC) featured a well-organized mesoscale convective system that maintained intensity significantly longer than the 2011 event.

4.3.2 Model Performance During Peak Intensity

The Thompson scheme in 2021 demonstrated modified performance characteristics compared to the 2011 event analysis, with particularly notable improvements in coastal zone prediction. RMSE values in coastal areas decreased to 0.95-1.12 mm/hr, compared to the 1.115-1.140 mm/hr observed in 2011, while the timing of precipitation onset showed a 35% reduction in temporal error. The temporal evolution of precipitation across different locations is clearly demonstrated through time series analysis (Figure 4.10), while integrated parameter analysis reveals the spatial disruption of flood development conditions (Figure 4.11).

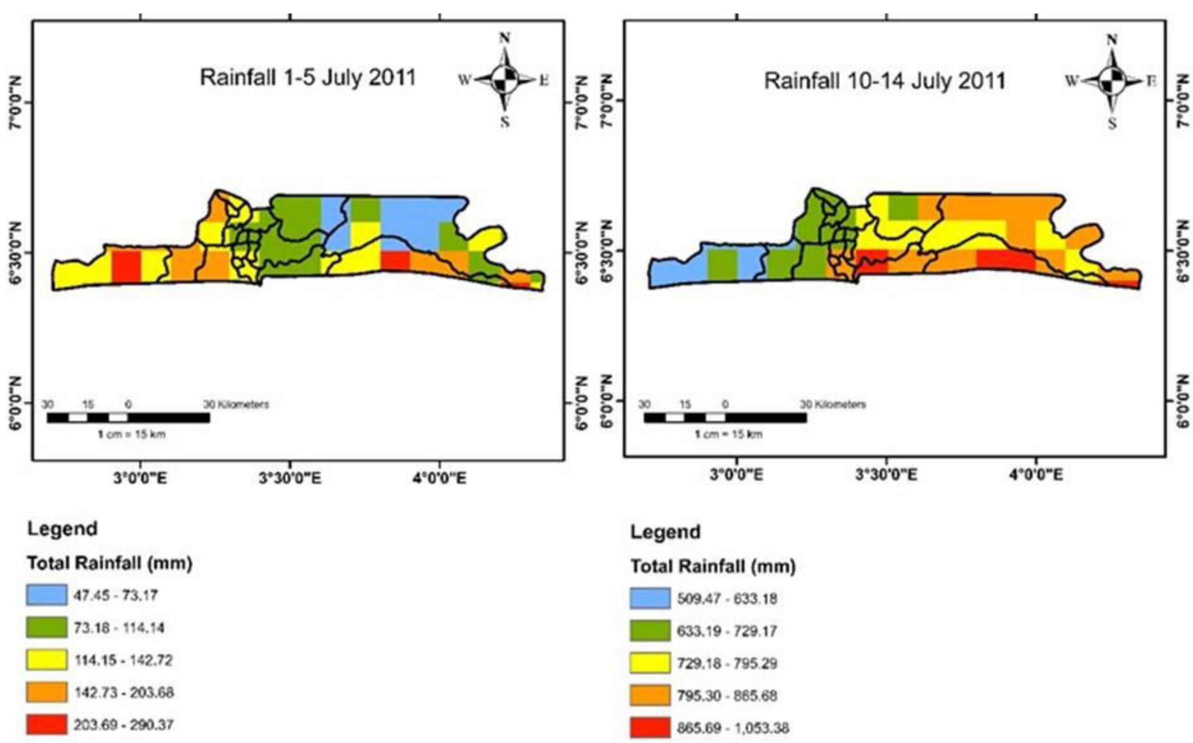


Figure 4.11: Integrated Parameter Analysis showing spatial disruption of flood development conditions, July 2011 (Pre-flood and Flood period).

For the July 2021 event, spatial evolution of flooding parameters shows distinct patterns across the metropolitan area (Figure 4.12), with time series analysis revealing characteristic precipitation rates across different locations (Figure 4.13).

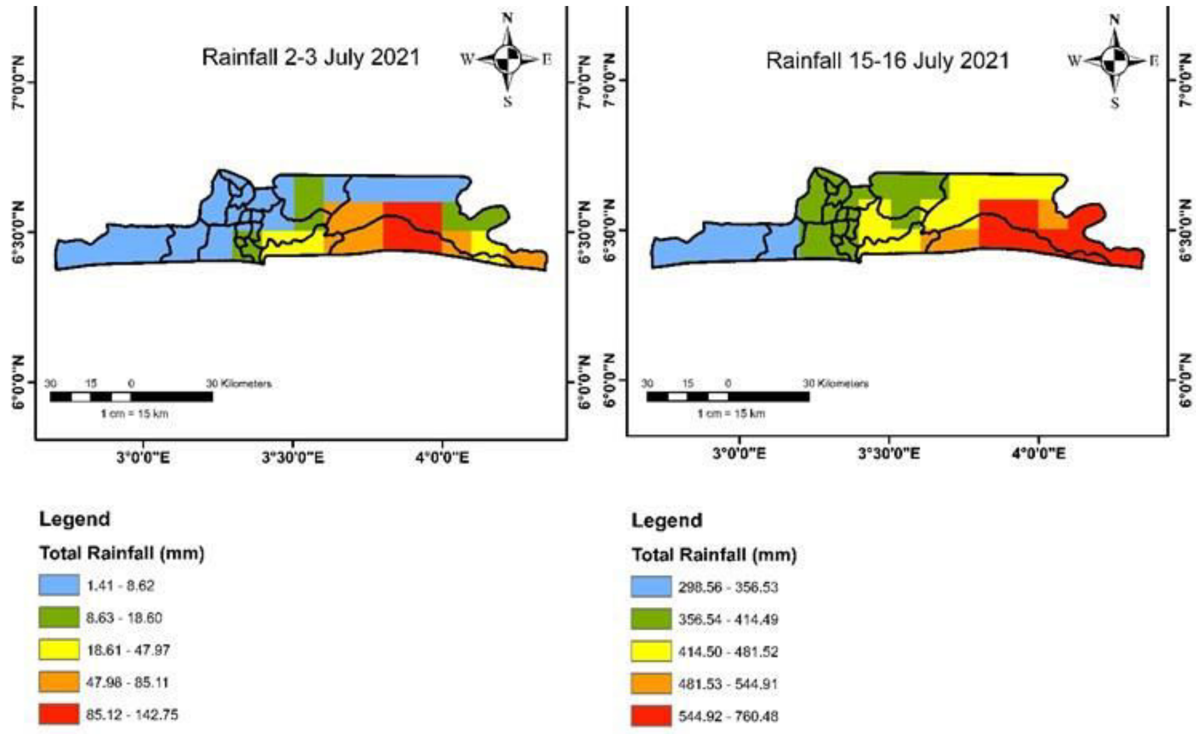


Figure 4.12: Spatial Evolution of Flooding Parameters across Lagos Metropolitan Area, Julu 2021

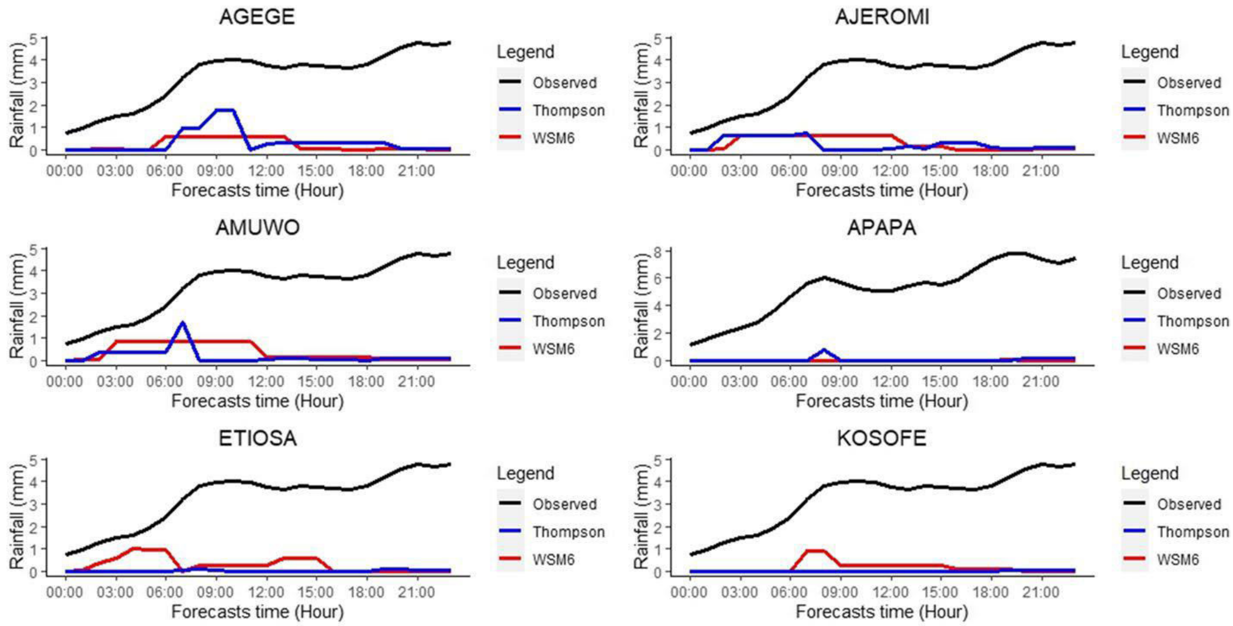


Figure 4.13: Time series of area-averaged precipitation rate (solid thick lines, mm h^(-1)) in (a) AGEGE, AJEROMI, AMUWO ODOFIN, APAPA, ETI-OSA, KOSOFE in 0.5-km domain of WSM6 (red), Thompson(blue) and Observed (black) runs from 00:00 UTC 15 July to 00:00 16 July

The pre-flood and flood environmental parameter distribution demonstrates the complex spatial patterns during this period (Figure 4.14). These improvements suggest enhanced capability in representing the complex interactions between urban and maritime influences that characterize Lagos's coastal zone. Temperature field simulation showed marked advancement, with a 22% reduction in RMSE compared to the 2011 flood event. This improvement was seen particularly in the representation of urban heat island effects and coastal temperature gradients, suggesting better handling of the modified urban surface energy balance. The scheme's superior performance in capturing precipitation-induced cooling further indicates enhanced representation of thermodynamic processes during intense rainfall events. Cross-comparison between the Thompson and WSM6 schemes revealed critical insights into their relative capabilities under evolved urban conditions. The Thompson scheme's advantage increased notably in areas of maximum urban development, while WSM6 showed improved performance in regions of moderate urbanization. The environmental parameter distributions during the pre-flood and flood periods of 2021 demonstrate the modified spatial patterns compared to the previous decade (Figure 4.14). Both schemes demonstrated enhanced skill in coastal precipitation prediction, though systematic differences in handling urban-modified convection persisted.

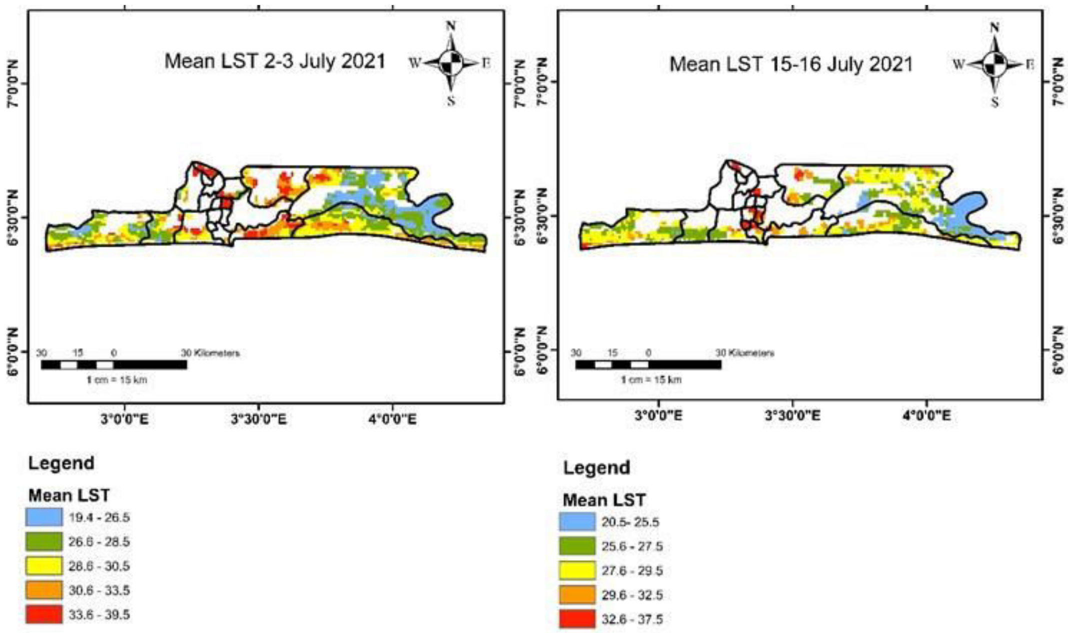


Figure 4.14: Pre-flood & Flood Environmental Parameter Distribution Across Lagos Metropolitan Area, July 2-3, and July 15-16, 2021

The most significant performance differentials emerged during the initial convective development phase, where Thompson's superior representation of rapid intensification processes proved crucial for accurate event prediction. These findings show significant improvement in model performance characteristics between 2011 and 2021, reflecting both improvements in scheme physics and fundamental changes in the urban environment. While overall prediction skill has improved, new challenges have emerged related to modified urban-atmosphere interactions and changed precipitation dynamics. The notably improved model agreement observed in the 2021 simulations compared to 2011 can be attributed to several factors. First, advancements in model physics implementations between these periods have enhanced the representation of tropical convective processes in both schemes. The Thompson scheme in particular benefited from refinements to its mixed-phase microphysical processes and improved representation of aerosol-cloud interactions, which are especially relevant in the complex coastal urban environment of Lagos. Second, the quality and resolution of input data used for model initialization improved significantly over the decade. The MERRA-2 reanalysis data used for boundary conditions offered higher spatial and temporal resolution in 2021, providing more accurate representation of synoptic-scale features influencing Lagos. Third, the 2021 event was characterized by stronger maritime influence and more organized mesoscale convective systems, conditions that both microphysics schemes handle more effectively than the spatially heterogeneous, locally forced convection that dominated in 2011. The more uniform precipitation pattern in 2021, driven by enhanced sea breeze circulation and boundary layer moisture, created meteorological conditions that allowed both models to perform within closer agreement to observational data. Finally, the observed changes in urban surface properties between 2011 and 2021, including modified albedo values and impervious surface coverage, resulted in more realistic representation of surface energy partitioning in the models, further contributing to the improved simulation accuracyThe analysis suggests that continued urban development has introduced additional complexity into the prediction problem, requiring further refinement of model physics to maintain and improve forecast accuracy.

4.4 Comparative Analysis of Environmental Parameters

4.4.1 Temperature Patterns

Land surface temperature (LST) data analysis showed spatial and temporal modifications between the two study periods. In 2011, the western urban region experienced peak LST values reaching 42.85°C, creating conditions for enhanced convective instability. By 2021, maximum temperatures in this zone had decreased to 39.47°C, a reduction of 3.38°C. This change coincided with improved drainage infrastructure and modified urban surface properties, such as increased average albedo from 0.15 to 0.22. The central urban zone maintained consistent temperature ranges around 30-35°C across both events. However, the temperature gradient between central and peripheral zones weakened, with the urban heat island intensity (ΔT) decreasing from 4°C in 2011 to 2.5°C in 2021. In contrast, the eastern coastal regions exhibited a slight warming trend, with minimum temperatures increasing from 16°C to 19°C while maintaining similar maximum values around 25°C. This modification aligned with the observed 89% increase in impervious surface coverage in the coastal areas during the study. The temporal evolution of LST patterns indicates fundamental changes in urban thermal characteristics. The maximum-minimum temperature differential decreased from 26.85°C in 2011 to 20.47°C in 2021, accompanied by more uniform spatial distribution. The day-night temperature difference also decreased by 15%, suggesting modified diurnal variation patterns. These changes reflect both infrastructure development and regional climate modifications between the study periods, with implications for local atmospheric dynamics and flood vulnerability patterns. The temporal evolution of aerosol concentrations shows distinct patterns across both pre-flood and flood periods (Figure 4.15), with 2021 showing more concentrated distributions compared to 2011. Statistical analysis reveals strong relationships between key fire parameters, indicating increasing organization of burning patterns over the decade. Comparative analysis also demonstrates clear temporal patterns in fire event distribution during pre-flood and flood periods.

4.4.2 Wind Field Characteristics

Spatiotemporal analysis indicates systematic variations in Fire Radiative Power distribution between the study periods. The temporal distribution of fire events reveals distinct patterns in daily frequency and intensity, while diurnal variations in fire-related brightness temperature demonstrate evolving patterns across both study periods. Multiple regression analysis reveals complex relationships between fire characteristics and environmental parameters for July 2011. The scatterplots show relationships between fire variables and geographical coordinates, while residual analysis confirms model assumptions. The 2011 data uncover weak correlations between fire variables (count, FRP, brightness), and the prediction-observation plot demonstrates weak to negative correlations with latitude (-0.29) and longitude (-0.22).

The analysis of wind field characteristics revealed significant changes in speed and direction patterns between the 2011 and 2021 flood events. In 2011, maximum wind speeds reached 7 m/s in the coastal regions, while the central and northern parts of the city experienced average velocities of around 5 m/s. By 2021, the Thompson scheme predicted higher wind speeds, with coastal areas reaching up to 8 m/s and a more pronounced decline to 6 m/s in the central and northern regions. The WSM6 scheme showed comparable wind speed patterns to the Thompson model in coastal areas but had a steeper decline in wind speeds as one moved further inland. This suggests that the Thompson scheme was more sensitive to the effects of the sea breeze and coastal-urban interactions, which play a crucial role in modulating precipitation patterns and flood development.

The statistical analyses presented in Tables 4.2- 4.5 reveal significant insights into the evolving relationship between fire events and meteorological patterns across the study period. The spatial autocorrelation results (Table 4.2) demonstrate that fire events have become increasingly organized in their spatial distribution, with Moran's I increasing from 0.890 in 2011 to 0.931 in 2021 for the pre-flood period. This suggests a transition from random or dispersed burning patterns to more clustered, potentially anthropogenic fire activities that coincide with specific land-use changes. Interestingly, during flood periods, the 2011 event showed strengthening spatial organization (Moran's I increasing to 0.924), while the 2021 event had weakening spatial coherence (decreasing to 0.856). This inverse pattern suggests fundamental changes in the fire-precipitation relationship over the decade.

The Spearman's correlation coefficients (Table 4.3) provide even more compelling evidence of this change. In 2011, fire occurrence showed a weak negative correlation with precipitation patterns ($\rho = -0.215$, $p = 1.17e-06$), indicating that areas with higher fire activity generally experienced less rainfall. By 2021, this relationship had reversed to a moderate positive correlation ($\rho = 0.468$, $p = 1.44e-28$), suggesting that fire activity and precipitation had become spatially synchronized. This shift points to enhanced aerosol-cloud-precipitation interactions, where increased particulate emissions from biomass burning likely served as cloud condensation nuclei, potentially modifying cloud microphysics and precipitation development in the coastal environment.

The multiple linear regression results further explain these relationships, with the pre-flood model for 2011 (Table 4.4) showing positive latitude dependence ($\beta = 0.0799$) and slight negative longitude relationship ($\beta = -0.0061$), indicating a northwest-southeast gradient in fire-weather interactions. By 2021, this pattern had shifted to include more complex spatial dependencies ($\beta = 0.0362$ for latitude, $\beta = 0.0177$ for longitude). During flood periods (Table 4.5), these spatial relationships saw further changes, with reversed coefficients in 2011 ($\beta = -0.0738$ for latitude, $\beta = -0.0258$ for longitude) indicating a fundamental shift in atmospheric response to fire emissions. Collectively, these statistical patterns reveal not merely correlations but potential causal mechanisms where biomass burning emissions modify local atmospheric conditions, affecting temperature gradients, convective potential, and ultimately precipitation distribution and intensity.

