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Wrfchem Simulations Of Aerosol Radiative Forcing Impacts On Extreme Climate Events In West African Region

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Abstract:
***Background**: West Africa is a region grappling with the impacts of climate change, including an increasing frequency and intensity of extreme weather events such as droughts, heat waves, and heavy precipitation leading to floods. These extremes pose significant threats to the region's agriculture, water resources, and socioeconomic development. Among the various factors influencing the regional climate, aerosols have emerged as a crucial player due to their ability to alter the Earth's radiative balance through scattering and absorption of solar and terrestrial radiation*
***Materials and Methods:** This study investigates the intricate interplay between aerosol radiative forcing and extreme climate events in West Africa through numerical modeling. The Weather Research and Forecasting model with Chemistry (WRFChem) is employed to simulate the dynamic interactions among aerosol emissions, atmospheric processes, and radiative forcing within the region. Observational data assimilation and numerical experimentation are combined to provide comprehensive insights into the influence of aerosol radiative forcing on atmospheric dynamics, energy distribution, and extreme climate events over diverse West African landscapes.*
***Results:** The findings contribute to advancing the understanding of regional climate dynamics in West Africa and provide valuable insights for climate modeling and prediction efforts. Furthermore, the outcomes offer important implications for climate resilience and adaptation strategies, emphasizing the need for targeted interventions to mitigate the impacts of aerosol-induced radiative forcing on extreme weather events in the region.*
***Conclusion**: In conclusion, this research highlights the crucial role of aerosols in modulating extreme climate events and their potential to exacerbate the region's vulnerability to climate change impacts. By elucidating the intricate mechanisms involved, the study paves the way for more accurate climate projections and informed decision-making processes aimed at enhancing the resilience of West African communities and ecosystems against the escalating threats posed by a changing climate.*
***Key Word**: aerosol, radiative forcing, extreme, climate, events and modelling*

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I. Introduction

Aerosols are suspended particulate matter in the atmosphere and play a crucial role in modulating the Earth's radiative balance and climate system[1]. Through their interactions with solar and terrestrial radiation, aerosols can exert a direct radiative forcing by scattering and absorbing radiation, as well as an indirect radiative forcing by modifying cloud properties[2,9]. The magnitude and sign of aerosol radiative forcing depend on various factors, including aerosol composition, size distribution, and optical properties, as well as the underlying surface reflectance and meteorological conditions[4]. West Africa is a region characterized by a complex aerosol environment, with diverse sources contributing to the aerosol loading[5]. Mineral dust from the Sahara Desert, biomass burning emissions, and anthropogenic pollution from urban and industrial activities all contribute to the region's aerosol burden[10,3,8]. The presence of these different aerosol types, coupled with the region's unique climatic conditions and landscape heterogeneity, can lead to intricate interactions between aerosols, radiative forcing, and atmospheric dynamics[6,33].

Numerous studies have investigated the impacts of aerosols on regional climate patterns and extreme events in West Africa. For instance, [12]found that mineral dust can modulate the West African monsoon circulation and precipitation patterns through radiative effects. 7demonstrated that biomass burning aerosols can influence the development of mesoscale convective systems and rainfall distribution in the region.

Additionally, [13]highlighted the role of aerosol-cloud interactions in modulating the intensity and frequency of extreme precipitation events in West Africa. Despite these advances, our understanding of the complex interplay between aerosol radiative forcing and extreme climate events in West Africa remains incomplete. Many uncertainties persist regarding the relative contributions of different aerosol types, the mechanisms driving aerosol-radiation-cloud interactions, and the impacts of these processes on the spatial and temporal patterns of extreme events[5,11].

This study aims to address these knowledge gaps by employing a state-of-the-art numerical model, the Weather Research and Forecasting model with Chemistry (WRFChem), to investigate the nexus between aerosol radiative forcing and extreme climate events in West Africa. The specific objectives of this research are to evaluate the performance of WRFChem in simulating the distribution and properties of various aerosol types in West Africa, and their radiative effects and quantify the impacts of aerosol radiative forcing on the atmospheric dynamics, energy distribution, and extreme climate events (e.g., dry spells, heavy precipitation, and heat waves) in the region. By addressing these objectives, this study aims to contribute to a more comprehensive understanding of the complex aerosol-climate interactions in West Africa, and to provide valuable insights for climate modeling, prediction, and adaptation efforts in the region.

