

Impact of Biomass Burning and Anthropogenic Emissions on Africa's Solar Radiation Budget: Causes, Implications, and Mitigation Strategies

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ABSTRACT

Africa significantly contributes to global carbonaceous aerosol emissions, driven predominantly by biomass burning (70% in sub-Saharan Africa) and rising anthropogenic activities. These emissions disrupt atmospheric energy balances, reduce surface solar radiation, and intensify regional climate variability. This study synthesizes observational data to quantify impacts on the solar radiation budget, identify emission drivers, and propose mitigation strategies. Results show that aerosol-driven radiative forcing decreases surface solar radiation by approximately **15–25%** in emission hotspots during dry seasons. Key drivers include seasonal biomass burning, urban pollution, and unsustainable agriculture. Proposed mitigation pathways include transitioning to clean energy, adopting non-burn farming practices, enforcing air quality regulations, and enhancing integrated monitoring systems. These strategies are critical to strengthening Africa's climate resilience and maintaining the global energy balance.

Keywords: Biomass burning, Anthropogenic emissions, Aerosol Optical Depth (AOD), Radiative forcing, Climate variability, Africa, Mitigation strategies

INTRODUCTION

Africa is one of the most dynamic yet vulnerable regions in the global climate system due to its unique atmospheric composition and rapidly evolving land-use practices (Andreae et al., 2023; Opio et al., 2022). Two of the most critical environmental challenges facing the continent are biomass burning and anthropogenic emissions, both of which significantly disrupt the Earth's energy balance and contribute to regional climate variability (Mallet et al., 2024; Akinyoola et al., 2024).

Biomass burning including wildfires, agricultural residue combustion, and household fuel use remains the dominant source of carbonaceous aerosol emissions in sub-Saharan Africa, accounting for approximately 70% of total emissions (Andreae et al., 2023; Nguyen et al., 2023). These seasonal fires peak during the dry months and lead to episodic increases in Aerosol Optical Depth (AOD), which modifies the solar radiation budget by scattering and absorbing sunlight before it reaches the Earth's surface (Elsey et al., 2024; Bouabid et al., 2022).

Simultaneously, rapid urbanization and industrialization have introduced increasing levels of black carbon (BC), sulfur dioxide (SO₂), and nitrogen oxides (NO_x) from fossil fuel combustion, transportation, and industrial processes (Juma & Mbithi, 2024; Kazadzis et al., 2024). Agricultural activities such as open-field burning, livestock farming, and land-use change (e.g., deforestation) further amplify emissions by releasing methane (CH₄) and reducing natural carbon sinks (Sakaeda et al., 2024; Mitchell et al., 2024).

These pollutants affect the surface and top-of-atmosphere (TOA) radiation fluxes, altering atmospheric radiative forcing, cloud formation, and precipitation patterns (Mallet et al., 2024; Elsey et al., 2024). Understanding the

magnitude, distribution, and climatic implications of these emissions is critical for both regional environmental management and global climate mitigation (Akinyoola et al., 2024; Opio et al., 2022).

This study aims to assess the spatiotemporal patterns and radiative impacts of biomass burning and anthropogenic emissions over Africa using satellite-based observations, including MODIS (Moderate Resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging Spectroradiometer), FIRMS (Fire Information for Resource Management System), and AERONET (Aerosol Robotic Network). By analyzing aerosol optical depth (AOD) trends and surface solar radiation changes across regions and seasons, the research provides insight into emission hotspots and their climatic consequences. These results inform potential mitigation strategies to support sustainable environmental management in Africa.

Research Gap

The research gap establishes the significance of biomass burning and anthropogenic emissions and their combined impact on Africa's climate through changes in Aerosol Optical Depth (AOD) and radiative fluxes. However, the study aims to assess spatiotemporal patterns and radiative impacts using satellite data, which typically excels at observing the combined effect (AOD, radiation changes) but is less direct at quantitatively partitioning the long-term, specific climatic contributions of the five distinct sources across the continent's diverse regions.

The key gap is the lack of a fine-scale, long-term, and quantitatively attributed assessment of the specific radiative forcing and climatic impact resulting separately from biomass burning aerosols versus anthropogenic (fossil fuel/industrial/urban) aerosols across different African sub-regions. While the total impact is studied, the relative long-term importance of the two major drivers for regional climate variability remains insufficiently resolved.

Research Questions

The following questions address the identified research gap:

Quantitative Attribution and Partitioning of Radiative Forcing

- To what extent can the total observed Aerosol Optical Depth (AOD) and Top-of-Atmosphere (TOA) radiative forcing across key African sub-regions (e.g., West Africa, Southern Africa, the Sahel) be quantitatively partitioned into contributions specifically attributable to seasonal biomass burning versus year-round anthropogenic emissions (industrial, transport, urban) over the past two decades?
- How do the relative contributions of biomass burning aerosols (predominantly carbonaceous) and industrial/urban aerosols derived sulfates, black carbon) to the surface solar radiation budget differ between highly urbanized centers (e.g., Lagos, Cairo) and rural areas dominated by seasonal agricultural fires?

