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Spatial Heterogeneity Of Aerosol Optical Depth (Aod) And Its Influencing Factors In Nigeria

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Abstract:
This study investigates the spatial distribution and heterogeneity of Aerosol Optical Depth (AOD) and its influencing factors: burned area (BA), dust (DU), sea salt (SS), and black carbon (BC), across Nigeria from 2011 to 2019. The work analyzed seasonal patterns and the interactions between these variables using Geodetector model. Results show distinct seasonal variations in AOD and its contributors, with high dust concentrations in the north during the DJF season suggestive of the influence from the Harmattan winds originating from the Bodélé Depression in Chad. Burned areas significantly influence AOD, particularly in central and northern regions, during the dry seasons, reflecting biomass burning activities. SS concentrations peak along the coast, influenced by marine aerosols, and BC shows seasonal variability due to biomass burning, industrial emissions, and vehicular activities. The Geodetector analysis reveals that dust and black carbon consistently impact AOD across all seasons, while interactions between variables, particularly sea salt with burned area and dust, indicate strong combined effects on AOD. This study shows how natural and human activities together affect air pollution in Nigeria. It emphasizes the need for comprehensive strategies to manage air quality effectively.

***Key Words**: AOD; Geodetector model; Nigeria ; Bodélé Depression; Wildfire; Sea Salt*

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I. Introduction

Aerosol optical depth (AOD) is an important statistic for measuring air quality and understanding the intricate interactions between atmospheric contaminants and natural emissions. Among these pollutants, BC, which comes from both human and natural sources such as wildfires, stands out as a substantial contributor to AOD variability[1,2]. BC's unique tendency to absorb solar radiation worsens the local climatic consequences, impacting regional temperature and air quality dynamics[3].

Black carbon (BC) emissions, which mostly come from combustion processes such as vehicle exhaust and industrial activity, have an important influence in AOD fluctuation. These small particles absorb sun light, influencing the local temperature and health. For example, locations like as Russia and Canada have significant BC emissions from both industrial sources and wildfires, demonstrating the diversity of sources that contribute to regional AOD patterns[2,4].

Furthermore, biomass burning, which is especially common in sub-Saharan Africa, has a substantial influence on AOD because it emits BC and other aerosols. The geographical variability of AOD in Nigeria, for example, is the result of a complex interaction of local elements such as climatic conditions, land use patterns, and socioeconomic activity. Understanding these factors necessitates the use of robust spatial analysis methodologies such as geographical detector model, which can reveal the complex relationships between aerosol concentrations and influencing variables[5,6].

Geodetector, according to Wang *et al.*[7], is an effective spatial statistics method for identifying and explaining spatial differences in a structured way. It can quantify how much, individual factors contribute to these differences and assess interactions between two variables, as highlighted by Jing *et al.*[8]. This approach not only analyzes how different factors influence each other but also unveils complex relationships among them, offering more reliable and insightful results compared to conventional statistical methods.

The fundamental goal of this research is to investigate the high-resolution geographic variability of air pollution (AOD) distribution patterns and to uncover regional heterogeneity in the interaction between air pollution and aerosol variables (BC, OC, SS, and DU), as well as burnt regions.

II. Material And Methods

Study Area:

Nigeria, located in West Africa, has a diverse environmental profile due to its geographical location between the Atlantic Ocean to the south and the Sahara Desert to the north. This geographical arrangement has a profound impact on the region's climate and ecosystem. The northern states of Nigeria, which are near the Sahara Desert, frequently encounter dusty conditions as a result of dust particle transmission from the desert. These dust-laden winds may affect air quality and sight, especially during dry seasons when desertification and dust storms are common.

The southern portions of Nigeria, bordering the Atlantic Ocean, have a more humid and rainy climatic regime. This region benefits from maritime effects, which lead to increased precipitation and moisture. However, this moisture-laden atmosphere can also lead to specific air quality concerns, such as elevated humidity levels, which may affect air quality measures.