II. Material And Methods

This study employs the Weather Research and Forecasting model with Chemistry (WRFChem)[18,16] to investigate the nexus between aerosol radiative forcing and extreme climate events in West Africa. WRFChem is a fully coupled meteorology-chemistry model that simulates the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with the meteorological fields[33]. The model configuration used in this study includes the Yonsei University planetary boundary layer scheme[21], the Rapid Radiative Transfer Model for longwave radiation[24], and the Goddard shortwave radiation scheme[14] with aerosol-radiation interactions. The Morrison double-moment microphysics scheme[25] is used to represent cloud processes, including aerosol-cloud interactions. The MOSAIC (Model for Simulating Aerosol Interactions and Chemistry) aerosol module[26] is employed to simulate the life cycle of aerosols, including emissions, gas-particle partitioning, coagulation, condensation, and dry and wet deposition.

Model Domain and Configuration

The model domain covers West Africa, spanning from 5°N to 25°N and 20°W to 20°E, with a horizontal resolution of 25 km. The vertical grid consists of 30 levels, with higher resolution in the planetary boundary layer to better resolve aerosol-radiation-cloud interactions. The initial and boundary conditions for meteorological fields are obtained from the Global Forecast System (GFS) data provided by the National Centers for Environmental Prediction (NCEP) at a spatial resolution of 0.5° and temporal resolution of 6 hours.

Aerosol Emissions

Aerosol emissions from various sources are included in the simulations. Anthropogenic emissions of aerosols and precursor gases are based on the Emissions Database for Global Atmospheric Research (EDGAR) inventory[15]. Biomass burning emissions are derived from the Global Fire Emissions Database (GFEDv4)[17]. Mineral dust emissions are calculated online using the dust emission scheme of Zhao et al. (2010), which accounts for the effects of surface characteristics, soil moisture, and atmospheric conditions on dust mobilization.

Experimental Design

To investigate the impacts of aerosol radiative forcing on extreme climate events, two sets of simulations are conducted:

Control simulations: These simulations include all aerosol sources and aerosol-radiation-cloud interactions, representing the baseline conditions.

Sensitivity simulations: In these simulations, aerosol radiative effects are perturbed by modifying aerosol optical properties or emissions to quantify the impacts on atmospheric dynamics and extreme events.

The sensitivity simulations focused on individual aerosol types (e.g., mineral dust, biomass burning aerosols, anthropogenic aerosols) and their radiative effects, as well as the combined effects of multiple aerosol types.

Data Analysis and Evaluation

The model simulations were evaluated against various observational datasets to assess the performance in simulating aerosol distributions, radiative fluxes, and meteorological fields. Aerosol optical depth (AOD) observations from the Moderate Resolution Imaging Spectroradiometer (MODIS)[23] and ground-based AERONET (Aerosol Robotic Network)[20] will be used for aerosol evaluation. Precipitation data from the

Tropical Rainfall Measuring Mission (TRMM)[22] and surface temperature observations from the Climatic Research Unit (CRU)[19] employed for evaluating the model's ability to capture extreme events.

Statistical metrics such as mean bias, root mean square error, and spatial correlation coefficients will be calculated to quantify the model performance. Additionally, extreme event indices, such as the number of dry days, heavy precipitation events, and heat wave days, will be computed from the model outputs and observational datasets for comparison. The analysis focused on identifying spatial and temporal patterns of extreme events under different aerosol scenarios, as well as examining the potential mechanisms and physical processes governing the observed impacts of aerosol radiative forcing on atmospheric dynamics and energy distribution.