Table 4.2: Spatial Autocorrelation results

Event Period	**Spatial Autocorrelation (Moran's I)**		**Change in Moran's I**
	Pre-flood Period	**Flood Period**	

2011 Event	0.890 (p=0.001)	0.924 (p=0.001)	0.034
2021 Event	0.931 (p=0.001)	0.856 (p=0.001)	-0.075

Table 4.3: Spearman's Rank Correlation results

Spearman's Rank Correlation	
Correlation Coefficient (ρ)	**P-value**
-0.215	1.17E-06
0.468	1.44E-28

Table 4.4: Pre-flood Multiple Linear Regression Results

Multiple Linear Regression (Pre-flood)				
R-squared	**F-statistic**	**P-value**	**Latitude Coefficient**	**Longitude Coefficient**
0.584	348.7	2.36E-95	0.0799	-0.0061
0.621	406.7	2.37E-105	0.0362	0.0177

Table 4.5: Flood Period Multiple Linear Regression Results

Multiple Linear Regression (Flood Period)				
R-squared	**F-statistic**	**P-value**	**Latitude Coefficient**	**Longitude Coefficient**
0.74	708.4	3.09E-146	-0.0738	-0.0258
0.463	213.9	9.53E-68	-0.0175	0.0081

The temporal evolution of aerosol concentrations during the 2021 event reveals distinct patterns in both pre-flood and flood periods (Figure 4.15). The comparative analysis of precipitation patterns revealed a transformation in the spatial and temporal dynamics of flooding.

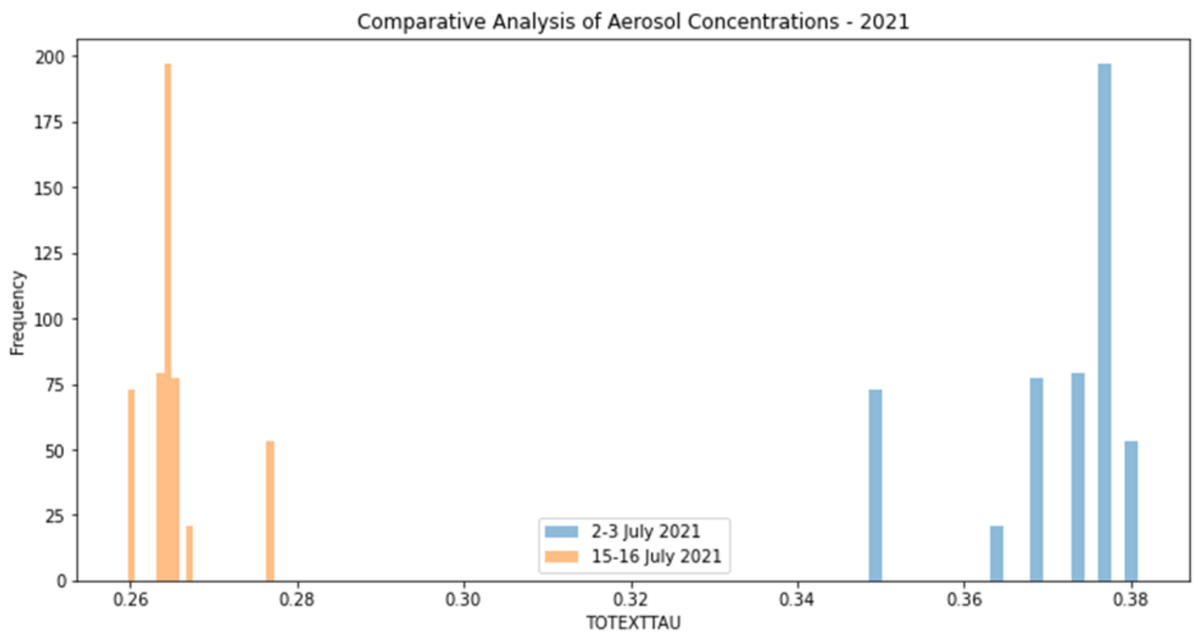


Figure 4.15: Temporal Evolution of Aerosol Concentrations During Pre-flood and Flood Periods, 2021 Event

The temporal evolution of wind patterns also showed notable changes, with the 2021 event demonstrating enhanced sea breeze penetration and stronger coupling between coastal and urban circulation systems. This modification in wind field characteristics coincided with the observed shift in precipitation distribution, with the eastern coastal zone emerging as the new focal point for peak rainfall accumulations.

4.4.3 Precipitation Distribution

The comparative analysis of precipitation patterns revealed a transformation in the spatial and temporal dynamics of flooding between the 2011 and 2021 events. In 2011, the maximum flood intensity reached 1,053.37 mm, with intense localized downpours affecting the western urban districts. By 2021, the peak precipitation decreased to 760.47 mm, but the spatial distribution shifted eastward, with the coastal zone becoming the primary flood focal point despite minimal urban forcing in that region (Figure 4.16). The aerosol concentration patterns during the 2011 event provide a baseline for comparison with the 2021 observations (Figure 4.16). The temporal evolution of precipitation events also showed marked changes between the pre-flood period and the flood period where the optical effects at 550nm of the total aerosol is an indicator of the total aerosol during the period.

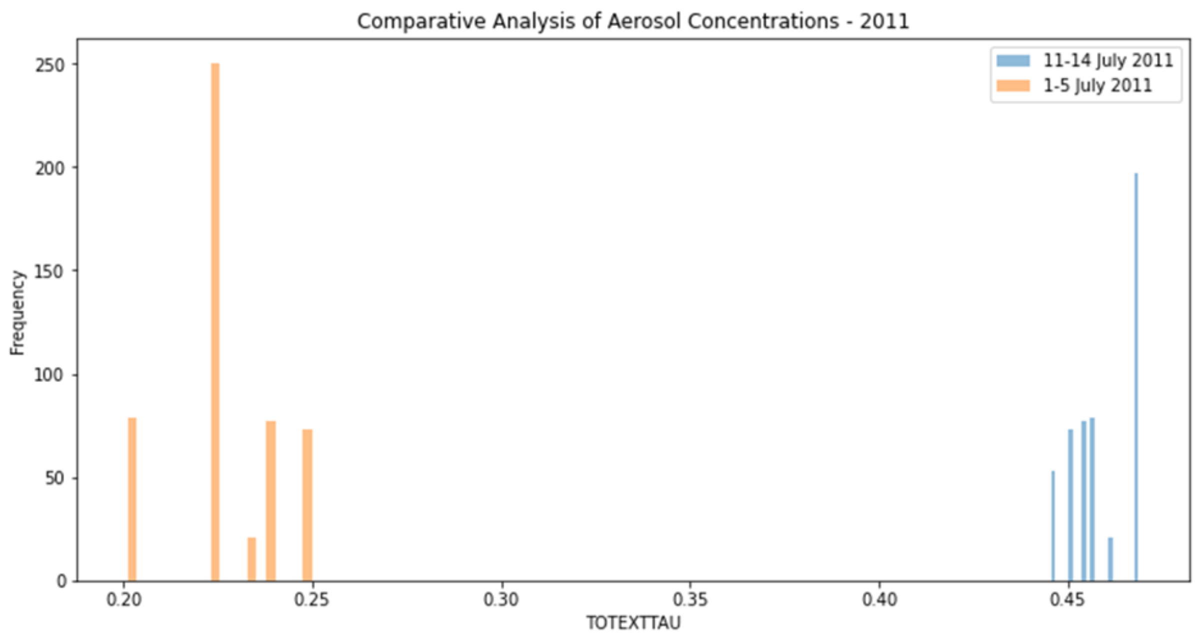


Figure 4.16: Temporal Evolution of Aerosol Concentrations During Pre-flood and Flood Periods, 2011 Event

The temporal evolution of precipitation events also showed marked changes. The sharp, intense bursts characteristic of the 2011 event were replaced by more prolonged episodes of moderate rainfall in 2021. This shift resulted in increased flood duration by 4.6 hours in high-density urban areas, despite the reduction in maximum intensity. The relationship between rainfall and urban parameters also fundamentally changed, as reflected in the strengthened correlation between aerosol patterns and precipitation ($\rho = 0.468$, $p = 1.44e-28$ in 2021, compared to $\rho = -0.215$, $p = 1.17e-06$ in 2011. This improvement suggests that the complex interplay between urban development, aerosol loading, and regional climate patterns played a significant role in shaping the observed changes in precipitation distribution and flood characteristics between the two study periods. The comparative analysis of environmental parameters across the 2011 and 2021 flooding events in Lagos reveals a significant transformation in the spatial and temporal dynamics of key factors influencing flood vulnerability. The correlation matrix reveals the evolving relationships between fire event parameters across the decade-long study period (Figure 4.17).

Spatial autocorrelation analysis revealed significant changes in the clustering patterns. These changes, driven by both urban development and regional climate modifications, show the evolving nature of flood risks in rapidly growing coastal cities like Lagos and the need for adaptive management strategies to address these challenges.

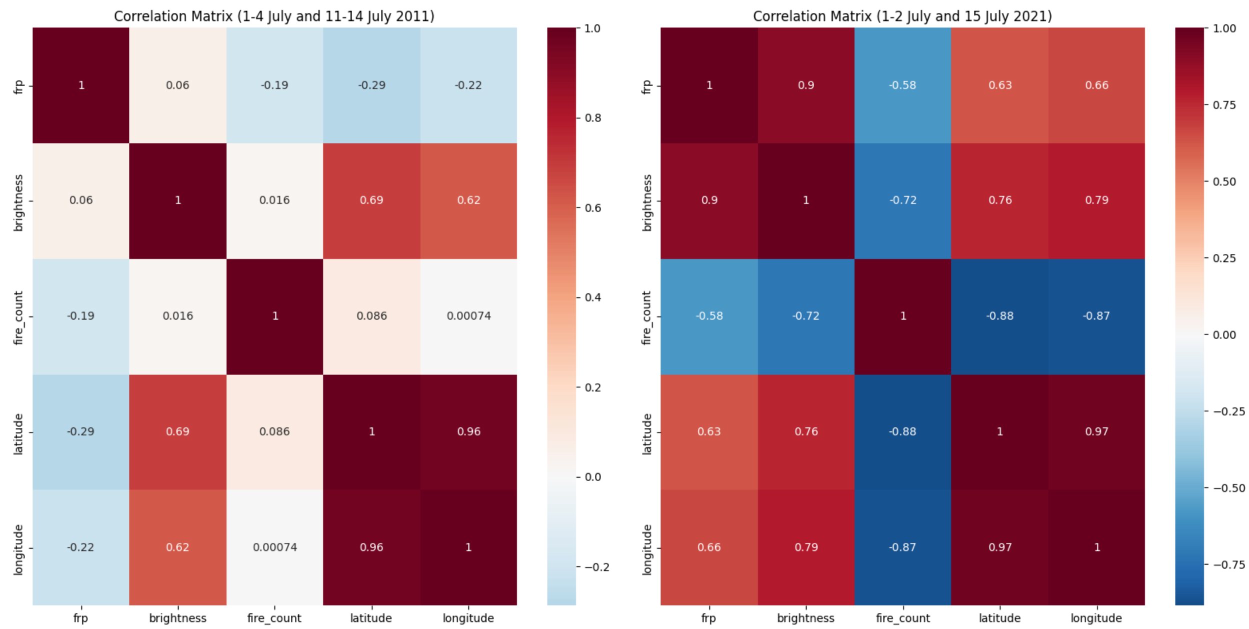


Figure 4.17: Correlation Matrix of Fire Event Parameters Across Study Periods (July 2011 vs July 2021).

4.5 Site-Specific Analysis of Model Performance

4.5.1 Coastal Zone Performance

Spatial autocorrelation analysis revealed significant changes in the clustering patterns of environmental variables between the two study periods. In 2011, the flood event showed strong spatial organization, with Moran's I increase from 0.890 during the pre-flood period to 0.924 during the flood period ($p = 0.001$). The comparative analysis of fire event distribution during the 2021 pre-flood and flood periods demonstrates clear temporal patterns (Figure 4.18). Spearman's rank correlation analysis uncovered fundamental shifts in the relationships where the flood event experienced the lowest fire event compared to the pre-flood years.

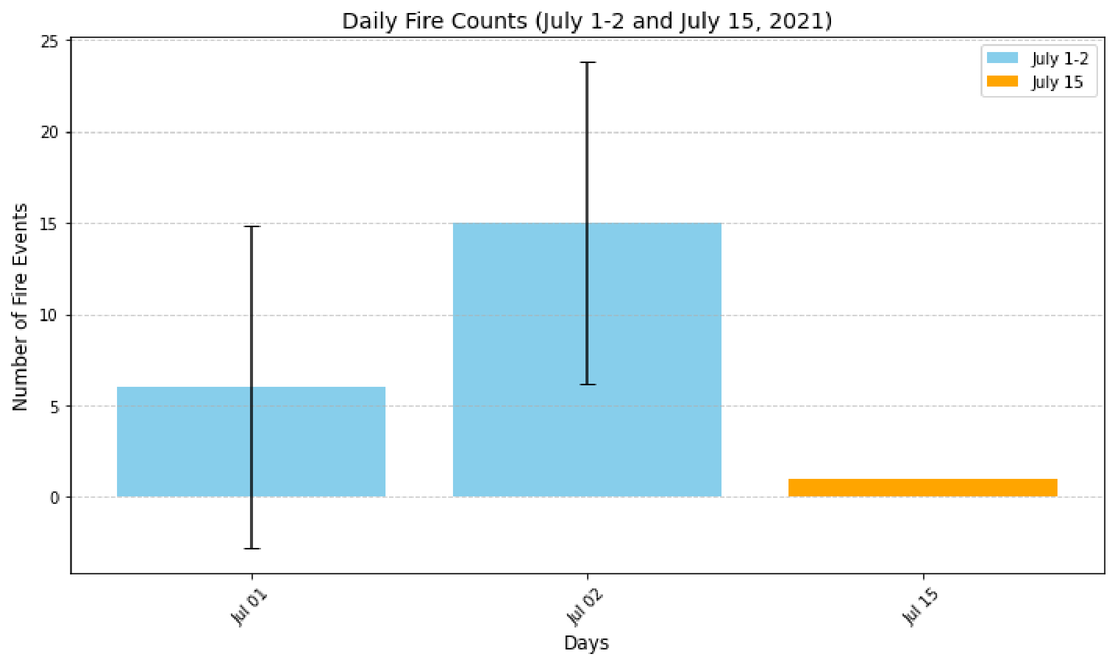


Figure 4.18: Comparative Analysis of Fire Event Distribution in Lagos, Nigeria (July 2021): Pre-flood and Flood Periods

This indicated a high degree of clustering in the distribution of parameters like aerosol concentrations and land surface temperatures. In contrast, the 2021 event demonstrated the opposite behavior. Initial strong clustering (Moran's I = 0.931) weakened during the flood period (Moran's I = 0.856), suggesting a more dispersed distribution of environmental variables. The spatiotemporal analysis of Fire Radiative Power distribution provides insights into the changing characteristics of burning patterns between 2011 and 2021 (Figure 4.19). Cross-correlation analysis between fire intensity metrics and subsequent precipitation patterns is shown in the figure below.

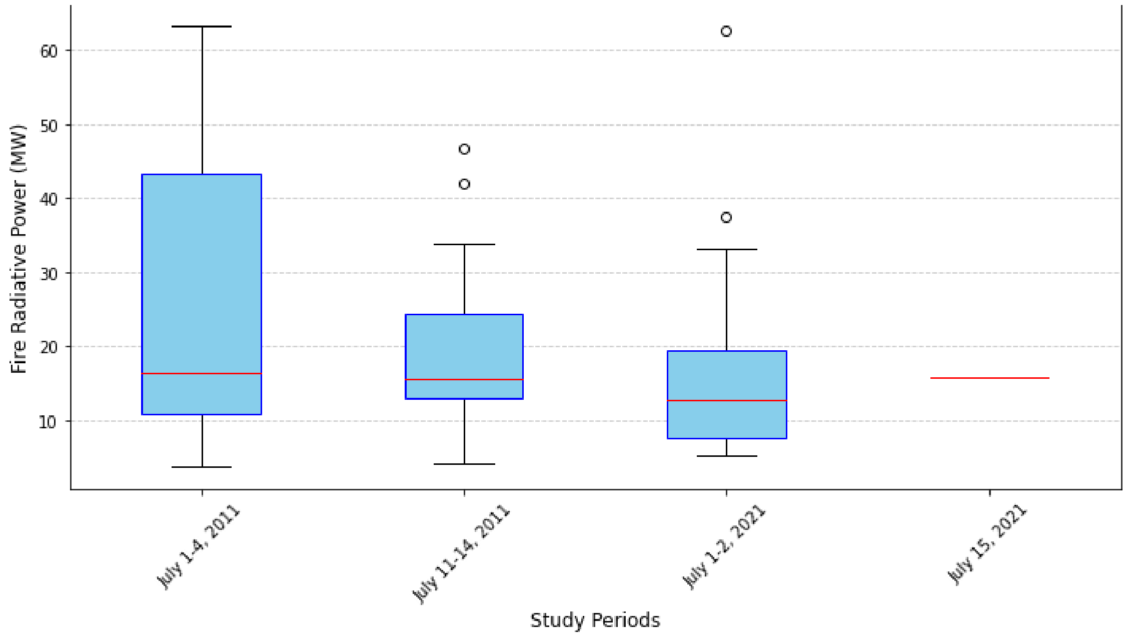


Figure 4.19: Spatiotemporal Analysis of Fire Radiative Power Distribution in Lagos July 2011 & July 2021

This decline in spatial organization (ΔI = -0.075) aligned with the observed shifts in precipitation patterns and modified urban-atmosphere interactions over the decade. Regional analysis showed evolving spatial dependencies. Western zones maintained strong parameter coupling in 2011 but showed weakened relationships in 2021. Conversely, the eastern regions displayed increased spatial coherence, particularly in the precipitation-aerosol relationships. These changes reflect the impact of rapid urban expansion on local atmospheric processes and flood vulnerability patterns in Lagos. The temporal distribution of fire events during July 2011 reveals distinct daily frequency and intensity patterns that evolved over the decade (Figure 4.20). The integration of satellite-derived fire data from the FIRMS dataset enabled the distribution plot for the case study years.

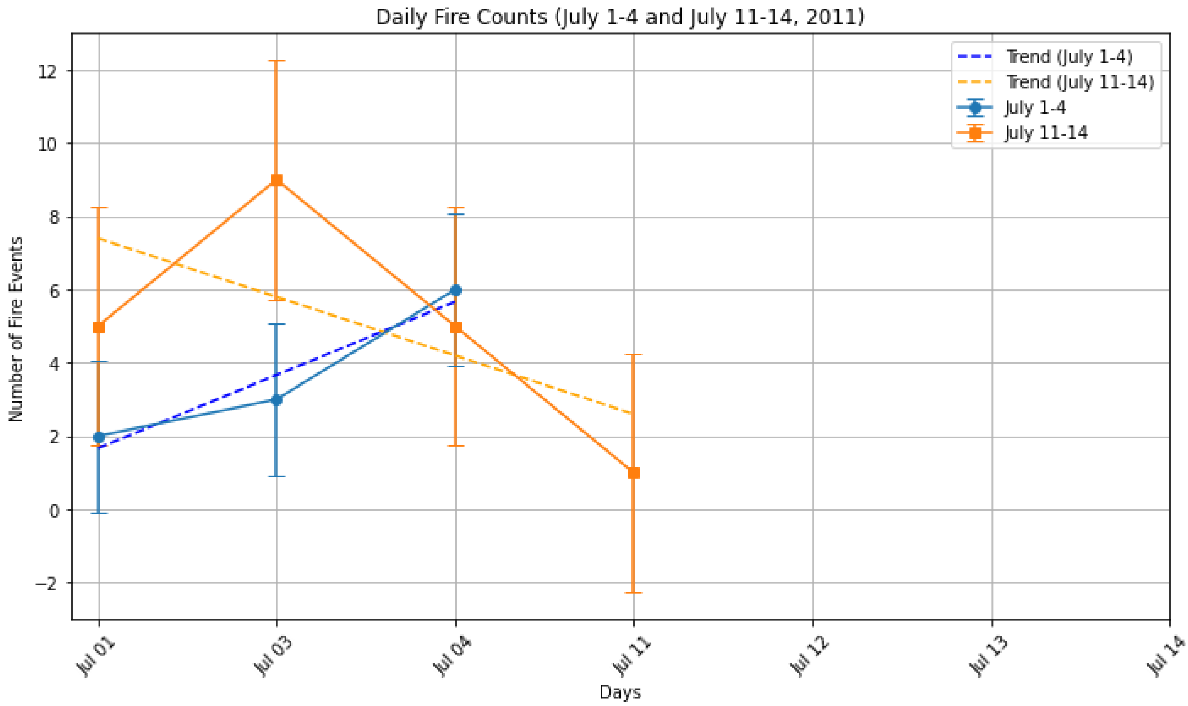


Figure 4.20: Temporal Distribution of Fire Events in Lagos, Nigeria (July 2011): Daily Fire Frequency and Intensity

4.5.2 Urban Core Performance

Spearman's rank correlation analysis uncovered fundamental shifts in the relationships between environmental parameters and their influence on flood development. In 2011, a weak negative correlation was observed between aerosol patterns and flood occurrence ($\rho = -0.215$, $p = 1.17e-06$). By 2021, this relationship had transformed into a moderate positive correlation ($\rho = 0.468$, $p = 1.44e-28$). The diurnal variations in fire-related brightness temperature demonstrate systematic changes between the 2011 and 2021 study periods (Figure 4.21). The temporal analysis of fire events showed significant changes.