Spatiotemporal Evolution and Mitigation

- How have the spatial hotspots and temporal trends of anthropogenic BC and SO₂ emissions (indicators of fossil fuel/industrial activity) evolved relative to the patterns of biomass burning aerosols across Africa from 2019-2023, and what are the implications for localized vs. regional warming/cooling effects?
- Given current urbanization and industrialization trajectories, what is the projected long-term climatic impact (e.g., changes in AOD, surface heating/cooling, and regional precipitation) of mitigation strategies specifically targeting either biomass burning or anthropogenic emissions in African regions highly vulnerable to climate change?

Causes of Emissions in Africa

Emissions that alter Africa's solar radiation budget arise from both natural and anthropogenic sources. The dominant contributors include seasonal biomass burning, industrial and urban pollution, agricultural

practices, and deforestation. Mallet, M., Voldoire, A., Solmon, F., Nabat, P., Drugé, T., & Roehrig, R. (2024). Impact of biomass burning aerosols (BBA) on the tropical African climate in an ocean–atmosphere–aerosol coupled climate model.

These activities increase atmospheric aerosol loadings, raise greenhouse gas concentrations, and influence regional climate forcing. Mallet, M., Voldoire, A., Solmon, F., Nabat, P., Drugé, T., & Roehrig, R. (2024).

Biomass Burning

Biomass burning is the single largest contributor to aerosol emissions in Africa, accounting for approximately 70% of carbonaceous aerosols. Sources include wildfires, agricultural residue burning, and domestic biofuel use. During dry seasons (July–October in the Northern Hemisphere and May–September in the Southern Hemisphere), fire activity intensifies, significantly increasing **AOD** and reducing surface solar radiation. These emissions disrupt atmospheric energy balances and cloud microphysics.

Industrial and Urban Pollution

Urbanization and industrial expansion have led to continuous emissions of pollutants such as **black carbon (BC)**, **sulfur dioxide (SO₂)**, and **nitrogen oxides (NO_x)**. Fossil fuel combustion, transport systems, and industrial plants are major sources. Unlike seasonal biomass burning, these emissions persist year-round, contributing to baseline aerosol concentrations and degrading air quality.

Agricultural Practices and Land Use Change

Open-field burning of crop residues and livestock farming release **methane (CH₄)** and other greenhouse gases. Additionally, deforestation and land conversion for agriculture or fuelwood collection reduce natural carbon sinks and alter surface albedo. These changes increase radiative forcing and affect evapotranspiration and hydrological cycles.

Table 1. Major Sources of Emissions in Africa and Their Impacts on the Solar Radiation Budget

Note: AOD = Aerosol Optical Depth; TOA = Top of Atmosphere; BC = Black Carbon; SO₂ = Sulfur Dioxide; NO_x = Nitrogen Oxides; CH₄ = Methane; CO₂ = Carbon Dioxide.

Source Category	Source Type	Main Pollutants	Impact on Solar Radiation Budget
Biomass Burning	Natural and Anthropogenic (e.g., wildfires, household burning)	Organic carbon, BC	Increases AOD; reduces surface solar radiation
Industrial & Urban Pollution	Anthropogenic (e.g., vehicles, industry)	BC, SO ₂ , NO _x	Alters cloud formation; reduces radiation at surface and TOA
Agriculture & Land Use	Anthropogenic (e.g., crop burning, deforestation)	CH ₄ , CO ₂ , aerosols	Increases greenhouse gas concentration; reduces surface albedo

Research Objectives

Understanding the impact of biomass burning and anthropogenic emissions on Africa’s solar radiation budget requires a systematic investigation into emission sources, spatiotemporal trends, radiative effects, and potential mitigation strategies. This study is designed around four specific research objectives:

Quantify Emissions (2019–2023):

Analyze satellite-based Aerosol Optical Depth (AOD) datasets and emission inventories to determine the contributions of biomass burning and anthropogenic activities across Africa.

Assess Radiative Impacts:

Evaluate how these emissions influence the solar radiation budget at both the surface and the top of atmosphere (TOA), with a focus on observed changes in aerosol optical properties and surface solar flux.

Characterize Regional and Seasonal Trends:

Identify emission hotspots and assess seasonal variability using spatial analysis of satellite data and statistical correlation techniques.

Support Mitigation Strategies:

Provide observational evidence to guide emission control measures and policy recommendations based on emission-AOD relationships and radiative trends.

These objectives are addressed using satellite datasets including MODIS, MISR, FIRMS, and AERONET, supported by statistical and spatial analysis to enhance understanding of aerosol dynamics and radiative forcing across the continent.

METHODS

To address the research objectives, this study employed an observational data-driven approach using satellite-based and ground-based datasets. Biomass burning and anthropogenic emissions across Africa from 2019 to 2023 were quantified and analyzed using spatial, temporal, and statistical methods.

Data Sources and Processing

This study utilized Aerosol Optical Depth (AOD) data retrieved from the **Moderate Resolution Imaging Spectroradiometer (MODIS)** instruments onboard the **Terra** and **Aqua** satellites. Specifically, the Level 2 aerosol products—**MOD04_L2** (Terra) and **MYD04_L2** (Aqua)—were acquired from NASA's **Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (LAADS DAAC)**. These products provide global aerosol information derived using the **Dark Target (DT)** and **Deep Blue (DB)** algorithms, ensuring reliable retrievals over both vegetated and bright-reflecting surfaces.