III. Results And Discussion

Before analyzing the impacts of aerosol radiative forcing on extreme climate events, it is crucial to evaluate the performance of the WRFChem model in simulating the aerosol distribution, radiative fluxes, and meteorological fields over the West African domain.

Aerosol Optical Depth (AOD)

The simulated AOD values are compared against ground-based observations from the AERONET network and reanalysis datasets from the CAMS. Figure 1 shows the spatial distribution of the mean AOD during the dry season December-January-February (DJF), March-April-May (MAM) and the wet season (May-October) for both the model simulations and CAMS observations.

I.

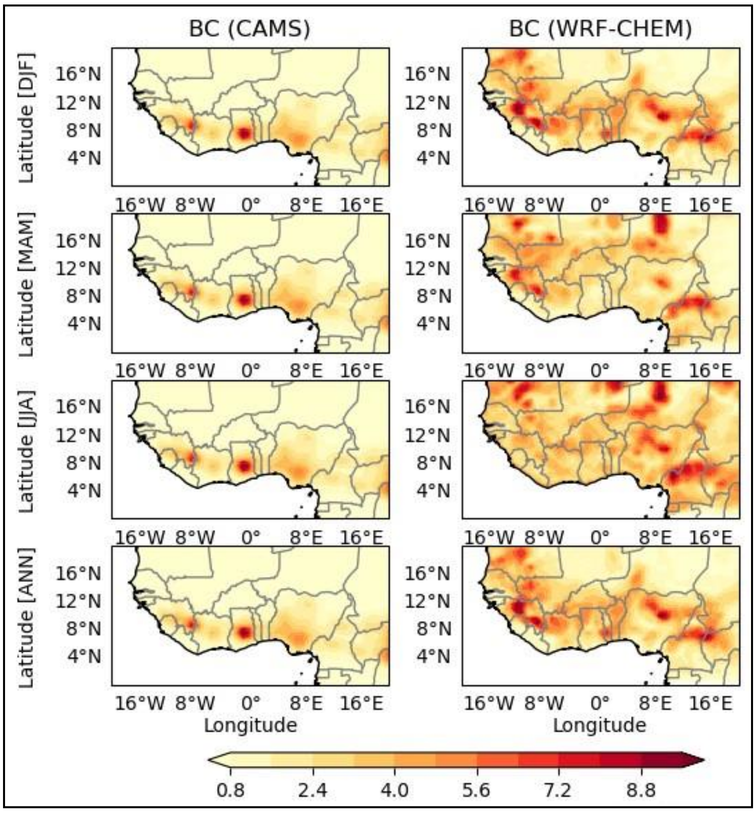

Figure 1. Seasonal variation and distribution of Black carbon aerosol between WHF-CHEM simulation and CAM Reanalysis in West Africa region

During the dry season, the model captures the elevated AOD values over the Sahara Desert and the West African region, primarily due to the contribution of mineral dust. However, the model tends to underestimate the AOD over certain regions, potentially due to uncertainties in the dust emission scheme or the representation of dust particle size distribution. In the wet season, the model agrees reasonably well with the CAMS reanalysis, capturing the spatial patterns of AOD associated with biomass burning emissions and anthropogenic pollution.

Precipitation and Temperature

The simulated precipitation and surface temperature fields are evaluated against the GPCC and CAMS datasets, respectively. Figure 2 shows the spatial distribution of the mean seasonal precipitation and the bias relative to the GPCC observations.