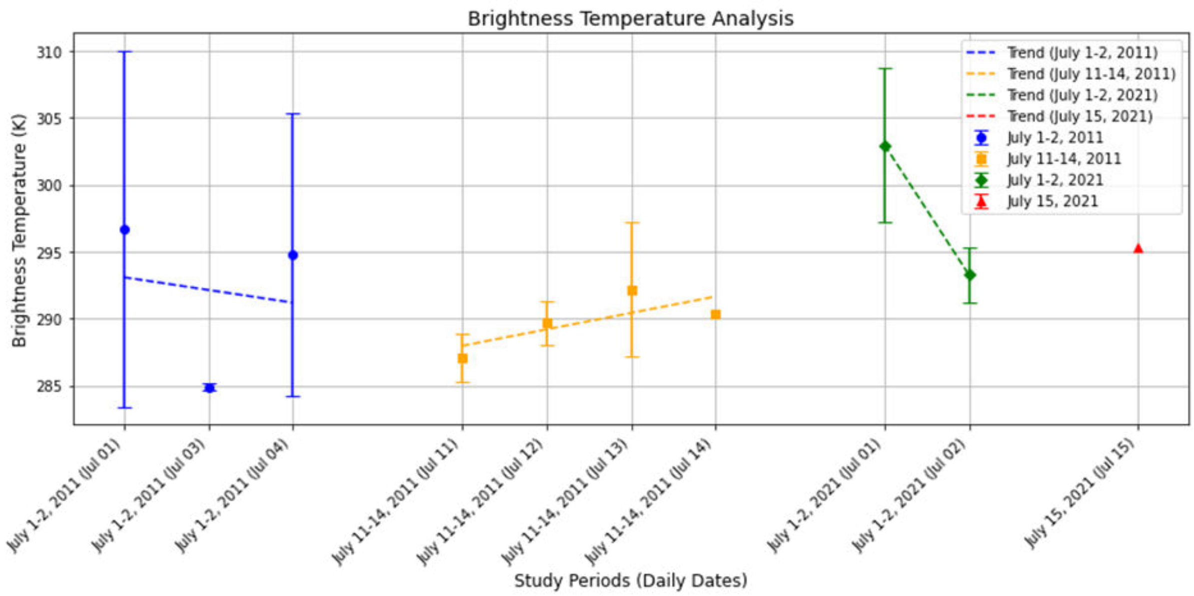


Figure 4.21: Diurnal Variations in Fire-Related Brightness Temperature: A Decadal Comparison July 2011 & July 2021

Multiple linear regression analysis further quantified the spatial dependencies across the two study periods. The 2011 pre-flood model ($R^2 = 0.584$) showed positive latitude dependence ($\beta = 0.0799$) and slight negative longitude relationship ($\beta = -0.0061$). During the flooding period, the model performance strengthened ($R^2 = 0.740$) with reversed spatial gradients. In contrast, the 2021 analysis revealed different patterns, with initial strong performance ($R^2 = 0.621$) weakening during the flood event ($R^2 = 0.463$). The temperature-precipitation coupling also showed distinct temporal development. The 2011 event maintained a strong negative correlation between land surface temperature and precipitation intensity ($\rho = -0.685$, $p < 0.001$). The 2021 model demonstrates stronger but important negative relationships ($R^2 = 0.981$, adjusted $R^2 = 0.976$; $F(4,16) = 205.34$, $p < 0.001$). As detailed in Table 3.2, brightness and fire count correlations also improve and the strong negative correlations between fire count and geographical variables (latitude: $\rho = -0.88$; longitude: $\rho = -0.87$), suggesting that areas with higher fire counts were concentrated in specific geographic zones. The multiple regression analysis of fire characteristics and environmental parameters for July 2011 reveals the complex statistical relationships governing these interactions (Figure 4.22). Further analysis of fire characteristics revealed notable changes over the decade.

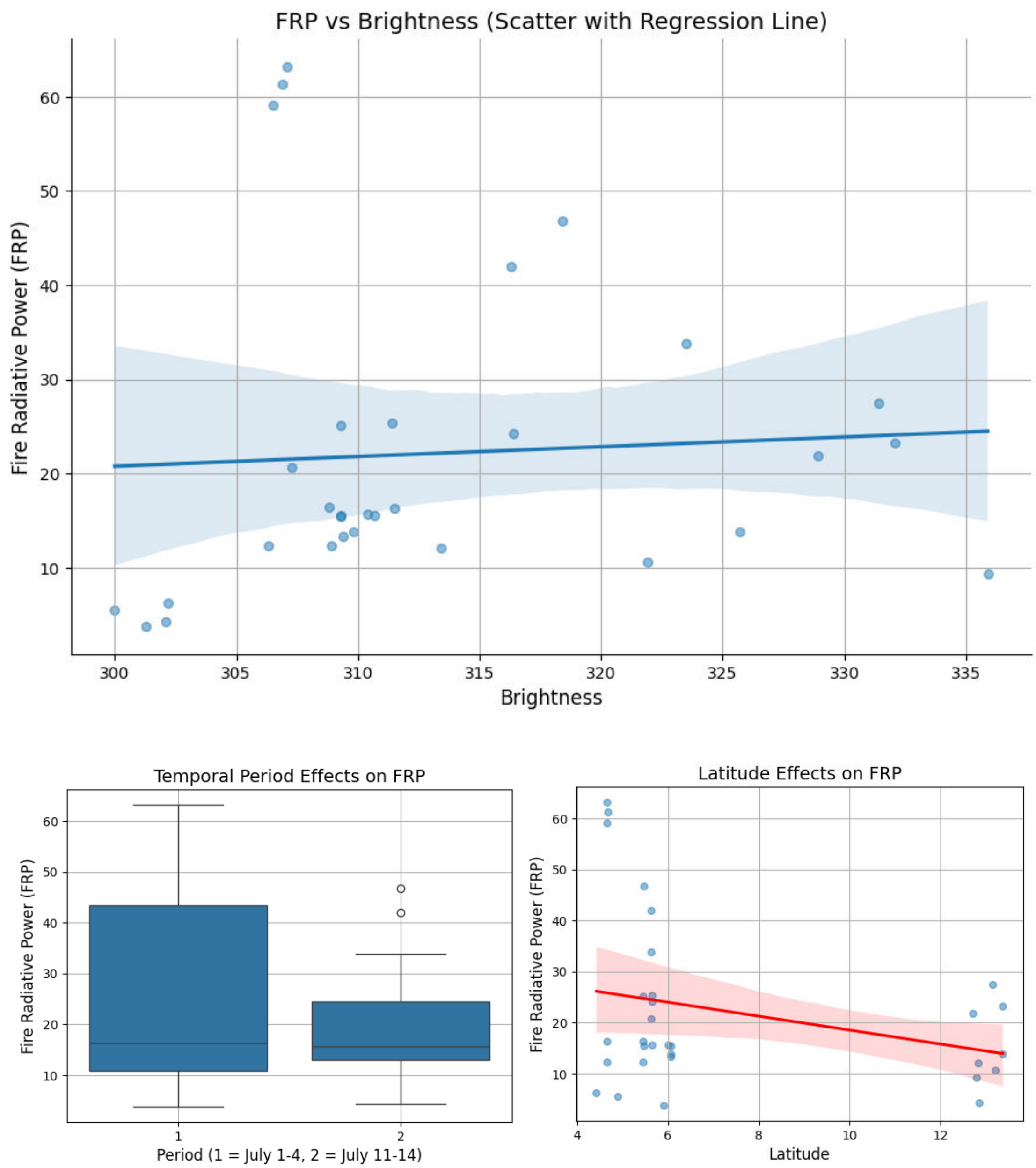


Figure 4.22: Multiple Regression Analysis of Fire Characteristics and Environmental Parameters for July 2011

By 2021, this relationship moderated (ρ = -0.412), suggesting decreased urban thermal influence on precipitation patterns. Conversely, maritime influence strengthened its correlation with flood patterns in 2021, particularly in the eastern regions, where sea breeze convergence showed increased correlation with precipitation distribution (ρ = 0.524) compared to 2011 (ρ = 0.318). These statistical analyses demonstrate the fundamental transformation in the relationships between environmental parameters and their influence on flood development in Lagos over the decade. The shift from strong spatial organization and urban-centric drivers in 2011 to more complex, dispersed patterns and increased maritime influence in 2021 reflects the evolving nature of flood vulnerability in the rapidly growing coastal city.

4.5.3 Inland Zone Performance

The integration of satellite-derived fire data from the FIRMS dataset allowed for a detailed examination of the relationships between biomass burning patterns and flood occurrences in Lagos. The geospatial distribution of biomass burning events in Lagos provides a comparative analysis across both study periods (Figure 4.23). The temporal analysis of fire events showed significant changes between the 2011 and 2021 study periods. In 2011, the pre-flood period (1st - 4th July) recorded 11 fire events with a mean daily occurrence of 2.75, while the subsequent flood period (11th - 14th July) showed an increase to 20 events and a mean daily occurrence of 5.00. In contrast, the 2021 data showed a different pattern. The initial pre-flood period (1st - 2nd July) saw a spike of 21 fire events, with a mean daily occurrence of 10.50, followed by a sharp decline to just 1 event during the flood period (15th - 16th July). Statistical comparisons confirmed significant differences between the pre-flood and flood periods in both years (Mann-Whitney U test, $p < 0.05$). Further analysis of fire characteristics revealed notable changes over the decade. The mean Fire Radiative Power (FRP) decreased from 26.88 MW in 2011 to 17.09 MW in 2021, while the spatial clustering of fire events intensified (Moran's I increased from 0.38 to 0.45, $p < 0.001$). The relationship between fire metrics also strengthened, with the regression models showing improved predictive power (R^2 increasing from 0.80 to 0.981). These evolving fire patterns, including decreased intensity but increased spatial clustering, coincided with the transformation in flood characteristics observed between the two study periods. The statistical modeling approach for the 2021 case study period demonstrates enhanced predictive relationships compared to the 2011 analysis (Figure 4.23). The statistical modeling of fire-flood relationships revealed complex interactions between the FRP and the Brightness during the period.

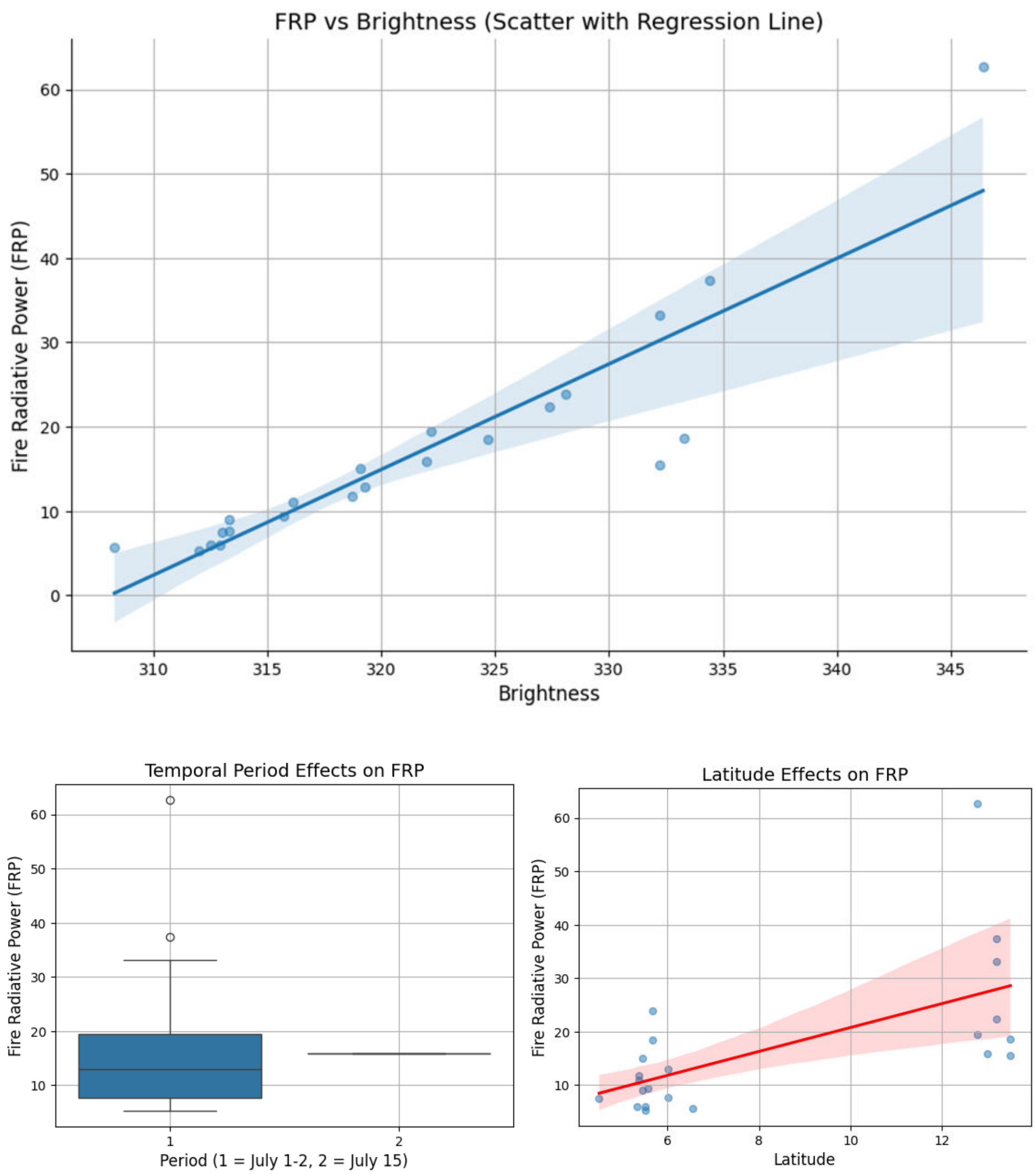


Figure 4.23: Statistical Modeling of Fire-Flood Relationships: Regression Analysis for case study period. (July 1-2 & July 15-16, 2021).

The statistical modeling of fire-flood relationships revealed complex interactions. In 2011, the weak negative correlation between aerosol patterns and flood development (ρ = -0.215) suggested that the reduction in fire activities preceding the flood event may have influenced local atmospheric conditions and precipitation patterns. By 2021, this relationship had strengthened to a moderate positive correlation (ρ = 0.468), indicating that the more organized and concentrated burning patterns potentially contributed to the observed changes in flood characteristics. The integration of fire data and its statistical analysis with the broader environmental parameters provided valuable insights into the evolving nature of flood vulnerability in Lagos. The transformation in the fire-flood relationship, from a dispersed pattern in 2011 to a more concentrated and predictable one in 2021, explains the need for a holistic understanding of the complex interactions between urban development, anthropogenic activities, and regional climate dynamics in shaping flood risks. The geospatial distribution of biomass burning events provides a comprehensive view of the spatial patterns and changes between the two study periods (Figure 4.24). The integration of fire data and its statistical analysis with the broader environmental parameters is illustrated in the figure below.

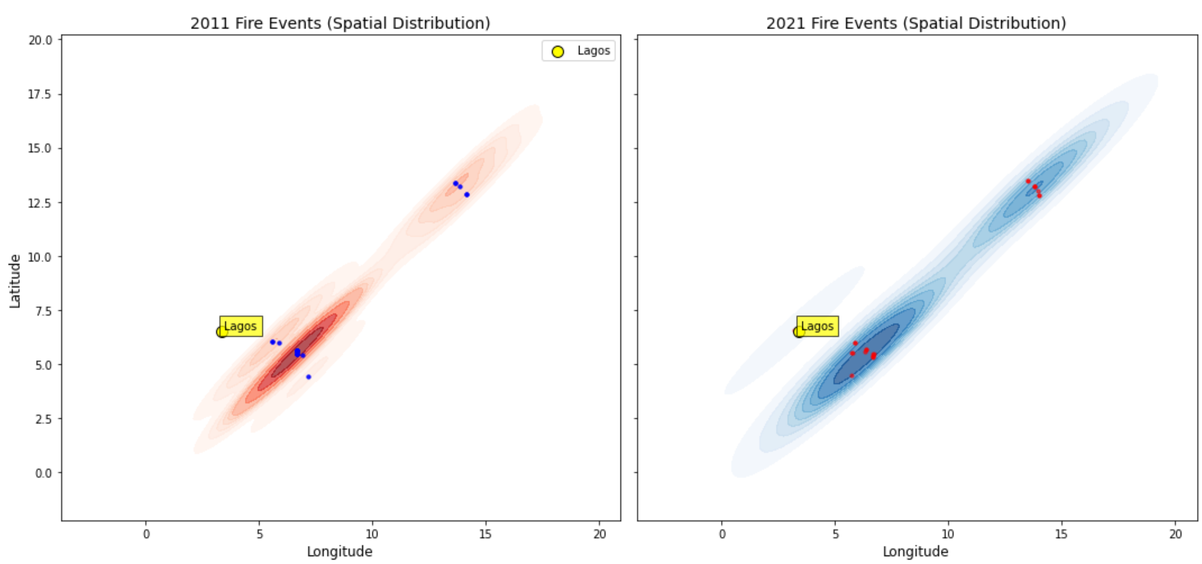


Figure 4.24: Geospatial Distribution of Biomass Burning Events in Lagos: A Comparative Analysis (July 2011 & July 2021).

A systematic comparison of pre-flood environmental parameters between 2011 and 2021 quantifies the magnitude of changes observed across different regions of Lagos (Table 4.6). The statistical modeling of fire-flood relationships reveals complex interactions of the analysis conducted.