Nigeria's air pollution comes from a variety of sources around the country. One major cause is biomass burning, mainly from agricultural operations and forest fires, which emits pollutants including particulate matter and carbon monoxide into the atmosphere. Vehicle emissions from transportation, particularly in metropolitan areas, lead to high levels of particulates. Industrial emissions from manufacturing operations, which are frequently concentrated in urban and industrial areas, emit pollutants such as sulfur dioxide and volatile organic compounds.

Furthermore, Nigeria is known for its extensive oil and gas industry, where gas flaring[9,10], a common practice during oil production emits air pollutants into the atmosphere, contributing to local and regional air pollution. Additionally, wildfires, seas salts[11], both natural and man-made, contribute to air quality issues, especially during dry seasons when vegetation is susceptible to ignition. Figure 1 shows the map of Nigeria.

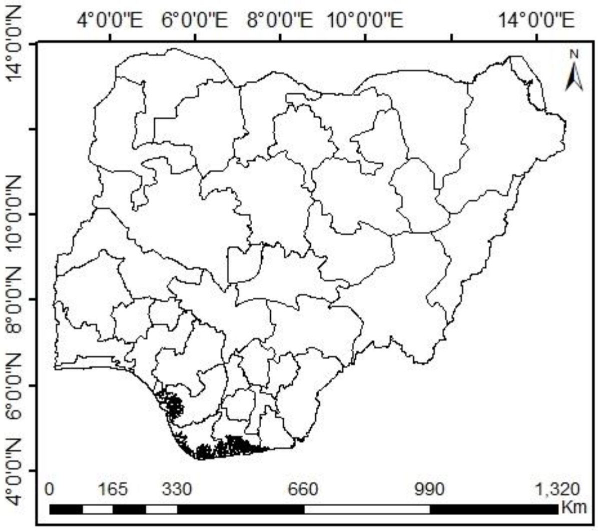

Figure 1 Study Area

Data:

The data used in this study include (i) AOD, BC, SS, and DU assessed from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) at 0.5° × 0.625° resolution, and (ii) burned area obtained from the Copernicus Climate Change Service, Climate Data Store (2019): Fire burned area, 2001 to present derived from satellite observations of the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) at 0.25° × 0.25° with DOI: 10.24381/cds.f333cf85 and accessed in June 2024.

Methodology:

The geodetector model (GDM) quantifies q which gives the degree of spatial heterogeneity observed in Y, reflecting how much X explains variations in Y across different layers within the region. The formula[7] is given by

$$q = 1 - \frac{\sum_{h=1}^{k} \aleph_h \sigma_h^2}{\aleph \sigma^2} = 1 - \frac{SSW}{SST} \tag{1}$$

where $SSW = \sum_{h=1}^{k} \aleph_h \sigma_h^2$, $SST = \aleph \sigma^2$, q represents a measure that represents the extent of spatial heterogeneity in a dependent variable Y across different layers L, where $\aleph_h$ denotes the units within a specific layer h, and $\aleph$ is the total number of units in the region. The terms σ_h^2 and σ^2 represent the variances within layer h and the variance of Y across the entire region, respectively. SSW refers to the variance within each layer, while SST denotes the total variance of Y in the entire region. The parameter q falls within the range of [0, 1], with higher values indicating more pronounced spatial variation in Y and a stronger explanatory relationship between the independent variable X and Y.

In this model, the interaction between two distinct factors (such as X1 and X2) is identified using a specific function (Interaction Detector). The algorithm creates a new layer by combining X1 and X2, denoted as X1∩X2, and then compares the effects on the outcome to determine the nature of their interaction. This approach categorizes interactions into five major types, as detailed in Table 1, based on how X1 and X2 jointly influence the outcome variable.

Table 1 Interactions between factors and their descriptions[7]

Type of Interaction	Description
Enhanced, Non-linear	$q(X1 \cap X2) > q(X1) + q(X2)$
Enhanced, Bi-linear	$q(X1 \cap X2) > Max(q(X1), q(X2))$
Independent	$q(X1 \cap X2) = q(X1) + q(X2)$
Weakened, Non-linear	$q(X1 \cap X2) > Min(q(X1), q(X2))$
Weakened, Unique	Min($q(X1),\ q(X2)) < q(X1 \cap X2) < Max\ (q(X1)), q(X2))$

III. Result And Discussion

Spatial Distribution of AOD, BA, DU, SS, and BC:

Figure 2 shows the spatial distribution of seasonal AOD, BA, DU, SS, and BC over Nigeria. Results show that the spatial distribution of AOD, BU, DS, SS, and BC in Nigeria shows different seasonal patterns. During DJF, AOD levels are typically low, with slightly higher values in the northern parts (0.15 to 0.4 µg/m^3), but BA values are significant, particularly in the central and northern regions (0 to 180 square kilometer), indicating substantial biomass burning. Dust concentrations peak in the north (0 – 150 µg/m^3), corresponding with the Harmattan season, but SS concentrations peak near the southern coast (0 to 4.5 µg/m^3), affected by marine aerosols. The southern areas have the greatest amounts of black carbon (0 to 3.5 µg/m^3), which is most likely attributable to biomass burning and urban emissions. In MAM, AOD increases in the northern and central areas (0.25 - 0.55).

BA values are still high, but significantly lower, while dust levels in the north remain high (0 to 120 µg/m^3). Sea salt levels decrease marginally but remain highest around the coast (0 to 4.5 µg/m^3), while black carbon levels remain high in the south (0 to 3.5 µg/m^3) due to ongoing burning and industrial emissions. AOD peaks in JJA, particularly in the northern half of the country (more than 0.75), whereas BA values decreases substantially (usually below 25 km^2) owing to the wet season. Dust levels fall (usually below 20 km^2), sea salt concentrations peak around the coast (up to 6), and black carbon concentrations peak in the north (up to 3.5 µg/m^3) due to agriculture-related burning. In SON, AOD remains high in the north and increases in the south, BA activity rises again in the central regions (0 to 180 km^2), dust concentrations rise in the north (0 to 120), sea salt levels rise along the coast (0 to 4.5 µg/m^3), and black carbon levels remain high (0 to 3.5 µg/m^3), indicating constant emission sources.

The spatial distribution of AOD, burned area, dust, sea salt, and black carbon across Nigeria shows distinct seasonal patterns. AOD and dust concentrations are highest during the dry seasons (DJF and SON), particularly in the north. Burned area activity peaks in the dry seasons, reflecting biomass burning practices. Sea salt concentrations are consistently high along the coast, influenced by marine aerosols. Black carbon levels are elevated in both the dry and wet seasons, indicating varied emission sources across the country. These patterns indicate the complex interactions between natural and anthropogenic factors influencing air pollution in Nigeria. Similar fluctuations in seasonal AOD and BC were observed by Fawole *et al.*[9] and Izah *et al.*[12] identified the pursuit of bush meat (a major source of animal protein), burning of solid wastes, careless disposal of cigarette butts, and intentional, uncontrolled burning by farmers as the primary causes of bushfires.