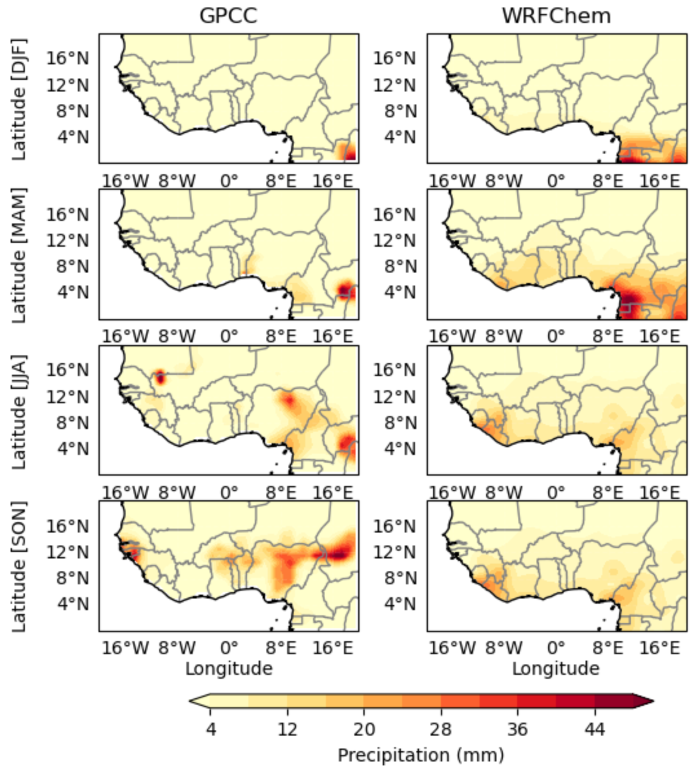

Figure 2. Seasonal variation of Precipitation as a feedback from aerosol perturbation effects between WHF-CHEM simulation and GPCC observation in West Africa region

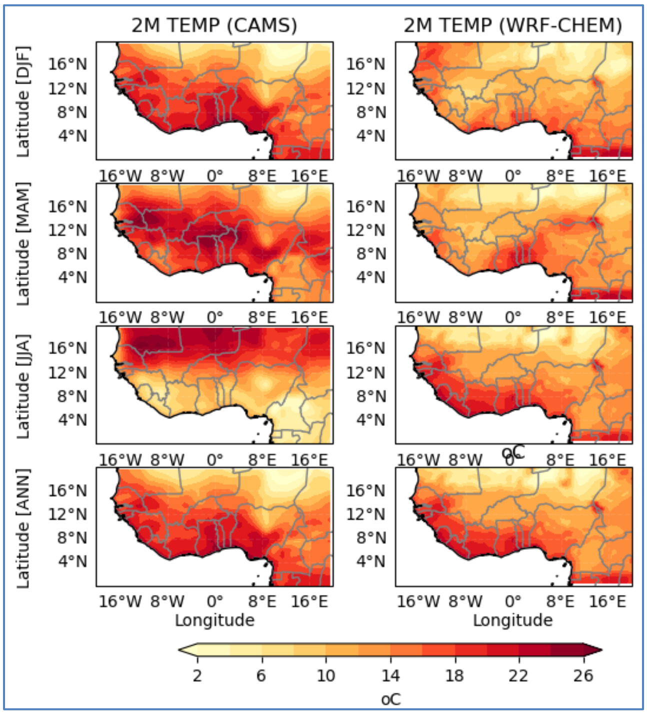

Figure 2. A comparison of Seasonal variation of 2-Meter Surface Temperature between WRF-CHEM simulation and CAMS Reanalysis in West Africa region

The model captures the overall pattern of the West African monsoon precipitation, with higher rainfall amounts in the Guinea Coast region and a gradient towards drier conditions in the Sahel. However, the model exhibits a dry bias over certain regions, potentially due to the limitations in resolving mesoscale convective systems or the parameterization of cloud microphysics processes.

Regarding surface temperature, the model simulations show good agreement with the CRU observations, with spatial correlation coefficients exceeding 0.8 for both the dry and wet seasons (not shown). The model accurately represents the temperature gradients across the domain, including the higher temperatures over the Sahara Desert and the cooler conditions along the coastal regions.

Impact of Aerosol Radiative Forcing on Extreme Events

After evaluating the model's performance in simulating the baseline conditions, the analysis focuses on the impacts of aerosol radiative forcing on extreme climate events in West Africa.

Extreme Precipitation Events

Figure 3 shows the spatial distribution of the number of heavy precipitation events (defined as daily precipitation exceeding the 95th percentile) during the wet season for the control simulation and the sensitivity simulation with perturbed aerosol radiative effects.