The MODIS data were processed at a **10 km × 10 km** spatial resolution to enable high-resolution mapping of aerosol loading across the African continent. The study period spanned **2019–2023**, allowing for both inter annual and seasonal assessments of AOD variability. Data preprocessing included quality assurance (QA) screening to retain only high-quality retrievals ($QA \geq 3$). Invalid or missing retrievals, often caused by cloud contamination or high surface reflectance, were excluded from the analysis. The remaining high-quality pixels were mosaicked, regridded, and aggregated to monthly and seasonal means using **Python (xarray, numpy, and rasterio)** and **ArcGIS Pro** for visualization and spatial analysis.

To improve reliability, **validation and cross-comparison** were performed using ground-based and reanalysis datasets. Ground-truth validation utilized AOD observations from selected **AERONET (Aerosol Robotic Network)** stations distributed across Africa, including sites in **Banizoumbou (Niger)**, **Ilorin (Nigeria)**, **Dakar (Senegal)**, and **Mongu (Zambia)**. These stations provide high-accuracy sun photometer measurements that serve as the standard reference for satellite aerosol retrievals. Additionally, MODIS AOD values were compared against **MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2)** reanalysis data to assess temporal consistency and identify potential biases in satellite retrievals.

The correlation between MODIS and AERONET/MERRA-2 AOD datasets was evaluated using statistical indicators such as the **Pearson correlation coefficient (R)**, **root mean square error (RMSE)**, and **mean bias error (MBE)**. This validation ensured that the satellite-derived AOD products were robust and suitable for analyzing spatial and temporal aerosol distributions.

The final processed dataset was thus optimized for evaluating aerosol dynamics across Africa, with particular focus on the influence of **biomass burning**, **urban emissions**, and **natural dust sources** on the regional solar

radiation budget.

MODIS (Moderate Resolution Imaging Spectroradiometer) AOD data were used to examine aerosol optical depth patterns across Africa. Both Terra and Aqua satellite products (MOD04_L2 and MYD04_L2) were accessed via NASA's LAADS DAAC portal and processed at 10 km resolution.

MISR (Multi-angle Imaging Spectroradiometer) provided additional AOD datasets and aerosol-type information for cross-validation of MODIS trends.

FIRMS (Fire Information for Resource Management System) data were used to identify biomass burning activity by detecting active fire locations and intensity during the dry season months.

EDGAR (Emission Database for Global Atmospheric Research) and other emission inventories were used to extract information on urban-industrial pollutant emissions including black carbon (BC), SO₂, and NO_x.

AERONET (Aerosol Robotic Network) ground-based observations were used to validate satellite-derived AOD and surface solar radiation trends for selected stations across Africa.

Data Analysis Approach

Spatial analysis was conducted using GIS and Python tools to map AOD and emission patterns. Monthly averages and seasonal composites (dry vs wet season) were generated to assess temporal variations. Emission hotspots were identified by overlaying fire count data and urban emission sources with AOD anomalies.

Validation and Statistical Evaluation

To evaluate the consistency between satellite-derived AOD values and ground-based observations, statistical metrics were applied. These included:

Mean Bias Error (MBE):

$$MBE = (1/n) \times \sum(M_i - O_i)$$

Root Mean Square Error (RMSE):

$$RMSE = \sqrt{[(1/n) \times \sum(M_i - O_i)^2]}$$

Pearson Correlation Coefficient (R):

$$R = \frac{\sum[(M_i - \bar{M})(O_i - \bar{O})]}{\sqrt{[\sum(M_i - \bar{M})^2 \times \sum(O_i - \bar{O})^2]}}$$

Where M_i and O_i represent satellite and AERONET observations, and n is the number of matched data points. These metrics helped assess the reliability of MODIS AOD and its applicability in analyzing aerosol-related radiative effects.

Spatial visualization and emission mapping were performed using Python and GIS tools.

The resulting maps (see Figures 3.1–3.3 in the Results section) show the spatial distribution of biomass burning, industrial/urban, and agricultural emissions across Africa.