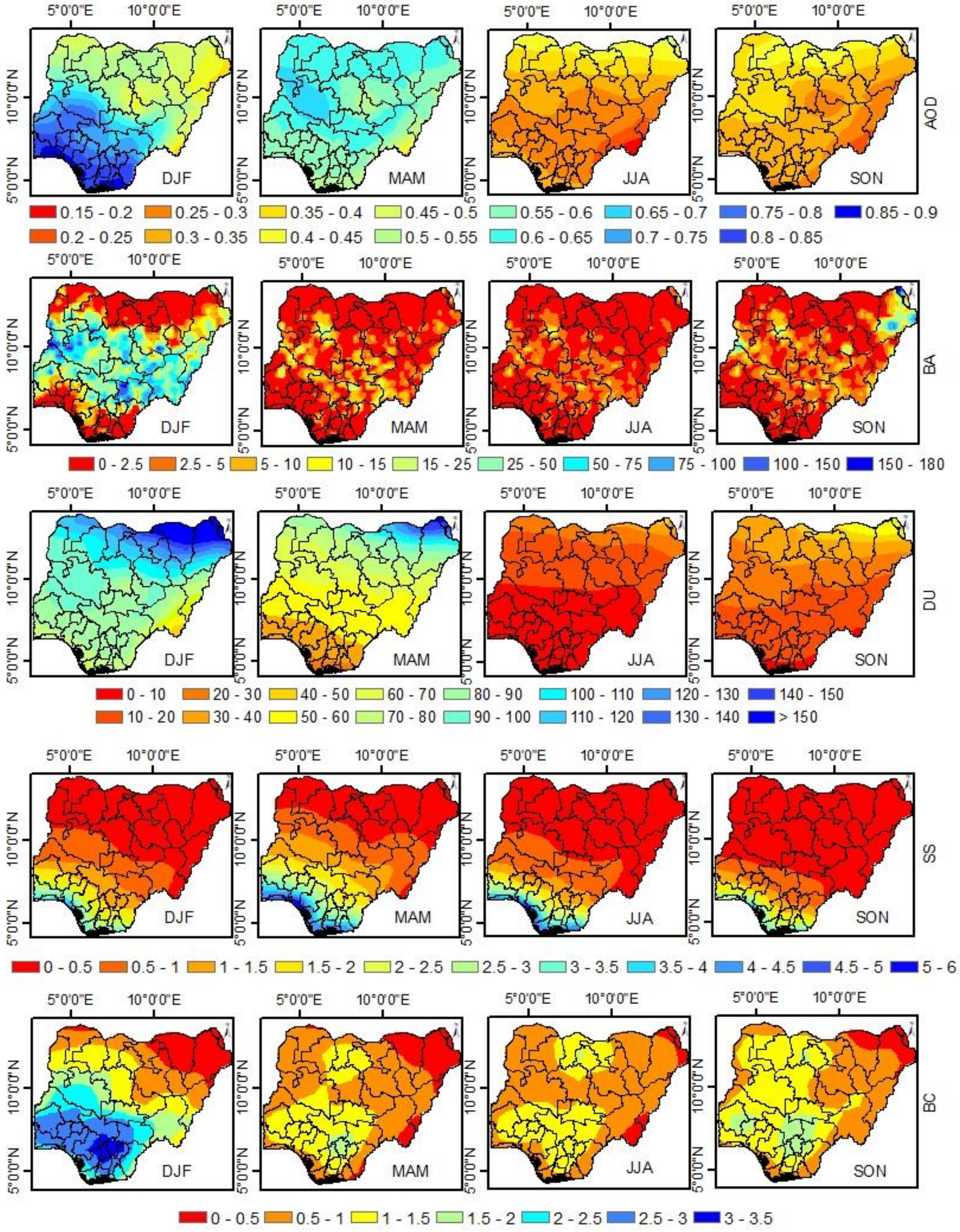

Figure 2 Spatial Distribution of AOD, BA, DU, SS, and BC in different seasons

Spatial Heterogeneity Analysis in different seasons:

The Geodetector analysis results (Table 1) indicate the spatial heterogeneity of Aerosol Optical Depth (AOD) in relation to burned area (BA), dust (DU), sea salt (SS), and black carbon (BC) across different seasons in Nigeria. In DJF, the influence of DU (q=0.456, p=0.000), SS (q=0.836, p=0.000), and BC (q=0.647, p=0.000) on AOD is statistically significant, while BA (q=0.028, p=0.478) shows no significant effect. During MAM, DU (q=0.413, p=0.000) and BC (q=0.325, p=0.000) remain significant, whereas BA (q=0.024, p=1.000) and SS (q=0.048, p=1.000) do not. In JJA, DU (q=0.500, p=0.000) and BC (q=0.175, p=0.000) significantly influence AOD, while BA (q=0.165, p=0.000) also shows a notable effect, and SS (q=0.070, p=0.402) does not. During SON, DU (q=0.568, p=0.000) and BC (q=0.216, p=0.000) continue to significantly affect AOD, while BA (q=0.125, p=0.122) and SS (q=0.012, p=1.000) do not show significant impacts. Ultimately, DU and BC provide major contributions to AOD fluctuations all through the seasons, although the effects of BA and SS differ, demonstrating the dynamic character of aerosol sources and their geographical distributions.