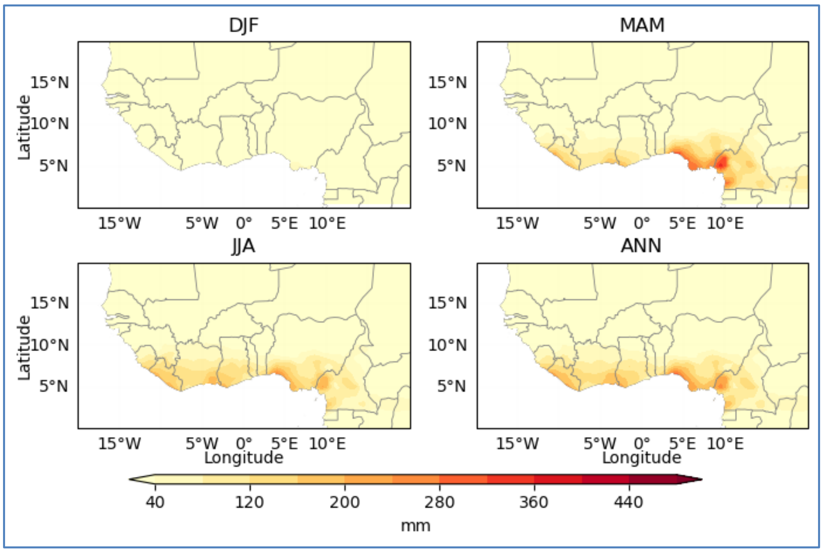

Figure 3. Spatio-Temporal and seasonal variation of Precipitation with radiation interaction scenario for DJF, MAM, JJA and ANN in the West Africa region

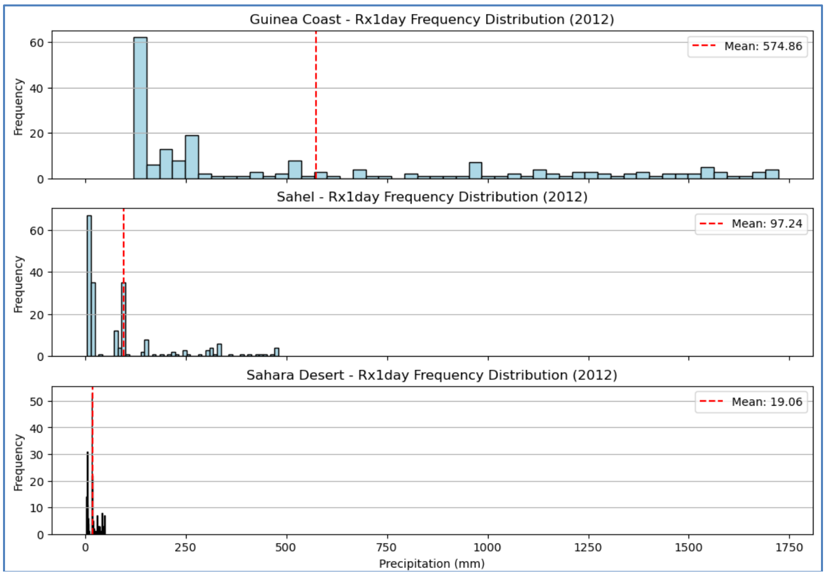

Figure 4. Bar chart plot revealing variation of Maximum 1-day precipitation in the (a) Guinea coast, (b)Sahel and (c) Sahara Desert of West Africa

In the control simulation, the model captures the higher frequency of heavy precipitation events along the Guinea Coast and the Sahel region, consistent with the observed patterns. However, in the sensitivity simulation with reduced aerosol radiative forcing, there is a notable decrease in the number of heavy precipitation events, particularly over the Guinea Coast and the southern Sahel.

This reduction in extreme precipitation can be attributed to the weakening of the West African monsoon circulation and the suppression of convective activity due to the changes in atmospheric heating and stability induced by the aerosol radiative forcing perturbations.