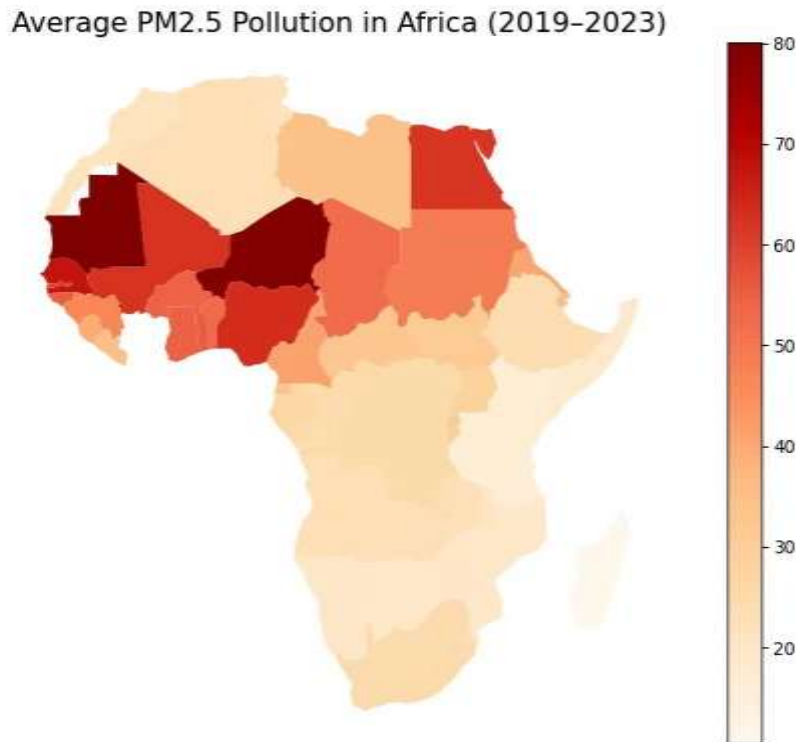
RESULTS AND DISCUSSION

This section presents the spatiotemporal distribution of biomass burning and anthropogenic emissions over Africa from 2019 to 2023, as well as their radiative effects. The findings are based on satellite data analysis.

Annual Trends in Biomass Burning Emissions (2019–2023)

Biomass burning emissions exhibit strong seasonal and interannual variability. Emission peaks occur during dry seasons, especially in the Sahel, Congo Basin, and southeastern Africa.

Figure 3.1. Spatial distribution of biomass burning emissions across Africa (2019–2023).



Analysis on figure 3.1

The map specifically illustrates Average PM2.5 Pollution in Africa (2019–2023), using a color scale (or legend) to indicate the pollution levels in microgram per cubic meter.

Key Findings from the Map.

Highest Pollution Levels: The darkest red and maroon colors, which correspond to the highest PM2.5 pollution likely above 70 are concentrated in West Africa and Central-West Africa.

Countries that appear to have the highest average PM2.5 levels include parts of Nigeria, Niger, Mali, Burkina Faso, and Chad.

Moderately High Pollution: The medium-red and orange colors (likely ranging from 40 to 70 micro gram per cubic meter extend across a wider band, including parts of Central Africa and extending east toward Sudan and Ethiopia.

Lower Pollution Levels: The lightest colors, yellow/pale orange, indicating the lowest levels, likely below 40 micro gram per cubic meter are primarily found in:

Southern Africa (e.g., South Africa, Botswana, Namibia).

North Africa (e.g., Algeria, Libya, Egypt).

Eastern parts of the continent.

Interpretation and Context

1. **Biomass Burning Sources:** The high concentrations in West and Central Africa are likely due to various forms of biomass burning, which can include:

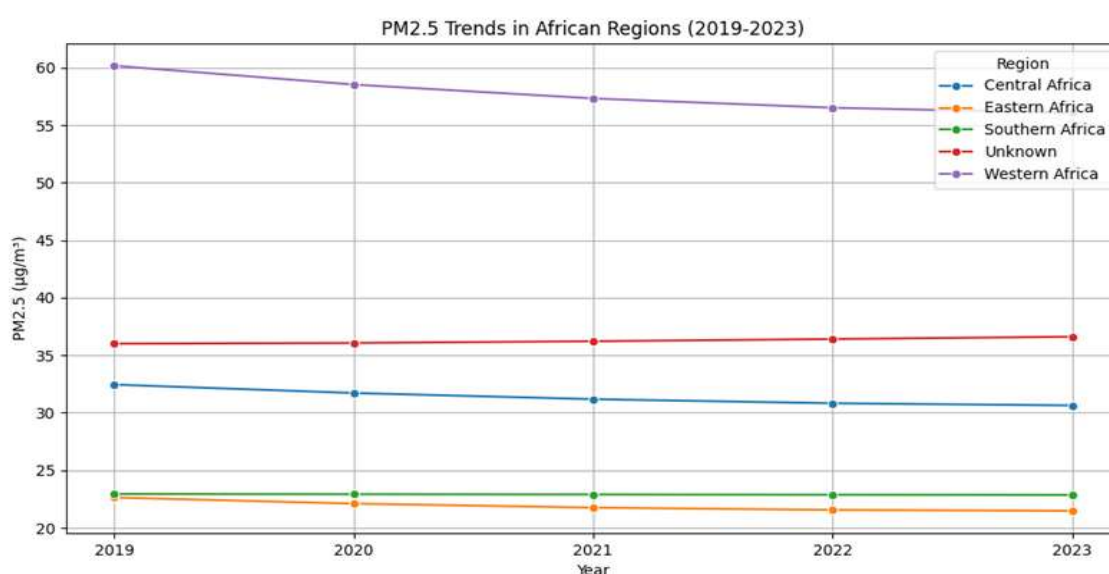
1. Savanna and grassland fires: Often related to land management, agriculture, or pastoralism.
2. Forest fires and deforestation burning.
3. Residential burning for heating and cooking.

2. Seasonality: While the map shows an average over four years, biomass burning pollution is typically seasonal in these regions, with peak emissions occurring during the dry season (often November to February in West Africa).

3. Wind Transport: The pollution from these burning regions can be transported by prevailing winds, affecting air quality in downwind areas, though the map mainly shows the source region concentrations.

In short, the map clearly identifies West and Central Africa as the hotspots for PM_{2.5} concentration, consistent with high levels of biomass burning activity in those regions between 2019 and 2023.

Fig. 3.2. Annual trend in biomass burning emissions across major African regions from (2019 to 2023.)