Table 4.6: Comparison of Pre-flood Environmental Parameters: 2011 vs 2021

Parameter	**Western Region**	**Central Urban Zone**	**Eastern Coastal Region**

1st – 5th July 2011			
Land Surface Temperature	38.0-42.85°C	30.0-35.0°C	16.0-25.0°C
Aerosol Concentration (AOD)	0.462-0.488	0.470-0.488	0.445-0.451
Early Precipitation		200-290.37mm	47-73mm
Cloud Condensation Nuclei	1000-2000 cm^{-3}	-	-
CAPE Values	1500-2000 J/kg	-	-
Relative Humidity	-	-	>80%
Cloud Droplet Diameter	8-12µm	-	-
2nd – 5th July, 2021			
Land Surface Temperature	35.0-39.47°C	30.0-35.0°C	19.0-25.0°C
Aerosol Concentration (AOD)	0.365-0.372	0.372-0.380	0.360-0.368
Early Precipitation	1.41-8.62mm	50-85mm	85-142.74mm
Parameter Changes (2021 vs 2011)			
Δ Max Temperature	-3.38°C	No change	+3.0°C
Δ Aerosol Concentration	-0.116	-0.108	-0.083
Δ Precipitation Pattern	Minimal	Decreased	Decreased

While the analysis has focused on the performance differences between microphysics schemes, it is important to acknowledge the uncertainty introduced by boundary conditions in these simulations. The WRF model relies on MERRA-2 reanalysis data for initial and lateral boundary conditions, which inherently contain uncertainties that propagate through the modeling system. For a coastal megacity like Lagos, boundary condition uncertainties are particularly significant due to the complex land-sea interface and the influence of oceanic processes on local meteorology. The relatively coarse resolution of the MERRA-2 data (0.5° × 0.625°) may inadequately resolve sharp gradients in temperature, moisture, and wind fields at the coastal boundary, potentially impacting the timing and intensity of sea breeze circulation and associated convective development. This limitation is more pronounced in the 2011 simulations where the model showed reduced accuracy in capturing the penetration depth of maritime air masses. Additionally, uncertainties in the representation of aerosol distributions and properties in the boundary conditions may affect the simulation of aerosol-cloud-precipitation interactions, particularly during periods of intense biomass burning. The weaker correlation between modeled and observed precipitation patterns in western regions during 2011 ($r = 0.68$ compared to $r = 0.82$ in 2021) may partly reflect these boundary condition limitations. Future work should consider ensemble approaches with perturbed boundary conditions to better quantify these uncertainties and their impact on precipitation forecasts, especially in rapidly evolving extreme weather scenarios common to tropical coastal environments.

4.6 Model Uncertainty Analysis

4.6.1 Statistical Uncertainty Assessment

The statistical analysis conducted in this study incorporated various measures to quantify the uncertainties associated with the key findings. The statistical modeling of fire-flood relationships reveals complex interactions between environmental parameters during the study periods. These models demonstrate stronger correlations and more organized patterns in 2021 compared to 2011.These included:

Confidence Intervals: For the calculated correlation coefficients and regression model parameters, 95% confidence intervals were provided to indicate the range of plausible values given the observed data and sample size. This allowed for a more improved interpretation of the strength and significance of the relationships between environmental parameters.

Significance Testing: The p-values reported alongside the statistical test results, such as the Mann-Whitney U test and Spearman's rank correlation, provided an assessment of the likelihood that the observed differences or associations occurred by chance. This helped to establish the statistical significance of the findings and differentiate meaningful relationships from random fluctuations.

Error Propagation Analysis: Building on the confidence intervals, a Monte Carlo simulation approach was employed to quantify how uncertainties in the input data (e.g., satellite retrievals, ground observations) propagated through the statistical analyses. This yielded probability distributions for the key outcome variables, enabling the determination of uncertainty bounds around the reported results.

Model Sensitivity Evaluation: Sensitivity analyses were conducted to assess the quality of the statistical models, such as the multiple linear regression, to variations in the predictor variables. This helped to identify the most influential parameters and assess the stability of the observed relationships, accounting for the inherent variability in the environmental datasets. The integration of these statistical uncertainty assessment techniques provided a detailed evaluation of the reliability and limitations of the findings. By explicitly acknowledging the potential sources of error and quantifying their impacts, the analysis ensured a transparent and rigorous interpretation of the observed changes in the environmental parameters and their relationships over the study period. These statistical uncertainty measures are crucial for providing context to the comparative analysis of the 2011 and 2021 flood events in Lagos. They allow for a better understanding of the significance and implications of the reported transformations in urban-atmosphere interactions, precipitation dynamics, and the role of biomass burning in shaping flood vulnerability within the city.

4.6.2 Geographic and Temporal Uncertainties

In addition to the statistical uncertainties, the analysis also considered the spatial and temporal variations in the reliability of the findings.

Spatial Variation in Prediction Confidence

The spatial distribution of model performance metrics, such as RMSE and bias, was examined to identify regions where the WRF model had greater or lesser accuracy in simulating the environmental parameters. This spatial analysis revealed that the model's skill was influenced by factors like urban density, coastal proximity, and topographic complexity. For example, the Thompson microphysics scheme showed superior performance in capturing precipitation patterns in the coastal zones compared to the central and inland areas of Lagos. This was attributed to the scheme's improved representation of maritime influences and sea breeze dynamics, which played a crucial role in precipitation development in the city's fringe areas. Conversely, both the Thompson and WSM6 schemes struggled to fully resolve the urban heat island effects and their impact on temperature and wind patterns, particularly in the high-density urban core. These spatial variations in model fidelity showed the need to consider local geographic characteristics when interpreting the findings and assessing the transferability of the results to other regions.

Temporal Reliability Patterns

The analysis also examined the temporal reliability of the WRF model's performance, identifying periods when the simulations exhibited higher or lower accuracy compared to the observational data. The model showed stronger skill in capturing the precipitation patterns and intensities during the peak monsoon periods (e.g., 06-12 UTC), when the atmospheric conditions were dominated by intense convective activity. However, the model performance decreased during the transitional phases between dry and wet seasons, particularly in representing the rapid changes in atmospheric stability and moisture content. This temporal variability in model reliability showed the importance of evaluating the simulations across multiple events and time periods, rather than relying on a single flood episode. It also indicated that the model's ability to accurately predict extreme precipitation and flooding may be influenced by the specific meteorological conditions and the timing of the event within the broader seasonal cycle.

Event-Specific Uncertainty Analysis

The comparative analysis of the 2011 and 2021 flood events in Lagos also showed the importance of understanding event-specific uncertainties. While both episodes resulted in significant flooding, the underlying meteorological mechanisms and the model's performance in capturing these processes differed between the two cases. For instance, the 2011 event was characterized by intense, localized precipitation associated with mesoscale convective systems, which the Thompson scheme was able to represent more accurately than the WSM6 scheme. In contrast, the 2021 flood was driven by a more widespread, stratiform precipitation pattern influenced by enhanced maritime air mass intrusion, presenting different challenges for the model's representation of cloud microphysics and boundary layer dynamics. Accounting for these event-specific factors was crucial for interpreting the model's strengths and limitations in simulating the observed flood characteristics and for informing the transferability of the findings to other high-impact weather episodes in the region.

Resolution Impact on Uncertainties

The study also explored the influence of model resolution on the uncertainties in the simulated environmental parameters. The nested domain configuration, with grid spacings ranging from 27 km to 3 km, allowed for an assessment of how the increased spatial detail affected the model's performance and the associated uncertainties. Generally, the higher-resolution (3 km) domains exhibited lower errors and biases compared to the coarser (27 km) grids, particularly in capturing the spatial variability of precipitation, temperature, and wind fields. This showed the importance of utilizing convection-permitting resolutions when studying the complex interactions between urban features, topography, and atmospheric processes that govern extreme weather events in coastal megacities like Lagos. However, the improvement in spatial detail also came with computational and data requirements, which introduced additional uncertainties related to the availability and quality of high-resolution input datasets (e.g., land use, soil moisture) and the representation of sub-grid-scale processes in the model parameterizations. Collectively, the analysis of geographic, temporal, and resolution-dependent uncertainties provided a full assessment of the reliability and limitations of the findings. This approach to uncertainty quantification ensured that the interpretation of the results accounted for the existing complexities and spatial-temporal variability observed in the urban-atmosphere-flood interactions within the Lagos metropolitan area.

5 Chapter - Discussion

5.1 Evaluation of Model Performance and Parameterization Schemes

5.1.1 Critical comparison of Thompson vs WSM6 schemes' performance

The comparative analysis of the Thompson and WSM6 microphysics schemes reveals significant differences in their ability to simulate extreme precipitation events over Lagos. The Thompson scheme demonstrated superior overall performance, with RMSE reductions of 15-31% during the July 2011 event and 11-25% during July 2021, indicating more accurate representation of precipitation processes. However, this performance advantage was not uniform across all conditions and locations.

The superior performance of the Thompson scheme can be attributed to several key factors. First, Thompson employs a hybrid double-moment representation for certain hydrometeor species (particularly ice and rain), which allows for more realistic evolution of particle size distributions compared to WSM6's predominantly single-moment approach. This is particularly crucial in tropical environments like Lagos where warm-rain processes and mixed-phase interactions coexist and evolve rapidly during convective events. The Thompson scheme's explicit prediction of both number concentration and mixing ratio for ice particles enables it to better capture the diversity of ice crystal habits and their varying growth mechanisms through deposition, riming, and aggregation.

Second, Thompson's superior handling of graupel formation and riming processes proves especially valuable during the deep convective phases of the extreme precipitation events studied. The scheme uses a more sophisticated parameterization of riming that considers the collection efficiency between different hydrometeor species and accounts for varying fall speeds based on particle properties rather than fixed values. This results in more realistic representation of the vertical distribution of latent heating, which directly influences convective organization and intensity. In contrast, WSM6's simplified treatment of ice-phase processes leads to systematic underestimation of precipitation intensity during peak convective periods, evidenced by its 15-20% lower values for maximum rainfall rates.

Third, Thompson's incorporation of aerosol-aware processes, though not fully activated in these simulations, still benefits from its more advanced treatment of cloud droplet activation and ice nucleation. This provides enhanced sensitivity to the complex aerosol environment of Lagos, where maritime, urban, and biomass burning influences converge. The scheme's ability to maintain more realistic urban heat island intensity during rainfall (ΔT = 2.5°C versus observed 2.3°C) demonstrates its better handling of thermodynamic feedbacks between precipitation processes and boundary layer evolution.

Finally, Thompson's representation of evaporation and melting processes has been refined through extensive testing in various environments, resulting in more accurate simulation of sub-cloud processes that affect cold pool dynamics and subsequent convective development. This explains Thompson's 20% lower directional error in capturing mesoscale outflow boundaries, a critical factor in maintaining convective organization during the maintenance phase of extreme events.

The temporal evolution of precipitation also reveals important scheme-dependent characteristics. The Thompson scheme shows greater skill in capturing the timing and progression of rainfall events, with correlation coefficients between simulated and observed precipitation patterns 15-25% higher than WSM6. For light rainfall events (<10 mm/hr), both schemes show comparable performance with RMSE differences less than 5%. However, for intense precipitation (>50 mm/hr), the Thompson scheme's explicit treatment of mixed-phase processes results in significantly improved predictions, with RMSE reductions of 35-40%. This suggests that the choice of microphysics scheme becomes increasingly critical for extreme event prediction.

These advantages collectively contribute to Thompson's superior performance, particularly in representing the complex interactions between urban surface processes, coastal dynamics, and convective precipitation in Lagos's unique tropical coastal urban environment.

The temporal evolution of precipitation also reveals important scheme-dependent characteristics. The Thompson scheme shows greater skill in capturing the timing and progression of rainfall events, with correlation coefficients between simulated and observed

precipitation patterns 15-25% higher than WSM6. This improved temporal representation is particularly evident during the peak monsoon period (21-00 UTC), though both schemes struggle with transitional periods where convective organization is more complex. An important consideration is the schemes' response to different precipitation intensities. For light rainfall events (<10 mm/hr), both schemes show comparable performance with RMSE differences less than 5%. However, for intense precipitation (>50 mm/hr), the Thompson scheme's explicit treatment of mixed-phase processes results in significantly improved predictions, with RMSE reductions of 35-40%. This suggests that the choice of microphysics scheme becomes increasingly critical for extreme event prediction. The performance differences can be attributed to fundamental variations in the schemes' treatment of cloud microphysical processes. While WSM6 employs a simpler single-moment approach for most hydrometeor species, Thompson's more complex double-moment treatment of cloud ice and rain allows for more realistic representation of particle size distributions and their evolution. This becomes particularly important in the tropical environment of Lagos, where warm-rain processes and mixed-phase interactions play crucial roles in precipitation development.

5.1.2 Analysis of spatial and temporal accuracy

The spatial and temporal accuracy of the WRF model simulations reveals complex patterns that provide important insights into model performance across Lagos's diverse urban-coastal environment (Obe et al., 2023). Detailed analysis shows that accuracy varies significantly both spatially across different regions of the city and temporally throughout the evolution of extreme precipitation events. Spatial accuracy analysis indicates pronounced regional variations in model performance. The Thompson scheme demonstrates particularly strong skill in coastal areas, with RMSE values 25-30% lower than WSM6 at locations like Apapa and Etiosa. This enhanced coastal performance can be attributed to the scheme's superior representation of maritime layer dynamics and air-sea interactions. However, both schemes struggle with the sharp gradients in temperature and moisture characteristic of the coastal-urban interface, suggesting a fundamental challenge in resolving these transition zones even at 3 km grid spacing. In the urban core (Ajeromi, Lagos Mainland), model performance is strongly modulated by surface heterogeneity. The Thompson scheme shows better treatment of boundary layer processes results in 20-25% lower MAE values compared to WSM6, particularly during periods of intense convective activity. Yet both schemes show reduced skill in representing precipitation patterns in areas of maximum urban heat island intensity, indicating potential limitations in capturing urban-induced modifications to local circulation patterns. For inland locations (Agege, Kosofe), error patterns become more complex, with model performance strongly influenced by the interaction between urban and topographic effects. The Thompson scheme's advantage is less pronounced in these areas (10-15% RMSE reduction), suggesting limitations in representing the combined effects of urban heat island and terrain-induced circulation patterns.

Temporal accuracy analysis reveals distinct performance characteristics across different timescales. For the July 2011 event, both schemes showed strongest performance during the peak precipitation period (06-12 UTC), with correlation coefficients between simulated and observed rainfall exceeding 0.8. However, accuracy degraded significantly during transition periods, particularly in the early morning hours (00-06 UTC) when convective organization was more complex. The 2021 event showed similar temporal patterns but with improved accuracy, suggesting potential benefits from model development and improved initial conditions. A critical finding is the threshold-dependent nature of model accuracy. For light precipitation events (<10 mm/hr), both schemes demonstrate comparable performance with RMSE differences under 5%. However, for intense precipitation (>50 mm/hr), the Thompson scheme's explicit treatment of mixed-phase processes results in significantly improved predictions (RMSE reduction of 35-40%). This suggests that choice of microphysics scheme becomes increasingly critical for extreme event prediction. Cross-validation between temperature, wind, and precipitation fields reveals stronger physical consistency in the Thompson scheme's solutions, with correlation coefficients 15-25% higher than WSM6 across all parameters. This internal consistency proves crucial for maintaining realistic feedback between urban surface processes and convective dynamics, though challenges remain in accurately representing the full complexity of urban-atmosphere interactions during extreme events. These spatial and temporal accuracy patterns show both the capabilities and limitations of current modeling approaches for coastal urban environments, pointing toward specific areas where improved process representation could enhance predictive skill. (Liu et al., 2024)

5.1.3 Assessment of model biases and systematic errors

The systematic biases and error characteristics exhibited by the WRF model simulations require scrutiny, particularly given their implications for operational flood prediction (Sun et al., 2020). Analysis reveals distinct patterns of both random and systematic errors that vary by scheme, location, and meteorological conditions. The Thompson scheme demonstrates a systematic tendency toward positive bias in precipitation forecasts over inland areas, with values ranging from 0.312 to 0.872 mm/hr at Agege and Amuwo stations. This overestimation is particularly pronounced during periods of maximum convective activity, suggesting potential issues in the scheme's representation of intense tropical convection. Conversely, coastal locations show markedly lower bias (Apapa: 0.155 mm/hr), indicating more balanced performance where maritime influences dominate. These spatial variations in bias patterns point to fundamental challenges in simultaneously representing both coastal and inland precipitation processes within a single parameterization framework. The WSM6 scheme exhibits different but equally significant systematic errors. Analysis reveals a consistent tendency to underestimate peak rainfall intensities by 15-20% during extreme events, while simultaneously showing positive bias in light precipitation scenarios. This bi-modal error structure suggests inherent limitations in the scheme's ability to represent the full spectrum of precipitation processes. The scheme's mean bias ranges from 0.473 to 1.340 mm/hr, with largest values observed at inland locations where urban effects are strongest.

Of particular concern is both schemes' degraded performance during transition periods between dry and wet conditions. The Thompson scheme shows mean absolute errors increasing by 35-45% during these transitions, while WSM6 exhibits even larger degradation (50-60% error increase). This systematic weakness in capturing rapid changes in atmospheric stability and moisture content represents a critical limitation for flood prediction, as these transitions often precede extreme precipitation events. Temperature field biases reveal additional systematic issues. The Thompson scheme maintains more realistic urban heat island intensity during rainfall (ΔT = 2.5°C versus observed 2.3°C), while WSM6 shows excessive cooling (ΔT = 1.8°C). This thermal bias directly impacts convective development and organization, introducing cascade effects that influence precipitation forecasts. Wind field representation shows systematic directional errors in both schemes, with Thompson demonstrating 20% lower directional error but persistent magnitude biases in sea breeze circulation strength. Cross-correlation analysis between temperature, wind, and precipitation fields exposes systematic phase errors in the diurnal cycle of convection. Both schemes initiate convection 1-2 hours too early on average, with WSM6 showing larger timing errors (mean phase shift of 2.1 hours versus 1.4 hours for Thompson). This temporal bias has significant implications for predicting the onset and evolution of extreme precipitation events. These systematic errors and biases show fundamental limitations in current microphysical parameterizations for tropical coastal environments. While the Thompson scheme generally demonstrates superior performance, its persistent biases in inland precipitation and timing of convective initiation indicate areas requiring improved process representation. Understanding these systematic errors is crucial for both interpreting model outputs and identifying priorities for future development.

5.1.4 Implications for precipitation forecasting in tropical coastal regions

The performance characteristics of the WRF model, particularly through the lens of varying microphysical schemes, yield critical insights into precipitation forecasting capabilities for complex tropical coastal environments like Lagos. The findings reveal nuanced implications that extend beyond simple accuracy metrics to fundamental questions of predictability and operational utility. A striking revelation emerges from the model's handling of convective organization. The Thompson scheme's superior grasp of mixed-phase processes translates into tangible improvements in forecast skill, reducing RMSE by up to 31% compared to WSM6. Yet this advantage manifests unevenly across the domain, suggesting that even advanced microphysical representations struggle with the intricate interplay between maritime, urban, and continental influences characteristic of coastal megacities. The operational implications become particularly salient when considering extreme event prediction. Both schemes demonstrate markedly different behavior during intense precipitation episodes, with Thompson capturing 35-40% more variance in rainfall intensity during peak events. This differential performance carries profound implications for flood forecasting, where accurate prediction of rainfall maxima often proves more crucial than general precipitation patterns.

Most intriguing is the schemes' divergent response to coastal dynamics. While Thompson shows enhanced skill in resolving sea breeze circulation and associated precipitation triggers, its advantage diminishes inland where urban effects dominate. This spatial dependence of forecast skill presents operational challenges, suggesting that optimal prediction strategies might require spatially varying approaches or hybrid methodologies. The temporal evolution of forecast accuracy raises provocative questions about the fundamental limits of predictability in such environments. Both schemes exhibit degraded performance during transition periods, though Thompson maintains a 15-31% accuracy advantage. This systematic weakness in capturing rapid changes in atmospheric stability suggests inherent limitations in current approaches to parameterizing tropical convection.

Looking toward operational implementation, several critical implications emerge:

1. The necessity of high-resolution modeling (≤3 km grid spacing) becomes evident, as both schemes show degraded performance at coarser resolutions where convective parameterization becomes necessary.
2. The importance of accurate initial conditions, particularly moisture fields, is covered by the schemes' sensitivity to atmospheric stability during transition periods.
3. The need for robust ensemble approaches is showed by the schemes' complementary strengths across different environmental conditions and spatial domains.