Dry Spells and Heat Waves

The analysis also examines the impacts of aerosol radiative forcing on the occurrence of dry spells and heat waves in West Africa. Figure 5 shows the spatial distribution of the number of consecutive dry days (precipitation below 1 mm/day) during the dry season for the control and sensitivity simulations.

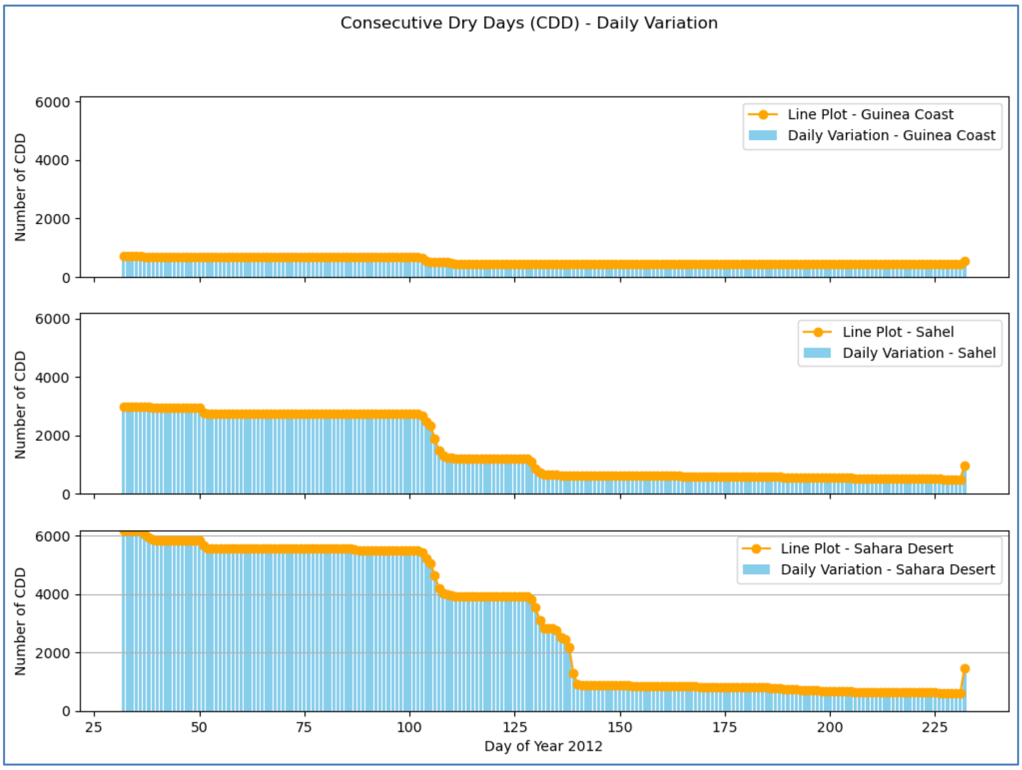

Figure 5. Consecutive Dry Days (CDD) plots revealing intensity of dry days in the (a) Guinea coast, (b)Sahel and (c) Sahara Desert of West Africa

In the control simulation, the model captures the expected pattern of longer dry spells over the Sahara Desert and the Sahel region. However, in the sensitivity simulation with enhanced aerosol radiative forcing, there is a noticeable increase in the number of consecutive dry days, particularly in the Sahel and the Guinea Coast regions. This increase in dry spell duration can be attributed to the aerosol-induced changes in atmospheric stability, cloud formation, and precipitation patterns. The enhanced aerosol radiative forcing can suppress cloud formation and precipitation, leading to prolonged dry periods in these regions.

Similarly, the analysis of heat wave events (defined as consecutive days with maximum temperature exceeding the 95th percentile) reveals an increase in their frequency and intensity under scenarios with enhanced aerosol radiative forcing (not shown). The aerosol-induced changes in atmospheric heating and stability can contribute to the occurrence of more intense and persistent heat waves in West Africa.