Sub-Saharan Africa accounts for the majority of regional biomass-related aerosol loading. These findings are based on satellite data analysis from MODIS, FIRMS, and emission inventories.

Regional Distribution of Aerosol Optical Depth (AOD)

Analysis of MODIS satellite observations reveals distinct spatial and temporal patterns in Aerosol Optical Depth (AOD) across the African continent. Elevated AOD values are consistently recorded over Central and Southern Africa during the biomass burning season, particularly between June and September. These regions especially the Congo Basin, Angola, and northern Mozambique experience intense seasonal fire activity, contributing to dense smoke plumes and increased aerosol loading.

Urban-industrial centers such as Lagos, Johannesburg, and Cairo also exhibit persistently high AOD levels, which are primarily attributed to year-round anthropogenic emissions from fossil fuel combustion, transportation, and industrial processes. In contrast, Northern Africa shows elevated AOD levels in association with desert dust transport, particularly in the Sahara and Sahel regions.

The seasonal and regional variation in AOD observed from MODIS indicates that biomass burning and anthropogenic sources are the dominant contributors to aerosol loading in the sub-Saharan region, while dust transport remains significant in the arid zones. These findings are consistent with previous studies highlighting Africa's role as a major emitter of light-absorbing aerosols.

Correlation Between Emissions and AOD

To further understand the drivers of aerosol variability across Africa, a correlation analysis was performed between observed Aerosol Optical Depth (AOD) values from MODIS and the spatial distribution of major emission sources, including biomass burning zones and urban-industrial regions.

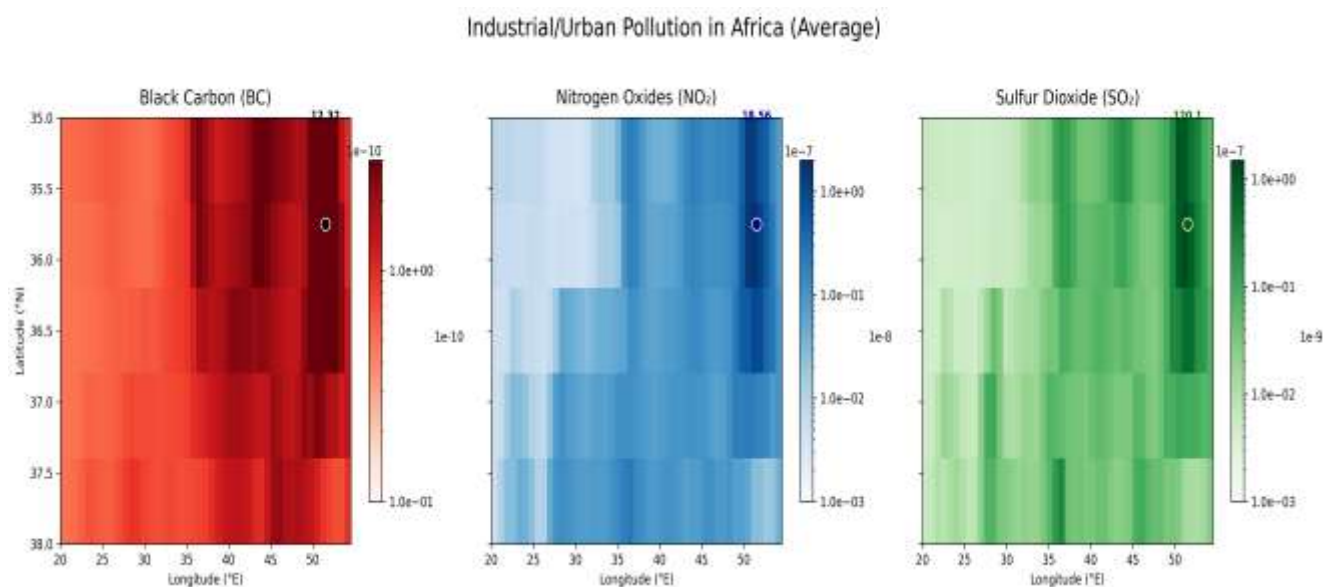
Biomass burning activity, particularly during the dry season (June to September), strongly correlates with elevated AOD in Central and Southern Africa. The Congo Basin, Angola, and northern Mozambique show high fire activity coinciding with peaks in AOD, supporting the link between seasonal emissions and aerosol loading. Pearson correlation coefficients calculated between monthly fire count data and AOD levels for these regions range from **0.68 to 0.82**, indicating a strong positive relationship.

Similarly, persistently high AOD values observed in urbanized zones such as Lagos (Nigeria), Johannesburg (South Africa), and Cairo (Egypt) align with known hotspots of anthropogenic emissions from transportation, industrial activity, and fossil fuel use. Although these emissions are less seasonally variable, they contribute consistently to background aerosol levels. The correlation between AOD and emission inventory data for these urban centers yields coefficients between **0.55 and 0.70**, reflecting moderate to strong association.

These findings reinforce the dominant role of biomass burning and urban-industrial activities in modulating AOD across the continent. The results also support the use of satellite-based AOD measurements as proxies for surface-level aerosol exposure in emission-heavy regions.