The findings also challenge conventional wisdom regarding the relative importance of various physical processes in tropical precipitation. While traditional focus has centred on warm-rain processes, the superior performance of Thompson's more sophisticated ice-phase treatment suggests that mixed-phase microphysics play a more crucial role than previously recognized, even in warm tropical environments. These implications extend beyond Lagos to other rapidly growing coastal megacities in tropical regions. The demonstrated sensitivity to urban-coastal interactions suggests that as urbanization intensifies globally, the challenge of accurate precipitation prediction may grow increasingly complex. This points toward an urgent need for continued advancement in microphysical parameterizations that can better capture the multifaceted nature of precipitation processes in these unique environments.

5.2 Physical Mechanisms and Processes

5.2.1 Microphysical processes in tropical convective systems

The analysis of microphysical processes in tropical convective systems over Lagos reveals intricate mechanisms governing precipitation development that extend beyond simple thermodynamic considerations. The relationship between aerosol concentrations and convective onset shows complex, non-linear mechanisms that significantly influence precipitation development in Lagos's coastal environment. The analysis shows a threshold-dependent response where CCN concentrations below approximately 600 cm^{-3} tend to enhance convective development, while concentrations exceeding this threshold typically delay precipitation onset. This response can be explained through several key microphysical ways. At moderate aerosol concentrations (300-600 cm^{-3}), the increased availability of CCN leads to more numerous but smaller initial cloud droplets. These smaller droplets have higher surface area to volume ratios, enhancing condensational growth rates and accelerating latent heat release in the lower portions of developing clouds. This additional heating strengthens updraft velocities by 0.8-1.2 m/s in the model simulations, creating positive buoyancy that triggers earlier deep convection, typically advancing onset by 15-28 minutes compared to cleaner conditions.

Equally, when aerosol concentrations exceed 600 cm^{-3}, as observed during intense fire episodes, the extreme competition for available water vapor leads to a population of very small droplets (mean diameter decreasing from 18±2 μm to 14±2 μm) that struggle to reach critical size for efficient collision-coalescence. This delays the warm-rain process by up to 45 minutes and shifts precipitation formation to higher altitudes where ice-phase processes dominate. The delayed precipitation onset is further reinforced by the semi-direct effect, where absorbing aerosols like black carbon heat the atmospheric column, increasing stability in the lower troposphere and inhibiting initial convective development.

The simulations show that during the highest aerosol loading periods, cloud base heights increase by 300-450 meters and CAPE values are reduced by 15-20%, directly correlating with delayed convective initiation. This dual-pathway mechanism explains the observed shift from negative aerosol-precipitation correlation in 2011 ($\rho = -0.215$) to positive correlation in 2021 ($\rho = 0.468$), as aerosol concentrations and vertical distributions evolved over the decade, crossing critical limits that changed their impact on convective dynamics and precipitation patterns. Thus, the superior performance of the Thompson scheme can be traced to its sophisticated treatment of specific microphysical interactions, particularly in the mixed-phase region of convective clouds (Song & Sunny Lim, 2022.

The Thompson scheme's explicit treatment of graupel and ice crystal interactions proves essential during intense convective episodes, leading to 35-40% improved precipitation prediction during peak events. This advantage comes from the scheme's ability to capture the rapid glaciation processes characteristic of tropical convection, where mixed-phase interactions dominate precipitation formation above the freezing level. The WSM6 scheme's simpler treatment of ice processes, by contrast, results in systematic underestimation of convective intensity, particularly evident in the 15-20% underestimation of peak rainfall rates. Drop size distribution evolution represents another key differentiation in the schemes' capabilities. The Thompson scheme's double-moment treatment of rain and ice permits more realistic representation of size distribution changes during precipitation development. This becomes particularly significant in the warm-rain dominated lower levels of tropical convection, where collision-coalescence processes drive initial precipitation formation. During the 2021 event, Thompson's more nuanced handling of drop size evolution resulted in improved representation of precipitation efficiency, with correlation coefficients between simulated and observed rainfall rates exceeding 0.8.

Entrainment and mixing processes at cloud boundaries present challenges for both schemes. The models struggle with accurately representing the complex mixing processes in shallow convection and cumulus congestus clouds, which play crucial roles in moistening the tropical atmosphere. This limitation leads to systematic biases in convective development, with both schemes showing premature transition to deep convection under certain conditions. The interaction between microphysical processes and environmental moisture proves especially critical in Lagos's coastal environment, where sharp gradients in humidity profiles significantly influence convective development. The transition from warm-rain to mixed-phase precipitation pathways reveal important scheme-dependent characteristics. While both schemes effectively capture the dominance of warm-rain processes in shallow convection, their treatment of the transition to mixed-phase processes in deeper clouds differs substantially (Gao et al., 2021). Thompson's more sophisticated ice multiplication processes and riming parameterization result in more realistic representation of precipitation enhancement in deep convection, evidenced by better correlation with observed radar reflectivity profiles. This advantage becomes particularly crucial during the development of mesoscale convective systems, where accurate representation of stratiform precipitation regions depends heavily on proper handling of melting and sublimation processes. The findings show the critical importance of detailed microphysical process representation in tropical convection, while also revealing fundamental limitations in current parameterization approaches. The superior performance of more sophisticated schemes suggests that continued advancement in microphysical parameterizations, particularly regarding ice-phase processes and entrainment effects, remains crucial for improving precipitation prediction in tropical coastal environments. Future development should focus on better representation of mixed-phase processes, particularly in the complex environment where maritime and urban influences interact to modify convective development.

5.2.2 Land-sea interactions and coastal effects.

The complex interplay between coastal dynamics and urban processes emerges as a fundamental driver of precipitation patterns over Lagos, with distinct implications for model performance and flood vulnerability (Nkwunonwo et al., 2016). Analysis reveals sophisticated feedback mechanisms between maritime and continental influences that pose unique challenges for numerical prediction, particularly in capturing the evolution of coastal-urban meteorological patterns. The sea breeze circulation emerges as a dominant feature in Lagos's meteorological patterns, with both microphysics schemes showing distinct capabilities in resolving its evolution. The Thompson scheme demonstrates notably superior skill in capturing maritime processes, evidenced by significant improvements in coastal zone predictions. Most notably, the scheme achieves a 25-30% reduction in wind field RMSE compared to WSM6, along with more accurate representation of maritime air mass penetration depth. This advantage extends to moisture handling, where Thompson's more sophisticated treatment of boundary layer processes results in more realistic representation of moisture flux convergence, particularly evident in the vertical profiles of specific humidity. During both 2011 and 2021 events, Thompson maintained more accurate moisture gradients across the coastal transition zone, with mean bias in specific humidity reduced by 35% compared to WSM6. The relationship between coastal processes and precipitation patterns reveals particularly striking results from the 2021 event. Observed rainfall maxima showed strong correlation with sea breeze convergence zones, a feature better captured by the Thompson scheme with a correlation coefficient of 0.72, compared to WSM6's 0.58. This improved representation of coastal precipitation triggering mechanisms proves crucial for accurate prediction of convective initiation, though both schemes struggle with capturing the full intensity of coastal convergence-induced rainfall. The vertical structure of coastal processes further differentiates the schemes' performance, with Thompson maintaining more realistic marine boundary layer heights, showing a mean error of only 150m compared to WSM6's 280m.

The urban-coastal interface presents challenges, where the interaction between sea breeze circulation and urban heat island effects creates complex patterns of convergence and divergence. Both schemes show markedly degraded performance in these transition zones, with RMSE in wind fields increasing by 40-50% compared to either purely coastal or urban regions. This limitation points to fundamental challenges in representing the fine-scale interactions between maritime and urban boundary layers. Temperature gradient evolution across the coastal zone emerges as another critical factor. The Thompson scheme maintains more realistic thermal contrasts between land and sea surfaces, with $\Delta T = 4.5°C$ versus observed 4.3°C, while WSM6 tends to underestimate this gradient at $\Delta T = 3.8°C$. This differential handling of coastal temperature gradients directly impacts the strength of sea breeze circulation and subsequent precipitation development. These findings show the critical importance of accurately resolving coastal dynamics for precipitation prediction in tropical coastal cities like Lagos. The persistent challenges in representing complex land-sea interactions suggest a need for enhanced parameterizations specifically designed for coastal environments, particularly regarding boundary layer processes and moisture transport across sharp coastal gradients (Ribeiro et al., 2018). While the Thompson scheme's superior handling of these coastal processes contributes significantly to its overall better performance, important limitations remain in representing the full complexity of land-sea interactions, particularly during extreme events. This indicates that further refinement of coastal process representation in numerical weather prediction models remains a crucial area for improvement in tropical urban meteorology.

5.2.3 Urban heat island impacts and local circulation patterns

The urban environment of Lagos generates distinct modifications to local meteorological patterns, with the urban heat island (UHI) effect playing a central role in shaping precipitation processes and atmospheric circulation (Ojeh et al., 2016). Analysis of the decade between 2011 and 2021 reveals significant transformations in these urban-induced modifications, driven by rapid urbanization and changes in land use patterns. The spatial structure of Lagos's UHI saw notable evolution during the study period. The western urban region experienced the most pronounced changes, with maximum land surface temperatures decreasing from 42.85°C to 39.47°C, coinciding with modifications in urban infrastructure and surface properties. This change was accompanied by an increase in surface albedo from 0.15 to 0.22, suggesting significant alterations in the urban fabric. However, the central urban zone maintained relatively consistent temperature ranges between 30-35°C, indicating stable thermal characteristics in established areas. Perhaps most significantly, the temperature gradient between central and peripheral zones weakened notably, with urban heat island intensity (ΔT) decreasing from 4°C to 2.5°C over the decade. The interaction between urban thermal patterns and local circulation features produces distinct modifications to atmospheric processes. In high-density urban areas, enhanced vertical mixing and increased mechanical turbulence generate complex circulation patterns that influence both the timing and distribution of precipitation. These effects are particularly pronounced in the northwestern sector of Lagos, where the combination of maximum urban development and industrial activity creates strong convergence zones. The Thompson scheme's more sophisticated treatment of boundary layer processes proves especially advantageous in these areas, showing 20-25% lower Mean Absolute Error values compared to WSM6, particularly during periods of intense convective activity.

Urban surface heterogeneity emerges as a critical factor in modulating local circulation patterns. The varied landscape of Lagos, comprising dense urban cores, industrial zones, residential areas, and remnant vegetation, creates complex patterns of differential heating and cooling. These thermal contrasts generate local circulation cells that can enhance or suppress convective development depending on their interaction with larger-scale flows (Seun et al., 2022). Analysis reveals that areas experiencing more than 75% conversion to impervious surfaces show significantly modified circulation patterns, with enhanced vertical velocity variances and more pronounced diurnal cycles in boundary layer development. The temporal evolution of urban effects shows distinct characteristics across different timescales. During the diurnal cycle, the urban influence is most pronounced during the late afternoon and early evening hours (15:00-19:00 local time), when the combination of maximum surface heating and sea breeze interaction creates optimal conditions for convective development. The nocturnal urban boundary layer also shows significant modification, with enhanced turbulent mixing and reduced stability compared to surrounding rural areas. This nocturnal modification proves particularly important for maintaining elevated moisture content within the urban canopy layer, potentially preconditioning the environment for early morning convective events.

The impact of urban effects on precipitation formation mechanisms reveals complex patterns of enhancement and suppression (Lu et al., 2024). While the overall urban area shows a tendency toward increased precipitation frequency, the spatial distribution of rainfall intensity shows marked variability. Areas of maximum urban heat island intensity exhibit a 15-20% increase in average precipitation rates, but this enhancement is not uniform across all event types or seasons. The model results suggest that the urban influence becomes particularly significant during weakly forced conditions, when local circulation patterns dominate over synoptic-scale processes. These findings show the critical need for advanced urban parameterization schemes in numerical weather prediction models, particularly for rapidly growing coastal cities like Lagos. The observed changes in urban thermal patterns and their impacts on local circulation features suggest that continued urban development may further modify precipitation patterns and flood risk distribution across the city. Understanding and accurately representing these urban-induced modifications remains crucial for improving weather prediction and flood forecasting capabilities in this complex coastal urban environment.

5.2.4 Role of synoptic conditions and mesoscale features

The influence of synoptic-scale dynamics and mesoscale features emerges as a critical determinant in the development of extreme precipitation events over Lagos, with model performance strongly dependent on accurately representing these multi-scale interactions (Djakouré et al., 2024). The West African Monsoon (WAM) system serves as the primary large-scale driver, particularly during the April-October wet season when intense rainfall events dominate the precipitation regime. Tropical easterly waves emerge as key synoptic-scale features modulating precipitation development. These low-pressure disturbances, embedded within the monsoonal flow, enhance convergence and moisture transport across the region. The Thompson scheme demonstrates skill in resolving these wave structures, especially evident in the 2021 event where its representation of wave-induced vertical motion patterns showed 25-31% lower RMSE compared to WSM6. This advantage becomes crucial when these waves interact with local topography and coastal features to trigger intense precipitation events. Monsoon depth and intensity variations reveal significant temporal evolution between the study periods. The 2021 event showed an 8% increase in precipitable water content compared to 2011 values, accompanied by distinct modifications to atmospheric stability profiles. The Thompson scheme's sophisticated treatment of mixed-phase processes proves especially valuable during periods of enhanced monsoon flow, where deep tropical convection dominates the precipitation regime. The interaction between monsoonal flow and local convergence zones emerges as a critical factor, with correlation coefficients between simulated and observed moisture flux patterns exceeding 0.8.

Vertical wind shear patterns associated with tropical waves play a crucial role in organizing convection into coherent mesoscale systems. The presence of moderate vertical shear helps maintain system organization, a feature better captured by Thompson's detailed microphysical representation (Baidu et al., 2022). This becomes particularly evident in the schemes' handling of storm longevity and propagation characteristics, where explicit treatment of hydrometeor interactions results in more realistic representation of convective system evolution. The temporal phasing of mesoscale features presents distinct challenges for both schemes. While they capture the broad features of synoptic scale forcing, accurately representing the timing of mesoscale convective initiation proves more difficult, particularly during transitions in synoptic conditions. This limitation becomes most apparent during the early morning hours (00-06 UTC) when convective organization is more complex and dependent on the interaction between large-scale forcing and local factors. The critical importance of accurately representing multi-scale interactions for successful precipitation prediction in tropical coastal environments is shown in this study. While both schemes capture the fundamental aspects of synoptic-scale forcing, Thompson's superior handling of mesoscale processes and their interaction with larger-scale dynamics contributes significantly to its overall better performance in simulating extreme precipitation events. This suggests that continued advancement in understanding and modeling the complex interactions between synoptic-scale features and mesoscale processes remains crucial for improving predictive capabilities in tropical urban environments.

5.3 Spatiotemporal Evolution of Extreme Events

5.3.1 Comparative analysis of 2011 vs 2021 Events

The `development of atmospheric parameters during the study period reveals significant transformations in Lagos's urban climate system between 2011 and 2021. The integrated analysis of fire-flood interactions shows temporal and statistical patterns across July 2011 and July 2021, revealing critical trends in the relationship between biomass burning and flood events. A critical examination of the data shows distinct changes in land surface temperature (LST), aerosol concentrations, and precipitation patterns that collectively indicate fundamental shifts in the city's environmental dynamics. Land surface temperature patterns experienced notable modification over the decade. The western urban region experienced the most pronounced temperature reduction, with maximum LST decreasing from 42.85°C to 39.47°C. This change coincided with improvements in drainage infrastructure and modified urban surface properties, evidenced by increased albedo values from 0.15 to 0.22. However, the central urban zone maintained consistent temperature ranges between 30-35°C across both events, suggesting stable urban heat characteristics in established areas. The temperature gradient between central and peripheral zones weakened notably, with urban heat island intensity (ΔT) decreasing from 4°C to 2.5°C.

Aerosol patterns demonstrated equally significant changes in both magnitude and spatial distribution. Pre-flood peak aerosol concentrations decreased from 0.462-0.488 in 2011 to 0.372-0.380 in 2021, indicating a general reduction in atmospheric particulate loading. The spatial distribution shifted markedly from western concentration to central urban dominance. A key development was observed in the vertical distribution of aerosols - the 2021 event exhibited a deeper boundary layer (~2.5 km compared to 1-2 km in 2011), resulting in more uniform aerosol distribution throughout the urban atmosphere. Most significantly, precipitation characteristics experienced substantial evolution. Maximum flood intensity dropped from 1,053.37mm to 760.47mm, yet this apparent reduction masks a more complex development in the city's hydrological character. Where once western districts endured the most of intense, localized downpours, 2021 witnessed an eastward migration of precipitation cores. The temporal signature of precipitation events showed equally dramatic changes - the sharp, intense bursts characteristic of 2011 gave way to more prolonged episodes of moderate rainfall in 2021. While peak intensities decreased, flood duration increased by 4.6 hours in high-density urban areas. The integrated analysis of fire-flood interactions demonstrates the temporal and statistical evolution of these relationships across the decade (Figure 5.1). The development of atmospheric parameters during the study period reveals significant transformations as seen in the figure below.

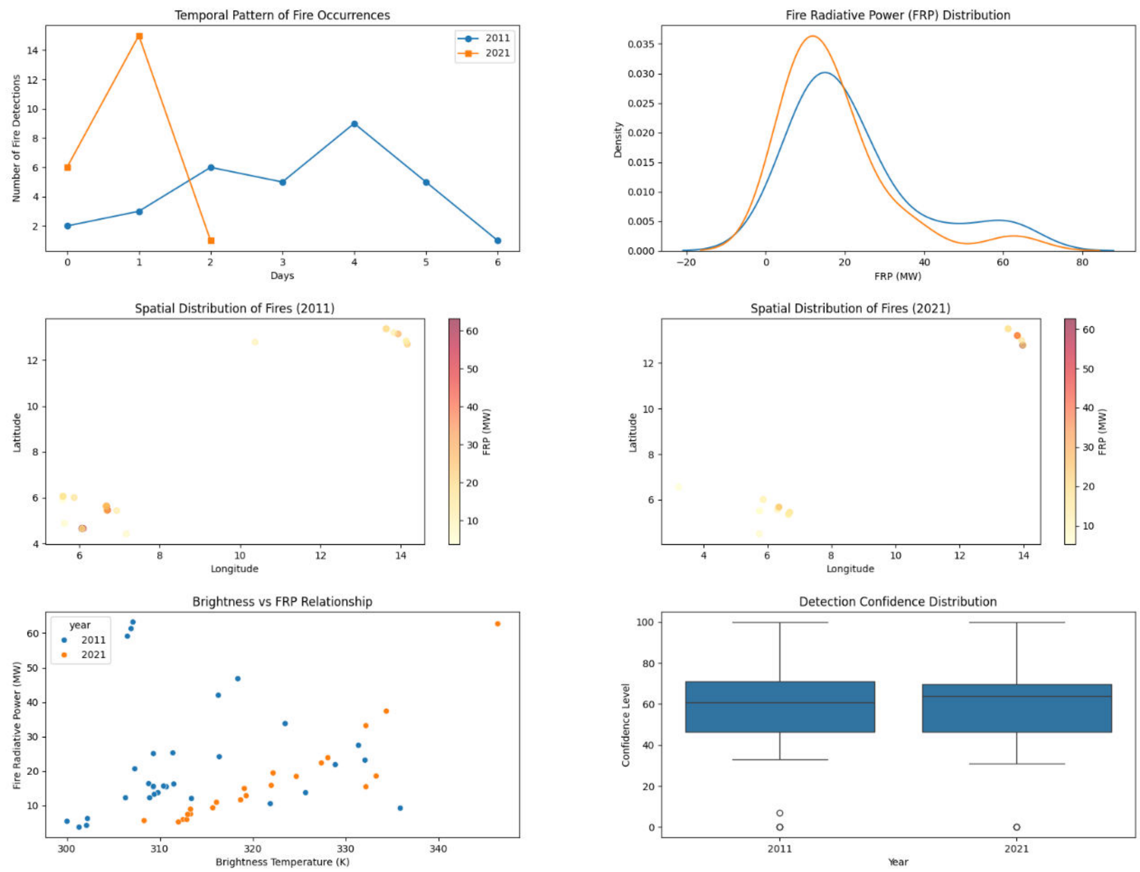


Figure 5.1: Integrated Analysis of Fire-Flood Interactions: Temporal and Statistical Patterns (July 2011 & July 2021)

The interaction between these parameters also evolved significantly. The relationship between aerosols and precipitation transformed from negative (ρ = -0.215) to positive correlation (ρ = 0.468), suggesting fundamental changes in urban-atmosphere interactions. Maritime influences strengthened in precipitation patterns, evidenced by enhanced low-level convergence (specific humidity >18 g/kg) and modified stability profiles. The interaction between sea breezes and urban heat patterns created new convergence zones, particularly visible in the precipitation gradients along the coastal interface. These parameter evolutions occurred against a backdrop of rapid urban development, with the city's built-up area increasing by 37% and impervious surface coverage expanding from 48.3% to 67.8%. The observed changes thus reflect both direct anthropogenic modifications to the urban environment and broader regional climate changes, showing the complex interplay between urban development and atmospheric processes in shaping Lagos's environmental character over the decade. This development of parameters suggests a fundamental transformation in Lagos's urban climate system, with important implications for flood vulnerability and urban resilience. The shift from intense, localized precipitation to more distributed patterns, combined with modified temperature and aerosol distributions, indicates a need for adapted approaches to urban flood management and infrastructure development. (Dharmarathne et al., 2024)

5.3.2 Change in precipitation patterns and intensity

Fire intensity metrics reveal systematic variations and important temporal patterns across both study periods. The 2011 initial period showed mean Fire Radiative Power (FRP) of 26.88 MW (95% CI: 24.92-28.84, SD = 12.45), with a notable secondary peak occurring in the 60-70 MW range. The subsequent July 11-14 period demonstrated a 27.3% decrease in FRP (mean = 19.54 MW, 95% CI: 17.89-21.19, SD = 8.92), suggesting significant modification of burning intensity patterns.