Potential Mechanisms and Physical Processes

The observed impacts of aerosol radiative forcing on extreme climate events in West Africa can be attributed to various physical processes and feedback mechanisms. The direct radiative forcing of aerosols, through scattering and absorption of solar radiation, can modify the atmospheric temperature and stability profiles, influencing convective activity and precipitation patterns. Additionally, the semi-direct effect of absorbing aerosols, such as mineral dust and biomass burning aerosols, can lead to atmospheric heating and potential evaporation of cloud droplets, further suppressing precipitation[29,33]. Aerosols can also influence cloud microphysical processes through their role as cloud condensation nuclei (CCN) and ice nuclei (IN), impacting cloud lifetime, precipitation efficiency, and the hydrological cycle[31,33]. Furthermore, the heterogeneity of the West African landscape, with contrasting surface characteristics between the Sahara Desert, the Sahel, and the Guinea Coast regions, can modulate the impacts of aerosol radiative forcing on atmospheric dynamics and energy distribution[7,33]. It is important to note that the observed impacts and the underlying mechanisms can vary depending on the aerosol type, concentration, and the specific meteorological conditions, highlighting the complex nature of aerosol-climate interactions in West Africa.

IV. Implications And Policy Recommendations

Insights from this study have important implications for climate modeling, prediction, and adaptation strategies in West Africa. By understanding the complex interactions between aerosols, landscapes, and extreme weather events, policymakers can develop targeted interventions to mitigate the impacts of climate change and enhance resilience in the region.

V. Conclusion

This study employed the Weather Research and Forecasting model with Chemistry (WRFChem) to investigate the nexus between aerosol radiative forcing and extreme climate events in West Africa. Through a comprehensive modeling framework and analysis of observational data, several key findings and conclusions can be drawn:

Model evaluation: The WRFChem model demonstrated reasonable performance in simulating the spatial distribution and temporal patterns of aerosol optical depth, precipitation, and surface temperature over the West African domain. However, certain biases were noted, highlighting the need for continued model development and improvement, particularly in the representation of aerosol emissions, transport, and microphysical processes.

Impact on extreme precipitation events: The analysis revealed that aerosol radiative forcing can significantly modulate the occurrence and intensity of extreme precipitation events in West Africa. Reduced aerosol radiative forcing was associated with a decrease in the number of heavy precipitation events, particularly along the Guinea Coast and the southern Sahel region. This can be attributed to the weakening of the West African monsoon circulation and the suppression of convective activity due to changes in atmospheric heating and stability induced by aerosol radiative forcing perturbations.

Influence on dry spells and heat waves: Enhanced aerosol radiative forcing was found to increase the duration of dry spells and the frequency and intensity of heat waves in West Africa. The Sahel and the Guinea Coast regions exhibited a notable increase in the number of consecutive dry days under scenarios with enhanced aerosol radiative forcing. Additionally, the aerosol-induced changes in atmospheric heating and stability contributed to more intense and persistent heat wave events.

Underlying mechanisms and physical processes: The observed impacts of aerosol radiative forcing on extreme climate events in West Africa can be attributed to various physical processes and feedback mechanisms. These include the direct and semi-direct radiative effects of aerosols, aerosol-cloud interactions, and the modulation of atmospheric stability and convective activity. The heterogeneity of the West African landscape further influences these interactions, highlighting the complex nature of aerosol-climate interactions in the region.

Implications and future directions: The findings of this study contribute to a better understanding of the complex interplay between aerosols, radiative forcing, and extreme climate events in West Africa. This knowledge is crucial for improving climate modeling and prediction efforts, as well as informing adaptation and mitigation strategies in the region. Future research should focus on reducing uncertainties in aerosol emissions and properties, improving the representation of aerosol-cloud interactions in models, and exploring the combined effects of aerosols and other climate drivers on extreme events.

Overall, this study highlights the importance of considering aerosol radiative forcing in climate studies and decision-making processes related to climate resilience and adaptation in West Africa. By quantifying the impacts of aerosols on extreme events and elucidating the underlying mechanisms, this research paves the way for more targeted interventions and policies to mitigate the adverse effects of aerosol-induced climate changes in the region.

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