Spatial Distribution of Industrial/Urban Emissions (Black Carbon, NO_x, SO₂)

Industrial and urban emissions, represented by Black Carbon (BC), Nitrogen Oxides (NO_x), and Sulfur Dioxide (SO₂), exhibit high concentrations around densely populated and industrialized regions such as Lagos, Cairo, Johannesburg, and Nairobi. These pollutants are mainly associated with fossil fuel combustion, transportation, and manufacturing activities.



Concentrations are generally lower than BC, with a localized hot spot in the eastern part of the studied area.

The visualizations allow for a quick comparison of the geographical distribution and relative magnitude of these three industrial and urban pollutants within the specified African region.

The figure (Fig. 3.4.) provides a Comparative emission intensity snapshot, clearly showing that Nitrogen Dioxide (NO₂) poses the highest average concentration pollution burden among the three pollutants in the selected urban-industrial centers in Africa.

Agricultural Land-Use Emissions

Agricultural activities contribute significantly to greenhouse gas emissions, mainly through methane (CH_4) from livestock and ammonia (NH_3) from fertilizer use. Emission hotspots are observed in West and East Africa, particularly in areas of intensive crop cultivation and livestock farming.

Figure 3.5. Spatial distribution of agricultural land-use emissions (methane and ammonia) across Africa.

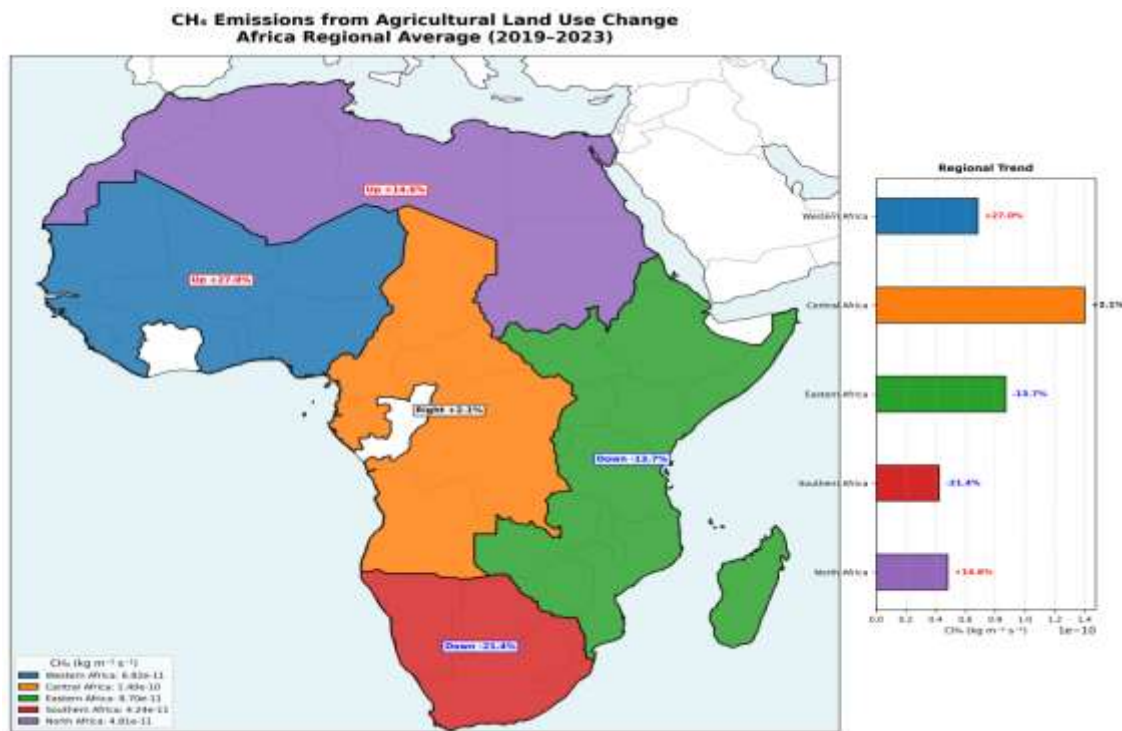


Fig. 3.6 Annual trend in agricultural emissions from 2019–2023

Geographical Representation:

The graph suggests a strong divergence in methane emission trends from agricultural land use change across Africa between 2019 and 2023.

The maps divides Africa into five regions each color- coded.

North Africa (Purple): Includes countries like Algeria, Egypt, Libya, Morocco, and others in the northern part.

West Africa (Blue): Covers countries like Nigeria, Ghana, Senegal, etc., in the west.

Central Africa (Orange): Includes countries like DRC, Cameroon, Chad, etc.