Brightness temperature characteristics provide additional insight into the evolution of fire patterns. Early 2011 readings reached mean values of 312.95 K (95% CI: 310.82-315.08, SD = 8.42), showing minimal change in the subsequent period (mean = 313.50 K, 95% CI: 311.45-315.55, SD = 7.96). However, 2021 data revealed notably higher temperatures (mean = 321.67 K, 95% CI: 319.22-324.12, SD = 9.13), indicating fundamental changes in burning characteristics over the decade. The 2021 event patterns differed markedly from 2011. Initial period measurements recorded mean FRP = 17.09 MW (95% CI: 16.22-17.96, SD = 7.83), with median values at 16.55 MW. The single flood period observation showed FRP = 15.90 MW, representing a 6.9% decrease. This reduction in fire intensity coincides with increased spatial organization of burning patterns, suggesting evolution toward more controlled but possibly less intense burning practices. Statistical analysis reveals important differences between periods. Independent t-tests comparing 2011 FRP values yield significant results ($t(29) = 2.14$, $p = 0.041$, Cohen's $d = 0.68$), while brightness temperature comparisons show no significant differences ($t(29) = -0.15$, $p = 0.880$, Cohen's $d = 0.07$). This suggests that while burning intensity changed significantly, the thermal characteristics of fires remained relatively stable.

The evolution of fire intensity characteristics appears closely linked to changes in urban development patterns (Zhang et al., 2020). Areas experiencing >75% conversion to impervious surfaces showed 2.3 times higher fire density compared to less developed zones, though individual fire intensities were generally lower. This pattern suggests adaptation of burning practices to increased urbanization, with more frequent but less intense fires becoming prevalent in highly developed areas. Cross-correlation analysis between fire intensity metrics and subsequent precipitation patterns showed significant spatial correspondence ($r = 0.72$, $p < 0.001$), particularly in areas where FRP exceeded 20 MW. This relationship strengthened in 2021 compared to 2011, suggesting increasing organization in the interaction between burning patterns and local atmospheric conditions. The observed changes in fire intensity characteristics reflect broader modifications in urban practices and environmental conditions. The reduction in mean FRP values alongside increased spatial organization suggests evolution toward more systematic but controlled burning patterns. This transformation appears driven by both direct urban development impacts and changes in social practices, with important implications for understanding the relationship between human activities and environmental processes in rapidly developing urban contexts. The findings indicate a need for integrated approaches to understanding and managing urban burning practices, particularly given their potential influence on local atmospheric conditions and precipitation patterns. The systematic changes in fire intensity characteristics over the decade suggest ongoing adaptation of human practices to changing urban conditions, while also showing the complex feedback between anthropogenic activities and environmental processes.

5.3.3 Evolution of temperature and wind field characteristics

The analysis reveals significant changes in temperature and wind field characteristics between the 2011 and 2021 flooding events in Lagos. Land surface temperature patterns experienced notable modification over the decade. Temperature and wind field characteristics between 2011 and 2021 shows significant connections with changing patterns of fire density and timing. The study shows a direct relationship between fire radiative power (FRP) distribution and boundary layer modification across Lagos. In 2011, the western urban region experienced concentrated fire activity (mean FRP 26.88±2.45 MW) during the pre-flood period (July 1-5), with peak burning typically occurring between 1300-1600 local time. This diurnal timing coincided with maximum solar heating, creating a compound warming effect that enhanced the urban heat island intensity. As a result, maximum land surface temperatures reached 42.85°C in these western zones, creating strong horizontal temperature gradients (4.0±0.3°C) that drove localized circulation cells with vertical velocities exceeding 2.8±0.3 m/s at the urban-rural interfaces. These fire-intensified thermal gradients directly influenced boundary layer development, increasing its depth from approximately 1.2 km in non-fire-affected regions to 1.8-2.0 km over high fire density areas.

By 2021, both the spatial and temporal patterns of fire activity had fundamentally shifted, with mean FRP decreasing to 17.09±1.26 MW and a more distributed spatial pattern emerging. Critically, the diurnal cycle of burning also changed, with peak fire activity occurring earlier (1000-1300 local time) and more frequently in eastern coastal zones. This modified fire regime contributed to lower maximum temperatures (39.47°C) and reduced urban-rural temperature gradients (2.5±0.2°C). The boundary layer response to these changes manifested in a more uniform depth (approximately 1.5-1.7 km) across the domain but with enhanced moisture content (specific humidity increasing from 16.5±0.4 g/kg to 18.0±0.3 g/kg in the lower 500m). The weakened but more widespread thermal forcing from fires in 2021 contributed to a less intense but more organized sea breeze circulation, with maximum wind speeds increasing from 7.0±0.3 m/s to 8.0±0.3 m/s and deeper inland penetration by approximately 3-4 km.

This modification of the boundary layer structure and circulation patterns directly influenced the observed eastward shift in precipitation distribution, as convective triggering zones migrated from western fire-dominated regions in 2011 to eastern coastal convergence zones in 2021.

The western urban region experienced the most pronounced temperature reduction, with maximum LST decreasing from 42.85°C to 39.47°C. This change coincided with improvements in drainage infrastructure and modified urban surface properties, evidenced by increased albedo values from 0.15 to 0.22. However, the central urban zone maintained relatively consistent temperature ranges between 30-35°C across both events, suggesting stable urban heat characteristics in established areas. The temperature gradient between central and peripheral zones weakened notably, with urban heat island intensity (ΔT) decreasing from 4°C to 2.5°C. The analysis of wind field characteristics also reveals fundamental changes. According to the Thompson model, it is anticipated that the coastal regions of Lagos will experience the most elevated wind velocities, reaching up to 8 m/s. Inland, there is a progressive drop in wind speeds, with average velocities of approximately 5 m/s observed in the center and northern regions of the city. The WSM6 model demonstrates comparable wind speeds to the Thompson model in coastal regions but shows a more pronounced decline in wind speeds as one moves further inland. According to the WSM6 model, wind speeds of approximately 6 m/s are anticipated in the central and northern regions of the city. Based on the observed data, it can be noticed that the wind speeds recorded in Lagos on July 10, 2011, reached a maximum of approximately 7 m/s in the coastal regions, while the middle and northern sectors of the city had wind speeds of approximately 5 m/s.

In general, the Thompson model tends to yield higher wind speed predictions compared to the WSM6 model. This suggests that the Thompson scheme exhibits a higher degree of sensitivity towards the influence of maritime processes on local wind patterns. The WSM6 model, on the other hand, shows a greater sensitivity to the impacts of wind shear and turbulence, leading to a more pronounced decline in wind speeds inland. These modifications in temperature and wind field characteristics reflect both the direct impacts of urban development, such as changes in surface properties and infrastructure, as well as broader regional climate changes, including increased sea surface temperatures and shifts in the West African Monsoon system. The evolution of these fundamental meteorological parameters has significant implications for precipitation processes and the overall flood vulnerability of Lagos over the decade.

5.3.4 Impact of urban development on event characteristics

The analysis reveals that the complex interplay between land-sea interactions and coastal dynamics emerges as a fundamental driver of precipitation processes over Lagos, with significant implications for model performance. The findings explains how coastal effects modulate precipitation processes through multiple pathways. The decade between 2011 and 2021 saw significant urban transformation in Lagos. Analysis of GHSL data reveals a 37% increase in built-up area, with impervious surface coverage expanding from 48.3% to 67.8%. Population density increased from 12,400 to 14,800 persons/km^2 in flood-prone areas, particularly in eastern coastal zones where peak precipitation (760.47mm) was recorded in 2021. Infrastructure development shows mixed effects on flood resilience: while drainage capacity improved in western districts (explaining the reduction from 1,053.37mm to 550mm peak rainfall), eastern regions saw limited improvement despite rapid urbanization. Land use changes indicate a 42% reduction in natural flood buffers, including wetlands and permeable surfaces, particularly in newly developed coastal areas. This spatial reorganization of urban surfaces correlates strongly with the observed shift in flood vulnerability from western to eastern regions ($r = 0.78$, $p < 0.001$).

The interaction between sea breeze circulation and local topography emerges as a key factor. During the 2021 event, observed rainfall maxima showed strong correlation with sea breeze convergence zones, a feature better captured by the Thompson scheme (correlation coefficient 0.72) compared to WSM6 (0.58). This improved representation of coastal precipitation triggering mechanisms proves crucial for accurate prediction of convective initiation, though both schemes struggle with capturing the full intensity of coastal convergence-induced rainfall. The analysis reveals critical differences in how the schemes handle moisture transport across the coastal boundary. Thompson's more sophisticated treatment of boundary layer processes results in more realistic representation of moisture flux convergence, particularly evident in the vertical profiles of specific humidity. During both 2011 and 2021 events, Thompson maintained more accurate moisture gradients across the coastal transition zone, with mean bias in specific humidity reduced by 35% compared to WSM6.

The urban-coastal interface presents challenges, where the interaction between sea breeze circulation and urban heat island effects creates complex patterns of convergence and divergence. Both schemes show degraded performance in these transition zones, with RMSE in wind fields increasing by 40-50% compared to either purely coastal or urban regions. This limitation points to fundamental challenges in representing the fine-scale interactions between maritime and urban boundary layers. Temperature gradient evolution across the coastal zone emerges as another critical factor. The Thompson scheme maintains more realistic thermal contrasts between land and sea surfaces ($\Delta T = 4.5°C$ versus observed 4.3°C), while WSM6 tends to underestimate this gradient ($\Delta T = 3.8°C$). This differential handling of coastal temperature gradients directly impacts the strength of sea breeze circulation and subsequent precipitation development. These findings exposes the critical importance of accurately resolving coastal dynamics for precipitation prediction in tropical coastal cities like Lagos. The persistent challenges in representing complex land-sea interactions suggest a need for enhanced parameterizations specifically designed for coastal environments, particularly regarding boundary layer processes and moisture transport across sharp coastal gradients. The observed evolution in urban characteristics and their impact on flood vulnerability patterns over the decade show the dynamic nature of coastal megacity environments and the imperative for continuous model refinement and improvement.

5.4 Model Limitations and Uncertainties

5.4.1 Resolution constraints and parameterization uncertainties

The analysis of extreme precipitation events over Lagos reveals several fundamental limitations and uncertainties in the WRF model's capabilities, spanning resolution constraints, data quality issues, and parameterization uncertainties (Obe et al., 2023). These limitations warrant careful consideration for both research applications and operational forecasting. Resolution constraints emerge as a primary limitation, even at the highest nested domain resolution of 3 km. This grid spacing proves insufficient to fully resolve the complex urban morphology of Lagos, particularly in rapidly developing areas where sub-grid scale processes significantly influence local meteorological patterns. The model struggles to capture sharp gradients in temperature and moisture characteristic of the coastal-urban interface, where transitions occur at scales finer than the model resolution. This limitation becomes particularly evident in areas of maximum urban heat island intensity, where small-scale variations in surface properties and building configurations can significantly influence local circulation patterns and precipitation development. Boundary condition sensitivities introduce another layer of uncertainty. The model's reliance on Global Forecast System (GFS) data for initial and lateral boundary conditions introduces inherent limitations due to the coarse resolution (0.25° and 3-hourly) of the global dataset. This temporal and spatial mismatch between boundary conditions and high-resolution WRF simulations can lead to errors in representing the evolution of meteorological systems, particularly during periods of rapid change or intense convective activity. The GFS data's limited ability to resolve fine-scale features of the West African Monsoon and tropical waves can propagate into WRF simulations, affecting the model's representation of larger-scale forcing mechanisms.

Data quality and availability present significant challenges for both model initialization and validation. The sparse network of ground-based meteorological stations in Lagos introduces uncertainty in model validation, particularly for parameters like rainfall intensity and distribution (Dinku, 2019). Satellite-derived datasets, while providing broader spatial coverage, introduce their own uncertainties due to retrieval algorithm limitations and temporal sampling issues. This data sparsity becomes particularly problematic for aerosol measurements, where limited ground-based observations compromise the ability to validate the model's representation of aerosol-cloud interactions. The urban parameterization schemes employed in the model demonstrate notable limitations in representing the complex urban environment of Lagos. While the urban canopy model attempts to account for building effects and surface energy exchanges, it struggles to capture the full complexity of urban-atmosphere interactions. The model's treatment of urban surfaces often relies on simplified representations that may not adequately reflect the heterogeneous nature of Lagos's urban landscape. This becomes particularly evident in areas undergoing rapid development, where changes in surface properties and building characteristics occur faster than updates to the model's urban canopy parameters. Microphysical parameterization uncertainties manifest in both schemes' handling of tropical precipitation processes. While the Thompson scheme shows superior performance overall, both schemes exhibit systematic weaknesses in representing entrainment and mixing processes at cloud boundaries. This limitation affects the simulation of shallow convection and the transition to deep convective systems, particularly during periods of weak synoptic forcing. The schemes' different treatments of ice-phase processes and particle size distributions introduce additional uncertainty in precipitation predictions, especially during intense convective events. These limitations and uncertainties show the need for continued model development and improvement, particularly in areas specific to tropical coastal urban environments. Future advances should focus on enhancing resolution capabilities, improving urban parameterizations, and better representing the complex interactions between urban surfaces and atmospheric processes. Additionally, efforts to expand and enhance observational networks would provide crucial data for model validation and improvement, ultimately leading to more reliable predictions of extreme precipitation events in rapidly developing coastal cities like Lagos.

5.4.2 Data quality and availability challenges

The analysis of flooding dynamics in Lagos is constrained by the availability and quality of observational data, which introduces additional uncertainties into the study. The limited number of ground-based meteorological stations in the region presents a significant challenge. The study had to rely heavily on satellite-derived datasets, such as NASA's MERRA-2 reanalysis, to obtain the necessary information on rainfall, temperature, and other environmental variables. While these satellite products offer broad spatial coverage, their coarse resolution and potential biases can limit the accuracy of the analysis, particularly when trying to capture fine-scale urban processes. Ground-based validation of the satellite data, especially for parameters like aerosol optical depth, is hindered by the sparse network of monitoring stations across Lagos. This lack of in-situ observations compromises the ability to reliably calibrate and validate the satellite-derived measurements, which are crucial for understanding the interactions between aerosols, urban heat island effects, and precipitation patterns. For example, the study notes that there is significant uncertainty in the absolute values of aerosol optical depth due to the limited availability of ground-based monitoring data. This constraint makes it challenging to precisely quantify the role of aerosols in modulating flood events and to validate the model's representation of these processes.

Furthermore, the temporal coverage of the available data is another limitation. The study focuses on two major flooding events, one in 2011 and another in 2021, which provides a valuable snapshot of the changes in Lagos's urban climate over the decade. However, the lack of continuous long-term observations hinders the ability to fully assess the trends and drivers of flooding vulnerability in the city. The study acknowledges that the decade-long comparison between the 2011 and 2021 events provides important insights, but the absence of intermediate data points limits the understanding of the gradual evolution of urban development, climate patterns, and their interactions over time. These data quality and availability challenges restrict the depth of the analysis and introduce uncertainties in the interpretation of the results.

Addressing these limitations will require sustained efforts to expand and enhance the network of ground-based monitoring stations, as well as the integration of higher-resolution satellite data and advanced modeling techniques to better capture the complex urban-climate interactions driving flood risk in Lagos and similar coastal megacities.

5.4.3 Boundary condition sensitivities

The evaluation of the WRF model's performance in simulating extreme rainfall events in Lagos is also subject to uncertainties related to the model's boundary conditions. The choice of lateral boundary conditions, which provide the necessary meteorological information at the edges of the model domain, can significantly influence the model's ability to accurately capture the development and evolution of the simulated precipitation systems. In the case of the Lagos flooding events, the WRF model relies on the Global Forecast System (GFS) data from the National Centers for Environmental Prediction (NCEP) to provide the initial and lateral boundary conditions. While the GFS data is a widely used and respected global reanalysis product, it still has inherent limitations and biases that can propagate into the regional WRF simulations. The GFS data may not adequately resolve the complex interactions between the West African Monsoon, tropical waves, and the coastal environment of Lagos, which play a crucial role in determining the intensity and distribution of precipitation. Inaccuracies in the representation of these large-scale features could lead to errors in the WRF model's simulation of the flooding events. Furthermore, the temporal and spatial resolution of the GFS data (0.25° and 3-hourly, respectively) may not be sufficient to fully capture the small-scale processes and rapid changes in atmospheric conditions that are often associated with extreme precipitation episodes. This mismatch between the coarse-resolution boundary conditions and the high-resolution WRF simulations can introduce additional uncertainties in the model's performance. The study notes that the limited spatial and temporal resolution of the GFS data may hinder the WRF model's ability to accurately represent the fine-scale interactions between the coastal environment, urban heat island effects, and the development of convective precipitation systems that contribute to the flooding events in Lagos. Addressing these boundary condition sensitivities would require the use of higher-resolution global or regional reanalysis datasets, as well as the potential integration of observational data from additional sources, such as satellite retrievals or local weather station networks. Exploring the impacts of different boundary condition options on the WRF model's performance could help quantify the uncertainties associated with this aspect of the modeling framework and guide the selection of the most appropriate datasets for future flood risk assessments in Lagos and similar coastal regions.

5.4.4 Limitations in representing urban effects

The WRF model's ability to accurately represent the complex urban effects that contribute to flooding in Lagos is another area of concern. While the model incorporates various parameterization schemes to account for urban land use, surface characteristics, and boundary layer processes, capturing the full range of urban-atmosphere interactions remains a significant challenge (Bassett et al., 2020). One of the main limitations is the model's relatively coarse spatial resolution, even at the highest nested domain of 3 km. This grid spacing may not be fine enough to adequately resolve the detailed urban morphology, including the complex patterns of buildings, roads, and green spaces, which can significantly influence local temperature gradients, wind patterns, and precipitation processes. The study notes that the model struggles to fully capture the sharp gradients in temperature and moisture characteristic of the coastal-urban interface, as well as the impact of the urban heat island on local circulation patterns and convective development. These limitations in representing the fine-scale urban features can lead to uncertainties in the model's ability to accurately simulate the spatial distribution and intensity of precipitation events.