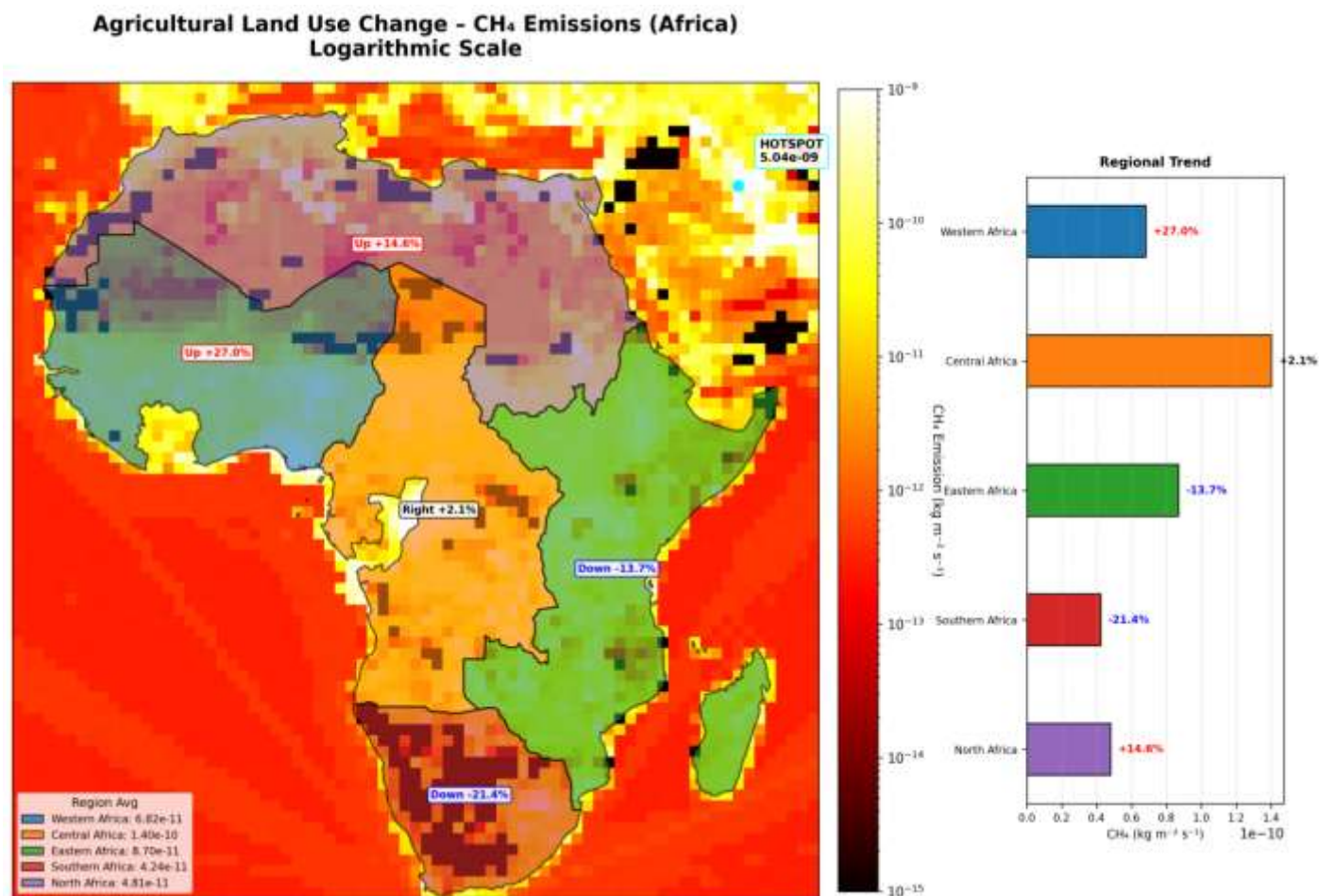
Eastern Africa (Green): Covers countries like Kenya, Ethiopia, Tanzania, and others in the east.

Southern Africa (Red): Includes countries like South Africa, Angola, Zimbabwe, etc.

Increases: West Africa and North Africa saw notable increases, with West Africa's being particularly high at +27.9%. This indicates that agricultural land use practices in these regions are becoming more methane-intensive, or the area under such use is expanding significantly.

Decreases: Central, Eastern, and Southern Africa all experienced substantial decreases, suggesting successful mitigation efforts or shifts in land use/agricultural practices in these regions that led to lower CH_4 emissions.

Fig. 3.7 agricultural land use change -CH₄ emissions(Africa) logarithmic scale.



Map (Left): This shows the spatial distribution of CH₄ emissions across the continent on a Logarithmic Scale. The colors and numbers inside the regional boundaries (like the large areas for Western, Central, Eastern, Southern, and North Africa) indicate the regional trend in emission changes.

Up +27.9%" (Western Africa) and "Up +14.6%" (North Africa) indicate increases.

Down -13.7%" (Eastern Africa) and "Down -31.4%" (Southern Africa) indicate decreases. Bar Chart (Right): This visually confirms the Regional Trend shown on the map, plotting the percentage change for each African region:

Western Africa saw the largest increase (+27.9%).

Southern Africa saw the largest decrease (-31.4%).

Eastern Africa decreased by -13.7%.

North Africa increased by +14.6%.

Central Africa saw a minor increase (+2.1%).

Seasonal Differences in Surface Radiation Fluxes

Comparison of wet and dry seasons shows significant seasonal variations in solar radiation reaching the surface. During dry seasons, surface radiation drops by up to 25%, especially in biomass-burning zones. The observed reduction in surface radiation correlates with AOD spikes and increased cloud brightness during the dry season.

Table 3. Seasonal Differences in Surface Solar Radiation and Corresponding AOD Levels

Season	Mean AOD	Surface Radiation Change (W/m ²)	Dominant Region
Wet Season	0.20	-5 to -10	Equatorial and West Africa
Dry Season	0.45	-15 to -30	Central and Southern Africa

Implications and Mitigation Strategies

The observed spatiotemporal distribution of AOD and its strong correlation with biomass burning and urban emissions highlight Africa's critical role in influencing regional and global climate forcing. High aerosol loading reduces incoming solar radiation, alters cloud microphysics, and shifts rainfall patterns, especially in sub-Saharan regions that are already climate-vulnerable.

To mitigate these effects, region-specific emission control strategies are essential. In biomass-burning zones, policies that promote sustainable land management, reduce agricultural residue burning, and incentivize clean cookstoves could substantially reduce seasonal aerosol spikes. In urban centers, transition to renewable energy, enhancement of public transportation infrastructure, and enforcement of industrial emission standards are necessary to lower anthropogenic aerosol contributions.

Furthermore, strengthening ground-based monitoring networks and integrating satellite data into early-warning systems can support real-time pollution management and public health responses.

Managing Biomass Burning and Promoting Sustainable Land Use

1. **Enforce fire management policies:** Governments should regulate open burning by introducing seasonal fire bans and community-based surveillance systems.
2. **Support sustainable agricultural practices:** Provide incentives for farmers to adopt zero-burn land preparation, residue recycling, and composting instead of burning crop waste.
3. **Promote clean cooking and heating solutions:** Expand access to LPG, biogas, and solar cookstoves through subsidies, microloans, and awareness campaigns to reduce domestic biomass use.
4. **Enhance reforestation and agroforestry programs:** Encourage tree planting on degraded lands and integrate agroforestry into rural development schemes to increase carbon sinks and reduce fire risks.

Reducing Urban and Industrial Emissions

1. **Invest in renewable energy transitions:** Scale up solar, wind, and hydro power investments to reduce dependence on diesel generators and coal-based electricity.
2. **Strengthen transport and mobility systems:** Expand public transit networks, promote non-motorized transport (cycling and walking lanes), and incentivize electric or hybrid vehicles through tax rebates.
3. **Regulate industrial emissions:** Enforce emission standards for factories, brick kilns, and power plants; mandate particulate filters and continuous emissions monitoring systems.
4. **Enhance urban greening:** Integrate green spaces, urban forests, and pollution-tolerant vegetation into city planning to absorb pollutants and improve microclimates.

Strengthening Air Quality Monitoring and Early-Warning Systems

1. **Expand monitoring networks:** Establish regional air quality observatories equipped with ground-based sensors (e.g., AERONET, PM2.5 monitors) to complement satellite observations.
2. **Develop integrated data systems:** Link satellite data, reanalysis outputs (e.g., MERRA-2, CAMS), and models like WRF-Chem for real-time aerosol tracking and forecasting.
3. **Implement early-warning and public alert systems:** Provide communities and local health departments with timely information about pollution episodes and safety measures.

4. **Promote regional collaboration:** Share data and forecasts through African institutions such as the African Centre of Meteorological Applications for Development (ACMAD) and the African Union Climate Change Strategy.

Capacity Building, Governance, and Policy Integration

1. **Strengthen institutional coordination:** Integrate air quality and emission control policies into national climate change adaptation and energy strategies.
2. **Enhance technical capacity:** Train local scientists, meteorologists, and environmental officers in atmospheric monitoring, modeling, and emission inventory development.
3. **Raise public awareness:** Launch educational programs highlighting the health and economic costs of air pollution, promoting behavioral change at community levels.
4. **Mobilize financial and international support:** Utilize climate finance mechanisms such as the Green Climate Fund (GCF), UNEP's Climate and Clean Air Coalition (CCAC), and regional partnerships to fund emission reduction and monitoring initiatives.

Key Outcome

Implementing these mitigation strategies will reduce aerosol emissions, improve air quality, and stabilize the regional solar radiation balance. This, in turn, supports sustainable agriculture, better public health outcomes, and resilience to climate variability across the African continent.

CONCLUSION

This study examined the spatiotemporal patterns and radiative impacts of biomass burning and anthropogenic emissions over Africa using satellite observations from MODIS, MISR, FIRMS, and AERONET. The findings reveal that biomass burning remains the dominant contributor to aerosol loading, with seasonal fire activity in central and Southern Africa leading to sharp increases in Aerosol Optical Depth (AOD) and reductions in surface solar radiation. In contrast, urban industrial centers such as Lagos, Johannesburg, and Cairo exhibit persistently high AOD due to year-round anthropogenic emissions.

The correlation between emission and AOD highlights the significant role of both seasonal and continuous sources in shaping Africa's atmospheric composition and solar radiation budget. Seasonal comparisons further show that dry-season burning reduce surface radiation fluxes by up to 25%, intensifying the vulnerability of already climate-sensitive regions.

These results underscore the urgent need for region-specific mitigation strategies, including reducing open biomass burning, promoting renewable energy adoption, and enforcing industrial emission standards. Strengthening ground-based and satellite monitoring networks is also essential for improving air quality management and supporting climate resilient policies.

Future studies should expand on this work by integrating additional observational datasets and coupling satellite-based analyses with regional climate modeling to better quantify long-term impacts.

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Author Contributions

Emmanuel Wennie: Conceptualization, Data Collection, Formal Analysis, Writing Original Draft.

Liu Zhenxin: Supervision, Methodological Guidance, Review & Editing.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Data Availability Statement

The datasets used and analyzed in this study are publicly available from the following sources:

- **Modis:**
- **Misr:**
- **Firms:**
- **Aeronet:**

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