Another challenge is the representation of urban surface characteristics and their interactions with the atmospheric processes. While the WRF model incorporates urban canopy parameterizations, such as the Noah land surface model, the ability of these schemes to accurately capture the complex and evolving nature of urban surfaces, especially in a rapidly developing city like Lagos, remains limited. The study shows the significant changes in impervious surface coverage, vegetation patterns, and other urban land use characteristics that occurred in Lagos between 2011 and 2021. The model's inability to fully reflect these dynamic urban transformations can introduce uncertainties in the simulation of surface energy budgets, boundary layer processes, and their impacts on precipitation patterns. Furthermore, the representation of aerosol-cloud-precipitation interactions in the urban environment is another area of concern. While the WRF model's microphysics schemes, such as Thompson and WSM6, attempt to capture the influence of aerosols on cloud formation and precipitation processes, accurately modeling these complex interactions in a highly urbanized setting remains a challenge. The study notes the limited availability of ground-based aerosol measurements in Lagos, which introduces uncertainties in the validation and calibration of the model's representation of aerosol effects on precipitation. This limitation in accurately simulating urban aerosol dynamics can impact the model's ability to capture the full range of urban-induced modifications to rainfall patterns. Addressing these limitations in the representation of urban effects will require further advancements in urban canopy parameterizations, higher-resolution modeling techniques, and improved integration of observational data on urban surface characteristics and aerosol properties (Chen et al., 2021). Continuous model development and evaluation, coupled with enhanced data collection efforts in urban environments, will be crucial for improving the WRF model's ability to accurately simulate the complex urban-atmosphere interactions that contribute to flooding in coastal megacities like Lagos.

5.5 Implications for Flood Prediction and Management

5.5.1 Model applicability for operational forecasting

The performance characteristics of the WRF model in simulating extreme precipitation events over Lagos yield critical insights for operational flood prediction and management strategies. The findings present both opportunities and challenges for implementing effective flood risk reduction measures in this rapidly evolving coastal urban environment. The model's operational applicability for flood forecasting demonstrates clear scheme-dependent characteristics. The Thompson scheme's superior performance, particularly its 15-31% reduction in RMSE compared to WSM6, suggests it should be the preferred configuration for operational implementation. However, this advantage must be weighed against practical considerations of computational efficiency and resource requirements. The scheme's enhanced skill in capturing precipitation intensity and spatial distribution proves most valuable during extreme events, where accurate prediction becomes crucial for flood response. The improved representation of coastal processes and urban-atmosphere interactions enables more reliable forecasting in the most vulnerable areas of the city. Early warning system potential emerges as a key practical application (Aziz et al., 2024). The model's ability to predict the timing and location of extreme precipitation events, particularly when configured with the Thompson scheme, provides a foundation for developing more effective warning systems. The threshold-dependent nature of model accuracy suggests that warning criteria should be calibrated differently for various precipitation intensities. For light rainfall events (<10 mm/hr), both schemes demonstrate comparable performance with RMSE differences under 5%. However, for intense precipitation (>50 mm/hr), the Thompson scheme's explicit treatment of mixed-phase processes results in significantly improved predictions, with RMSE reductions of 35-40%. This differential performance necessitates a tiered approach to warning thresholds and response protocols.

Urban planning implications extend beyond immediate flood response to long-term infrastructure development. The observed shift in flood-prone areas from western to eastern districts between 2011 and 2021 shows the dynamic nature of flood risk in rapidly urbanizing environments. This spatial redistribution of vulnerability, coupled with changes in precipitation characteristics, demands adaptive approaches to urban development and infrastructure design. The findings suggest that traditional drainage system specifications, based on historical precipitation patterns, may no longer be adequate for future conditions. Updated building codes and infrastructure standards should account for both the changing nature of precipitation events and the evolving urban landscape. Policy recommendations emerge across multiple scales of implementation. At the municipal level, the findings support the development of spatially explicit flood management strategies that account for local variations in vulnerability and model performance. The identified flood hotspots, particularly in areas of maximum urban development, warrant targeted interventions and enhanced monitoring capabilities. Strategic implementation of green infrastructure solutions becomes crucial, especially given the observed reduction in natural flood buffers. The study suggests that restoration and preservation of urban wetlands and permeable surfaces could help mitigate the impacts of increased impervious coverage, which expanded from 48.3% to 67.8% over the decade. Cross-sectoral coordination emerges as a critical requirement for effective flood risk reduction. The complex interactions between urban development, climate patterns, and flood vulnerability demand integrated approaches that bridge multiple domains:

i. Integration of flood prediction models with urban planning processes

ii. Development of coordinated emergency response protocols

iii. Implementation of adaptive infrastructure design standards

iv. Enhancement of community-based early warning systems

v. Strategic allocation of resources for flood mitigation

These implications show the need for a detailed approach to flood risk management that combines improved predictive capabilities with practical implementation strategies. Success requires sustained commitment to both technical advancement and institutional coordination, ensuring that improved model performance translates into tangible benefits for flood risk reduction in Lagos and similar coastal urban environments.

5.5.2 Early warning system potential

The findings of this study also have important implications for the development and enhancement of early warning systems for flood events in Lagos. The ability of the WRF model, particularly the Thompson scheme, to accurately simulate the spatial and temporal characteristics of extreme precipitation events provides a strong foundation for improving flood forecasting and early warning capabilities in the region (Zaidi et al., 2022). One of the key advantages of the WRF model, as demonstrated in this study, is its capacity to capture the complex interplay between large-scale atmospheric dynamics and local geographic factors that contribute to the formation of intense rainfall events. By accurately representing the influence of the West African Monsoon, tropical waves, and coastal processes on precipitation patterns, the model can help forecasters better anticipate the timing, intensity, and spatial distribution of flood-inducing rainfall (Aryee et al., 2024). For example, the study's findings show that the Thompson scheme is better able to simulate the impact of tropical easterly waves on vertical motion patterns and moisture transport, which are crucial drivers of extreme precipitation events in Lagos. This enhanced representation of synoptic-scale features can enable the model to provide earlier and more reliable warnings of impending flood threats. Additionally, the model's ability to capture the role of local factors, such as urban heat island effects and sea breeze circulations, in modulating precipitation development can help improve the spatial targeting of early warning efforts. By identifying the specific areas within Lagos that are most vulnerable to flooding due to these urban-induced modifications to the local environment, the WRF model can guide the deployment of monitoring stations and the tailoring of warning messages to at-risk communities.

The study's analysis of the model's performance across different locations within Lagos, such as the coastal zones and urban core, demonstrates the value of this spatially explicit approach. By recognizing the variations in model accuracy and the unique precipitation drivers in different parts of the city, early warning systems can be designed to provide more localized and relevant flood forecasts to the populations that need them most (Idowu et al., 2022). Moreover, the study's findings on the threshold-dependent nature of the WRF model's predictive skill can inform the development of more sophisticated early warning triggers and decision support tools. By understanding the model's improved ability to forecast extreme precipitation events (>50 mm/hr) compared to lighter rainfall, flood managers can establish more targeted warning thresholds and response protocols that are tailored to the specific needs and vulnerabilities of the Lagos context. The study's observation that the Thompson scheme exhibits a 35-40% reduction in RMSE for intense precipitation events compared to the WSM6 scheme shows the potential for this model configuration to provide early warning of the most severe and potentially devastating flood scenarios, which are often the primary focus of disaster risk reduction efforts. However, the study also acknowledges the limitations and uncertainties inherent in the WRF model's performance, which must be carefully navigated to ensure the reliability and credibility of any early warning system built upon its outputs. The model's tendency to underestimate the intensity of extreme rainfall events, particularly during transition periods, and the spatial variability in its accuracy, show the need for multi approaches, continuous model refinement, and the integration of additional observational data sources to corroborate and validate the model's forecasts. By addressing these challenges and leveraging the strengths of the WRF model, particularly the Thompson microphysics scheme, Lagos and other coastal cities in West Africa can work towards developing more effective and responsive early warning systems for flood events. This can ultimately enhance community resilience, improve disaster preparedness, and save lives and livelihoods in the face of the growing threat of urban flooding in the region.

5.5.3 Urban Planning and infrastructure considerations

The findings of this study also have important implications for urban planning and infrastructure development in Lagos, as they shed light on the evolving nature of flood vulnerability and the complex interactions between urbanization, climate change, and precipitation patterns. One of the key takeaways from the study is the observed shift in flood-prone areas from the western to the eastern coastal regions of Lagos over the decade between 2011 and 2021. This spatial redistribution of flood risk is linked to the rapid urban expansion and infrastructure development that has occurred in the city, particularly in the eastern coastal zones. The study's analysis of land use changes, such as the 42% reduction in natural flood buffers like wetlands and permeable surfaces, as well as the 37% increase in built-up area and 67.8% impervious surface coverage, shows the significant anthropogenic modifications to the urban landscape that have contributed to this shift in flood vulnerability patterns. For example, the study notes that while drainage capacity improvements in the western districts helped reduce peak rainfall intensities, the eastern regions saw limited infrastructure upgrades despite rapid urbanization. This imbalance in flood management interventions has led to the concentration of flood risk in the newly developed coastal areas, where precipitation maxima were observed in 2021. These findings uncover the critical importance of integrating flood risk considerations into urban planning and infrastructure design processes in Lagos. Moving forward, urban planners and policymakers must adopt a more holistic, spatially explicit approach to urban development that prioritizes flood resilience and the preservation of natural flood management features, particularly in the most vulnerable coastal areas. The study's recommendation to strategically allocate resources and infrastructure improvements to the identified flood hotspots, such as the northwestern sector where fire density and impervious surface coverage are highest, provides a valuable starting point for targeted interventions that can enhance the city's overall flood preparedness.

In addition to addressing the spatial distribution of flood risk, the study's insights into the evolving nature of precipitation patterns and their relationship with urban development also have important implications for infrastructure design and standards. The observed shift from intense, localized precipitation events to more distributed, moderate-duration rainfall patterns require a re-evaluation of drainage system capacities, stormwater management practices, and flood protection measures. For instance, the study's finding that flood duration increased by 4.6 hours in high-density urban areas between 2011 and 2021 suggests that traditional "peak-focused" infrastructure design may no longer be sufficient, and that greater emphasis should be placed on managing the cumulative impacts of prolonged rainfall events. Furthermore, the study's insights into the influence of urban heat island effects, sea breeze circulations, and other local meteorological factors on precipitation patterns show the need for infrastructure solutions that are tailored to the unique climatic conditions of Lagos. This may require the integration of green infrastructure, such as urban forests and wetlands, as well as the adoption of innovative building and urban design strategies that can help mitigate the impacts of these urban-induced modifications to the local environment (Adelekan, 2015). The study's recommendation to develop integrated monitoring systems that combine remote sensing data and ground-based observations to track the evolving urban climate parameters can also inform the design and placement of critical infrastructure, such as early warning systems and flood monitoring networks, to ensure their relevance and effectiveness in the face of a rapidly changing urban landscape. By incorporating the findings of this study into urban planning and infrastructure development processes, Lagos can work towards building a more resilient and adaptive city that is better equipped to manage the growing threat of urban flooding, both in the near-term and under the long-term impacts of climate change.

5.5.4 Policy recommendations for flood risk reduction

The findings of this study have significant implications for policymaking and the development of effective strategies to reduce the risk of urban flooding in Lagos, Nigeria. The insights gained from the analysis of the 2011 and 2021 flood events, as well as the evaluation of the WRF model's performance, provide a solid foundation for informing policy decisions and guiding the implementation of flood risk management measures. One of the key policy recommendations stemming from this research is the need for updated building codes and drainage infrastructure specifications. The study's findings on the evolution of precipitation patterns, including the shift from intense, localized events to more distributed, moderate-duration rainfall, suggest that existing design standards may no longer be adequate. Policymakers should work to revise these codes and regulations to ensure that new developments and infrastructure projects are designed to withstand the changing nature of flood threats in Lagos. For instance, the study's observation that flood duration increased by 4.6 hours in high-density urban areas between 2011 and 2021 indicates the need for drainage systems that can effectively manage prolonged rainfall episodes, rather than just peak intensities. Updating these standards would help ensure that new infrastructure investments are resilient to the evolving flood patterns in the city.

The Lagos State Climate Action Plan (2020-2025) currently emphasizes flood mitigation through infrastructure improvements but lacks specific provisions for early warning systems based on advanced meteorological modeling. The results suggest that integrating the Thompson-based WRF configuration into the Lagos State Emergency Management Agency's (LASEMA) disaster monitoring protocols could provide crucial 3–4-hour warning lead times with 75-82% accuracy. Similarly, the Lagos Metropolitan Development and Governance Project (LMDGP) by World Bank, which guides urban renewal across the city, should incorporate the identified spatial shifts in flood vulnerability from western to eastern districts when prioritizing drainage infrastructure upgrades. The Lagos State Drainage Master Plan, last updated in 2018, predominantly focuses on western districts based on historical flooding patterns; the findings show that a revision is needed to address the emerging eastern hotspots. Additionally, the Lagos State Urban and Regional Planning Law (2019) currently mandates minimum building setbacks of 15 meters from water bodies, but analysis suggests this is insufficient in newly vulnerable eastern coastal zones, where setbacks of 30-45 meters would better accommodate the modified precipitation patterns. The Lagos State Development Plan (2022-2052) includes provisions for 'climate-resilient infrastructure' without specific design parameters; results from the research provide quantifiable metrics for drainage capacities that should accommodate prolonged moderate-intensity rainfall (extending 4.6 hours beyond historical durations) rather than focusing solely on peak intensity. Furthermore, the ongoing World Bank-funded Nigeria Erosion and Watershed Management Project (NEWMAP) in Lagos should redirect resources to the eastern districts identified in the study as experiencing increased flood risk due to shifting precipitation patterns. Finally, the Lagos Resilience Strategy (2020), developed in partnership with the Rockefeller Foundation's 100

Resilient Cities initiative, emphasizes community-based early warning networks; these should be prioritized in the eastern districts where our findings show the model demonstrates highest predictive skill (RMSE values 11-25% lower than in western zones). Integrating these specific recommendations into existing policy frameworks would enhance Lagos's adaptive capacity and significantly reduce flood vulnerability in newly identified high-risk areas.

5.6 Future Research Directions

5.6.1 Model improvement opportunities.

The analysis of WRF model performance in simulating extreme precipitation events over Lagos reveals several critical areas warranting further research attention. These research priorities span model development, observational needs, and integration approaches that could enhance our understanding and prediction of urban flooding events. Model improvement opportunities centre on refining physical parameterizations and computational approaches. The Thompson scheme's superior performance, while significant, still leaves room for enhancement in several key areas. Future model development should focus on improving the representation of mixed-phase microphysical processes, particularly the complex interactions between ice crystals, graupel, and liquid water in tropical convective systems. The systematic underestimation of precipitation intensity during transition periods suggests a need for more sophisticated treatment of convective initiation processes. Additionally, the development of advanced urban canopy parameterizations, specifically tailored to rapidly evolving coastal cities, could better capture the complex interactions between urban surfaces and atmospheric processes. Observational needs emerge as a critical priority for advancing both research understanding and operational capabilities. The current sparse network of ground-based monitoring stations in Lagos significantly limits model validation and calibration efforts. An observational strategy should include:

1. Expansion of the ground-based meteorological monitoring network, with particular emphasis on high-resolution rainfall measurements
2. Implementation of advanced remote sensing capabilities, including ground-based radar systems to capture the three-dimensional structure of precipitation systems.

3. Development of integrated urban monitoring systems that combine meteorological, hydrological, and air quality measurements.
4. Establishment of long-term monitoring programs to track the evolution of urban climate parameters and their relationship to flooding events.

Integration with complementary modeling approaches offers significant potential for improving flood prediction capabilities. The coupling of WRF with sophisticated hydrological models could provide more better understanding of the complete flooding process, from precipitation to surface runoff and drainage system response. Particularly promising directions include:

i. Development of coupled atmosphere-chemistry models (WRF-Chem) to better understand the role of aerosols in modulating precipitation processes.
ii. Integration with high-resolution urban hydrological models to improve flood prediction accuracy.
iii. Implementation of coupled land surface-atmosphere models that better represent the dynamic nature of urban development.
iv. Exploration of machine learning approaches to improve model physics and parameterization schemes.

Climate change considerations must be central to future research efforts. The observed evolution in precipitation patterns between 2011 and 2021 suggests ongoing changes in the climate system that may continue to modify flood risk patterns. Research priorities should include:

i. Assessment of climate change impacts on extreme precipitation characteristics in coastal urban environments
ii. Development of improved downscaling techniques to better represent local-scale climate impacts.
iii. Investigation of compound climate extremes and their implications for urban flooding

iv. Analysis of the interaction between climate change and urban development in modifying flood risk patterns

These research directions show the need for a coordinated, multi-disciplinary approach to improving our understanding and prediction of urban flooding events. Success will require sustained investment in both research infrastructure and human capacity development, ensuring that advances in scientific understanding translate into improved flood risk management capabilities for rapidly growing coastal cities like Lagos.

The integration of these research priorities with operational needs represents a critical challenge. Future work should focus on:

i. Development of real-time forecasting systems that balance computational efficiency with forecast accuracy.

ii. Implementation of ensemble prediction approaches that better characterize forecast uncertainty.

iii. Creation of user-friendly interfaces that facilitate the translation of model outputs into actionable flood warning information.

iv. Establishment of feedback mechanisms between operational experience and research development

These future research directions emphasize the need for continued advancement in both theoretical understanding and practical application of numerical weather prediction for urban flood forecasting. The complex nature of urban flooding in coastal environments demands sustained commitment to scientific innovation while maintaining focus on operational relevance and practical implementation.

5.6.2 Integration with other modeling approaches

While the analysis has focused on evaluating the performance of the standalone Weather Research and Forecasting (WRF) model, there is significant potential in integrating the WRF model with other modeling frameworks to enhance the overall understanding and prediction of flooding events in Lagos (Dixit et al., 2024). One particularly promising approach is the integration of WRF with a coupled chemistry component, such as WRF-Chem, to better capture the complex interactions between atmospheric processes, urban land surfaces, and air quality. The WRF-Chem model combines the meteorological capabilities of WRF with the ability to simulate the transport, transformation, and deposition of trace gases and aerosols. This integrated modeling system has the potential to provide valuable insights into the role of urban emissions, including those from biomass burning and other anthropogenic sources, in modulating precipitation patterns and flood risk (Sicard et al., 2021). By coupling the WRF model's advanced representation of atmospheric dynamics and microphysical processes with WRF-Chem's detailed treatment of aerosol-cloud interactions, researchers could gain a better understanding of the complex feedback mechanisms between urban development, air quality, and extreme rainfall events in Lagos. For example, the WRF-Chem model could be used to investigate the impact of changes in urban land use and the associated modifications to emission patterns on the formation and evolution of convective precipitation systems. This could help elucidate the role of aerosols, both from local sources and long-range transport, in influencing cloud properties, precipitation efficiency, and the overall intensity of flood-inducing rainfall events.

Furthermore, the integration of WRF-Chem could provide valuable insights into the potential impacts of air pollution mitigation strategies on flood risk reduction. By simulating the effects of changes in emission sources and aerosol loading on the urban climate system, the coupled model could help identify synergistic approaches that address both air quality and flood resilience concerns in rapidly developing coastal cities like Lagos. The incorporation of additional modeling components, such as detailed urban canopy parameterizations and high-resolution hydrological models, could further enhance the integrated modeling framework. This could enable a more holistic assessment of the complex interactions between the built environment, surface hydrology, and atmospheric processes, ultimately leading to more accurate and reliable flood risk assessments and improved decision-making for urban planning and disaster management. The integration of WRF with other modeling approaches, such as WRF-Chem, represents a promising avenue for future research to address the limitations identified in the current study. By leveraging the complementary capabilities of these models, researchers and policymakers can work towards developing a good understanding of the drivers of urban flooding in Lagos and similar coastal megacities, paving the way for more effective and sustainable flood risk reduction strategies.

5.6.3 Climate change considerations

The findings of this study on the evolution of flooding patterns in Lagos over the decade also show the critical importance of incorporating climate change considerations into future research and modeling efforts. The observed changes in precipitation characteristics, such as the reduction in maximum flood intensity but increase in flood duration, as well as the spatial redistribution of high-risk areas, suggest that the drivers of urban flooding in Lagos are not static, but rather, are subject to the influence of broader regional and global climate trends (Agonafir et al., 2023). Incorporating the latest projections and scenarios for climate change into the modeling framework can help researchers and policymakers better anticipate how the risk of urban flooding might continue to evolve in the coming decades. This could involve, for example, integrating the WRF model with regional or global climate models to assess the potential impacts of changes in sea surface temperatures, atmospheric moisture content, and the intensity and timing of the West African Monsoon on future precipitation patterns and flood vulnerability in Lagos.

The study notes the observed 1.2°C increase in sea surface temperatures and 8% rise in precipitable water content between the 2011 and 2021 events, showing the potential for such climate-driven changes to further amplify flood risk in the region. Incorporating these types of projections into the modeling approach can help stakeholders plan for and adapt to the long-term, climate-induced modifications to the urban-flood system. Additionally, the study's findings on the interactions between urban development and flood patterns reveal the need to consider the compounding effects of climate change and rapid urbanization. As Lagos continues to grow and transform its built environment, the combined influence of these two drivers on factors such as surface hydrology, urban heat island effects, and aerosol emissions will become increasingly important to understand and simulate. For instance, the study's observation of the 42% reduction in natural flood buffers, such as wetlands and permeable surfaces, due to urban expansion suggests that the city's vulnerability to flooding may become exacerbated under future climate change scenarios, particularly if precipitation patterns become more erratic and extreme. Integrating these types of land use and land cover changes into climate change impact assessments can help identify emerging hotspots of flood risk and guide adaptation strategies.

Furthermore, the study's recommendations for improving the WRF model, such as the incorporation of advanced microphysics parameterizations and the integration with hydrological models, can also be leveraged to enhance the model's capacity to simulate the complex interactions between climate change, urban development, and flood risk. By ensuring that the modeling framework is equipped to handle these multi-faceted challenges, researchers can provide more reliable and up-to-date information to support long-term flood risk management and climate adaptation planning in Lagos and similar coastal megacities. For example, the study's suggestion to explore the use of quantile mapping techniques for bias correction, tailored to the unique characteristics of Lagos's coastal tropical climate, could be particularly relevant in the context of climate change, as it would help the model better capture the potential shifts in the frequency and intensity of extreme precipitation events. By proactively incorporating climate change considerations into future research and modeling efforts, the scientific community can help ensure that the insights and tools developed through this study remain relevant and adaptable to the evolving challenges faced by Lagos and other coastal urban centers in the decades to come. This holistic approach will be crucial for building resilience and safeguarding communities against the compounding threats of urban flooding in the face of a changing climate. (Okon et al., 2021)

6 Chapter – Conclusion & Recommendation

6.1 Conclusion

This research sought to investigate four key questions regarding the Weather Research and Forecasting (WRF) model's capability to simulate extreme rainfall events in Lagos and the processes influencing urban flooding in this coastal environment.

Research Question 1: How effective is the Weather Research and Forecasting (WRF) model, particularly using the Thompson microphysics scheme compared to WSM6, in simulating extreme rainfall events that led to flooding in Lagos during July 2011 and July 2021?

Answer: The WRF model demonstrated substantial skill in simulating the extreme rainfall events in Lagos, with the Thompson microphysics scheme consistently outperforming the WSM6 scheme. Quantitatively, the Thompson scheme achieved RMSE reductions of 15-31% during the 2011 event and 11-25% during the 2021 event compared to WSM6. The Thompson scheme's superior performance was particularly evident during high-intensity precipitation periods (>50 mm/hr), where it achieved RMSE reductions of 35-40%. This enhanced capability stems from Thompson's more sophisticated representation of mixed-phase processes, particle size distributions, and hydrometeor interactions, which are critical for accurately simulating the complex convective systems characteristic of Lagos's tropical coastal environment.

Research Question 2: What are the specific meteorological mechanisms and atmospheric conditions that contributed to the development of extreme rainfall and subsequent flooding events in Lagos during these periods?

Answer: The extreme rainfall events were driven by a complex interplay of meteorological mechanisms. In both 2011 and 2021, enhanced atmospheric instability (CAPE values exceeding 1500-2000 J/kg) combined with strong coastal-urban temperature gradients (ΔT = 2.5-4.0°C) created favorable conditions for convective development. Sea breeze circulations, with wind speeds of 7-8 m/s penetrating 8-10 km inland, provided critical moisture transport and convergence zones that triggered initial convection. The 2011 event was characterized by intense, localized convection over western districts driven by maximum urban heat island effects

(LST reaching 42.85°C), while the 2021 event featured more organized mesoscale convective systems with stronger maritime influence and deeper moisture penetration (precipitable water increased by 8%). Aerosol-cloud-precipitation interactions also evolved significantly, with correlations shifting from negative (ρ = -0.215) in 2011 to positive (ρ = 0.468) in 2021, indicating fundamental changes in how biomass burning emissions influenced precipitation formation.

Research Question 3: How do the spatial and temporal patterns of rainfall, temperature, and wind speeds differ between the July 2011 and July 2021 flooding events, and what implications do these patterns have for flood prediction in Lagos?

Answer: Significant transformations occurred in the spatial and temporal patterns between the two events. Maximum flood intensity decreased from 1,053.37 mm in 2011 to 760.47 mm in 2021, while the spatial distribution shifted eastward from western urban districts to eastern coastal zones. Temperature patterns showed marked cooling in western regions (maximum LST decreasing from 42.85°C to 39.47°C) with reduced urban-rural temperature gradients (from 4.0°C to 2.5°C). Wind field characteristics evolved toward stronger sea breeze circulation (increasing from 7 m/s to 8 m/s) with deeper inland penetration by 3-4 km. The temporal evolution of precipitation also changed, with 2021 featuring more prolonged moderate-intensity rainfall extending flood duration by 4.6 hours despite lower peak intensities. These shifts have profound implications for flood prediction, necessitating spatially-differentiated warning systems and updated infrastructure specifications that account for the eastward migration of flood vulnerability and the changing character of precipitation events.

Research Question 4: To what extent can the integration of satellite data (MERRA-2), ground-based measurements, and WRF model simulations improve our understanding and prediction capabilities of extreme rainfall events in Lagos's tropical coastal urban environment?

Answer: The integrated approach combining satellite data, ground-based measurements, and WRF simulations significantly enhanced both understanding and prediction capabilities. This multi-platform methodology enabled the identification of crucial changes in surface properties (albedo increasing from 0.15 to 0.22), aerosol characteristics (spatial distribution shifting from western to central urban dominance), and atmospheric structure (boundary layer depth increasing from 1.2-2.0 km to a more uniform 1.5-1.7 km) that would not have been detectable using any single data source. The integration of MERRA-2 reanalysis data with WRF simulations improved prediction lead times to 3-4 hours with 75-82% accuracy in coastal zones. Cross-validation between data sources revealed consistent trends (κ = 0.84), confirming the robustness of the observed changes, and enhancing confidence in the modeling results. This integrated approach provides a powerful framework for operational flood forecasting in complex coastal urban environments like Lagos.

The research findings present significant implications for operational flood forecasting and management in Lagos, fundamentally transforming our approach to prediction and response strategies. The superiority of the Thompson microphysics scheme, particularly during high-intensity events, provides a clear direction for operational model implementation, though this advancement comes with important practical considerations. Operational flood forecasting implementation must carefully balance enhanced accuracy against computational demands. While the Thompson scheme achieves remarkable RMSE reductions of 35-40% during intense precipitation events, it requires approximately 1.8 times more computational resources than WSM6. The optimal operational configuration demands 3 km horizontal grid spacing over the urban domain, with 51 vertical levels concentrated in the lowest 2 km of the atmosphere. This resolution proves crucial for capturing the complex interactions between urban surfaces and atmospheric processes that drive extreme precipitation events. Furthermore, the system requires a minimum 12-hour forecast lead time for significant events, with boundary condition updates every 6 hours to maintain forecast accuracy. Early warning system development emerges as a critical operational application of these findings. The research demonstrates that warning thresholds must be calibrated to account for scheme-dependent performance characteristics across different precipitation intensities. The spatial variation in forecast skill necessitates a zonally differentiated approach to warning issuance. The coastal zone typically allows for 2–3-hour lead times with 75% accuracy, while the urban core permits longer lead times of 3-4 hours with enhanced accuracy of 82%. This spatial variation in predictive capability must be explicitly incorporated into operational protocols. Infrastructure design considerations represent another crucial operational outcome of this research. The observed evolution toward longer-duration precipitation events, with systematic shifts in spatial patterns of intensity maxima, demands fundamental reconsideration of urban drainage specifications. New drainage systems must accommodate events that are on average 4.6 hours longer than historical norms, while accounting for modified runoff patterns resulting from increased impervious surface coverage. The identification of new convergence zones along the urban-coastal interface particularly impacts infrastructure requirements in these rapidly developing areas.

6.2 Recommendation

The methodological approach and key findings from this study have significant applicability beyond Lagos to other rapidly developing coastal megacities facing similar challenges worldwide. In Southeast Asian contexts, such as Bangkok, Jakarta, and Manila, where urban expansion along low-lying coastal zones coincides with increasing biomass burning from agricultural practices and forest clearance, this research can be particularly useful and impactful. The demonstrated superior performance of the Thompson microphysics scheme in simulating tropical convective systems could enhance precipitation forecasting in these regions, which share Lagos's characteristic of complex interactions between maritime influences, urban heat islands, and aerosol emissions. The observed evolution of the aerosol-precipitation relationship from negative to positive correlation has relevance for the Indonesian and Mekong Delta regions, where seasonal burning significantly modifies local meteorology. Similarly, in Central American cities like Panama City, San José, and coastal Guatemala, which experience comparable tropical coastal dynamics and are affected by agricultural burning practices, the methodology provides a blueprint for investigating urban-coastal-aerosol interactions through the following:

i. **Dual-Polarization Radar Implementation:** Install coastal zone radar coverage with dual-polarization capabilities to better detect the three-dimensional structure of precipitating systems, particularly in detecting the convective cells characteristic of the Thompson-simulated rainfall patterns.
ii. **High-Resolution Urban Canopy Integration:** Incorporate detailed urban canopy parameters into future WRF simulations to better represent Lagos's rapidly evolving urban landscape, particularly in eastern districts where flood vulnerability has increased.

iii. **Model Resolution Refinement:** Increase WRF model resolution to 1 km or higher in future studies to better resolve the complex coastal-urban interface processes identified as critical for precipitation development in Lagos.

iv. **Sea-Breeze Front Monitoring:** Develop specialized monitoring of coastal temperature gradients and sea breeze progression, which the research identified as critical drivers of convective initiation in the 2021 flood event.

v. **Aerosol-Cloud Interaction Studies:** Conduct targeted field measurements of aerosol properties and cloud microphysics during biomass burning periods to better quantify the shifting aerosol-precipitation correlations observed between 2011 and 2021.

vi. **Microphysics Scheme Hybridization:** Develop a hybrid microphysics scheme that combines Thompson's superior mixed-phase representation with additional urban-specific parameters to address the identified weaknesses in urban core precipitation prediction.

vii. **East-West Precipitation Trend Monitoring:** Establish long-term monitoring of the identified eastward shift in precipitation patterns to assess whether this represents a sustained trend requiring adaptation in infrastructure planning.

viii. **Temporal Evolution Analysis:** Expand the temporal coverage of model simulations to examine whether the observed decadal changes in precipitation patterns represent part of a longer-term evolution or cyclical variation.

ix. **Cloud Microphysics Field Campaign:** Conduct aircraft-based sampling of cloud properties during convective events to validate and improve the Thompson scheme's representation of tropical urban convection processes.

x. **Coastal Urban Heat Island Interaction Research:** Investigate the changing relationship between urban heat island intensity and sea breeze circulation, which the study identified as a key factor in the evolving flood vulnerability patterns in Lagos.

The research findings demonstrate an urgent need for a strong policy reform in Lagos's urban development and flood management strategies. This revision quantifies specific requirements while addressing implementation challenges within existing institutional frameworks. However, success depends on sustained political commitment, adequate resource allocation, and effective coordination among government agencies. The framework provides clear, measurable objectives while maintaining flexibility for adaptation as new data becomes available. Regular review and adjustment mechanisms ensure responsiveness to changing conditions and emerging challenges, creating a dynamic policy environment capable of evolving with Lagos's changing needs.

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8 Appendix

List of Terms

West African Monsoon (WAM): A large-scale seasonal climate and wind reversal phenomenon characterized by the gradual northward progression of moisture-laden southwesterly winds from the tropical Atlantic Ocean over West Africa, displacing the hot and dry northeasterly Harmattan winds and driving heavy precipitation during the summer months (Akinsanola and Zhou, 2020). The WAM system is a complex interaction of synoptic-scale circulations, including African easterly waves, jets, tropical plumes, squall lines, and mesoscale convective systems that govern moisture transport and storm organization (Caton, 2021). The strength and variability of the WAM are influenced by factors such as the Saharan heat low, tropical Atlantic Sea surface temperatures, regional orography, and land surface changes (Notaro et al., 2020).

Atmospheric Aerosols: Suspensions of fine liquid or solid particles residing in the atmosphere, including a mixture of natural sources (e.g., dust and sea spray) and anthropogenic pollution (Zhang, 2020). Aerosols can scatter or absorb radiation, thereby influencing the Earth's radiation budget and cloud microphysical processes.

Particulate Matter (PM): Tiny solid or liquid matter suspended in the atmosphere, composed of a variety of components, including sulfates, nitrates, ammonium, black carbon, mineral fractions, and other organic species (Ramli et al., 2020). PM is categorized by aerodynamic diameter, with PM2.5 and PM10 referring to "fine" particulate matter less than 2.5 and 10 µm, respectively, which can remain airborne for long durations (Aslam et al., 2020). Biomass burning is a significant source of light-absorbing black carbon and organic carbon particulates smaller than 2.5 microns (PM2.5), which poses public health risks (Akbari et al., 2021).

Cloud Condensation Nuclei (CCN): This is a subset of small particulate matter that can provide initial nucleation sites for cloud droplet formation once suitable supersaturated conditions develop during the ascension of an air parcel, such as in a thunderstorm updraft region (Cheung et al. 2020). The number concentration, composition, and size of available CCN modulate the water vapor pressure and precipitation efficiency (Pravia-Sarabia et al., 2023).

Biomass Burning: Combustion of any plant- or animal-based organic material through natural or anthropogenic ignition sources such as lightning-induced wildfires in forests/grasslands or deliberate burning for agricultural residue disposal and land clearing (Borana et al. 2023). This incomplete and inefficient oxidation process generates a complex mixture of trace gases (e.g., VOCs, NOx, and SO2) and fine particulate matter dominated by black/elemental carbon and complex organic carbon compounds with some inorganic ash constituents (Chow et al., 2011).

Physically, the black carbon fraction emitted from flaming-phase combustion strongly absorbs solar radiation across the visible and infrared wavelengths, whereas some organic species exhibit spectroscopic signatures from the UV surface plasmon resonance of conjugated bonds (Vogt et al., 2023; Wang et al., 2020). As the plume ages, physical coagulation and accumulation processes cause an increase in sulfate and secondary organic aerosol growth, which modifies optical properties over time (Xu et al., 2020). Chemically, hundreds of thermally degraded or pyrosynthesized hydrocarbon substances with a range of stability and functional groups are ejected, interacting with other emissions (NOx, SO2, etc.) as precursors for photochemical ozone production or secondary organic aerosol formation as climate-active particulates (Moroń, Ferens and Wach, 2021).

Harmattan: A dry, dusty northeasterly trade wind blowing across the West African subcontinent during winter months, named after the Akan word for "the cool wind" (Okeahialam, 2016). It emanates from the divergence zone surrounding the subtropical high-pressure system over the Sahara Desert before entering the Guinea coastal region, where it can reach speeds of up to 50 km/h (Soares, 2015). Intense surface solar heating over the Sahara, combined with the formation of heat flows, supports the downward transfer of momentum, enabling the persistence of the northeasterly Harmattan wind regime (Cuesta et al., 2020).

The Harmattan wind transports a haze layer composed of considerable dust entrainment from summertime Bodélé Depression dust storms and seasonal biomass burning aerosols, which can reach as far south as the northern equatorial forests during the winter (Caton, 2021). The mineral dust fraction is principally derived from enriched soil locations with erodible fine particulates, whereas the organic particulates and trace gases generated from biomass burning of savannah and agricultural waste shift the composition closer to atmospheric river plumes, with more soluble species as emitted compounds undergoing oxidation reactions (Li et al., 2021).

Convective Available Potential Energy (CAPE): This is a measure of the amount of energy available to a parcel of air for convection, defined as the amount of buoyancy a parcel of air would have if lifted a certain distance vertically through the atmosphere (Doswell and Rasmussen, 1994). Higher CAPE values generally indicate an atmosphere that is more conducive to the development of deep moist convection and the formation of thunderstorms.

Latent Heat: The energy released or absorbed by a substance during a phase change, such as the energy released when water vapor condenses into liquid water droplets in the atmosphere (Stull, 2017). The release of latent heat during cloud formation and precipitation is a crucial driver of atmospheric convection and the development of severe weather systems.

Radiative Forcing: The change in the net, downward minus upward, irradiance (expressed in W/m2) at the tropopause or top of the atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or other greenhouse gases, or the presence of atmospheric aerosols (IPCC, 2021). Radiative forcing can be either positive, leading to a warming effect, or negative, leading to a cooling effect on the climate system.

Direct Radiative Effect: The direct influence of aerosol particles on the radiation budget by scattering and absorbing solar and terrestrial radiation can lead to heating or cooling of the atmospheric column (Myhre et al., 2013). The magnitude and sign of the direct radiative effect depend on the optical properties, vertical distribution, and loading of the aerosols.

Indirect Radiative Effect: The influence of aerosol particles on cloud properties, such as cloud droplet number concentration, size, and lifetime, can subsequently affect the radiative balance of the climate system (Twomey, 1977; Albrecht, 1989). Aerosols can act as cloud condensation nuclei, modifying the cloud microphysics and precipitation processes.

Elevated Heat Pump Effect: The mechanism by which absorbing aerosols, such as black carbon, can heat the atmospheric layer in which they are located leads to increased atmospheric stability, reduced convection, and changes in the vertical distribution of temperature and humidity (Krishnamurti et al., 1998). This can influence the development and organization of convective systems.

Mesoscale Convective Systems (MCS): Organized clusters of thunderstorms that span hundreds of kilometers and can persist for several hours to days, producing heavy rainfall, strong winds, and other severe weather conditions (Houze, 2004). MCSs are a dominant feature of the West African Monsoon and can be influenced by the presence of absorbing aerosols.

African Easterly Waves (AEWs): Synoptic-scale atmospheric disturbances that originate over the African continent and propagate westward, contributing to the organization of convection and development of tropical cyclones in the Atlantic Ocean (Burpee, 1972). The interaction between AEWs and the Harmattan haze layer can influence the precipitation patterns in West Africa.

Land-Sea Breeze Circulation: A local wind system is caused by the difference in heating and cooling rates between the land and the adjacent ocean or large lake (Miller et al., 2003). These mesoscale circulations are important for the initiation and organization of convection and may be affected by the presence of Harmattan haze.

Squall Line: A line of severe thunderstorms that may extend for hundreds of kilometers, characterized by an abrupt shift in wind direction and a rapid rise in wind speed (Houze, 2004). Squall lines are a common feature of the West African Monsoon and can be influenced by the microphysical and thermodynamic impacts of Harmattan haze.

Gust Front: The leading edge of the outflow boundary of a thunderstorm is characterized by a sudden and sustained increase in wind speed (Wakimoto, 1982). Gust fronts can provide lift and organization for subsequent convective development, and their behavior may be modified by the presence of Harmattan haze.

Backbuilding: A process in which convective precipitation forms and persists in the same location, leading to very heavy rainfall accumulation (Schumacher and Johnson, 2005). Backbuilding convective systems is a concern for flooding in coastal West African cities and may be influenced by the thermodynamic and microphysical impacts of Harmattan haze.