This work agrees with findings of Fawole *et al.*[9] who observed a link between biomass burning and AOD. Though in this work, burned areas seemed to contribute minimally to AOD changes in Nigeria. High clusters of DU in the study, especially during the DJF season, are suggested to originate from the Bodélé Depression in Chad[13,14,15,16]. These dust aerosols can travel across the African savannah region towards the Gulf of Guinea and the equatorial Atlantic[14,15,16]. According to Fawole *et al.*[9], gas flaring contributes to increased BC levels. However, based on the spatial distribution of BC in Figure 2, BC exhibits seasonal variability, which can be attributed to several sources, including biomass burning from agricultural practices and wildfires, industrial activities such as combustion in factories and power plants, fluctuations in traffic and vehicular emissions, and meteorological conditions like wind patterns and temperature inversions.

Interaction among variables:

The Interaction Detector results (Table 2) from the Geodetector analysis provide insights into the interactive effects of burned area (BA), dust (DU), sea salt (SS), and black carbon (BC) on Aerosol Optical Depth (AOD) across different seasons. In DJF, the interactions of SS with BA (0.852**) and SS with DU (0.917**) show significantly enhanced bilinear interactions, indicating a strong combined effect of these interacting variables on AOD. The interactions of BC with BA (0.850*), DU (0.821**), and SS (0.890**) also indicate significant combined effects, with bilinear interactions being particularly strong. During MAM, notable interactions include BC with DU (0.796*) and SS with DU (0.809*), indicating enhanced non-linear interactions. In JJA, significant interactions are observed between BC and DU (0.672**) and SS with DU (0.544**), highlighting strong bilinear interactions. For SON, interactions of BC with DU (0.774**) and SS with DU (0.684*) are significant, showcasing the enhanced bilinear effects. Generally, the interactions between dust and black carbon consistently show significant effects on AOD across all seasons, with sea salt also playing a crucial role, particularly in the presence of other variables. The interaction effects underline the complexity of AOD determinants and the importance of considering multiple factors in understanding aerosol behavior.

Table 1 Spatial Heterogeneity using Geodetector Model

Season	Variable	q	p-value
DJF	BA	0.028	0.478
	DU	0.456	0.000
	SS	0.836	0.000
	BC	0.647	0.000
MAM	BA	0.024	1.000
	DU	0.413	0.000
	SS	0.048	1.000
	BC	0.325	0.000
JJA	BA	0.165	0.000
	DU	0.500	0.000
	SS	0.070	0.402
	BC	0.175	0.000
SON	BA	0.125	0.122
	DU	0.568	0.000
	SS	0.012	1.000
	BC	0.216	0.000

Table 2 Interaction Detector (Enhanced Non-linear = *, Enhanced, Bi-linear = **)

Season	Variable	BA	DU	SS
DJF	DU	0.690*		
	SS	0.852**	0.917**	
	BC	0.850*	0.821**	0.890**
MAM	DU	0.459*		
	SS	0.181*	0.809*	
	BC	0.385*	0.796*	0.397*
JJA	DU	0.549**		
	SS	0.267*	0.544**	
	BC	0.327**	0.672**	0.360*

SON	DU	0.624**		
	SS	0.236*	0.684*	
	BC	0.409*	0.774**	0.284*

IV. Conclusion

The analysis of the spatial distribution and heterogeneity of aerosol optical depth (AOD) and its influencing factors in Nigeria indicates large seasonal fluctuations as well as complex interactions between natural and anthropogenic sources. findings showed that during the DJF season, DU has a significant contribution AOD variability which is suggestive of DU which originate from Chad's Bodélé Depression and migrate over the African savannah to the Gulf of Guinea, dramatically increasing AOD levels. Burned areas (BA) have a modest impact on AOD fluctuations, particularly during certain seasons, reflecting the varying intensity of biomass burning techniques. Sea salt (SS) concentrations are typically high along the coast, driven by marine aerosols and exhibiting strong interactions with both burnt regions and dust, particularly in DJF.

Black carbon (BC) shows significant seasonal variations due to a variety of sources, including biomass burning, industrial activity, vehicle emissions, and weather circumstances. The geodetector study shows that DU and BC have a major effect on AOD across all seasons, but the contributions of BA and SS change, revealing the dynamic nature of aerosol sources and their regional distributions. The interaction effects between DU, BC, and SS emphasize the need of taking into account several elements when understanding aerosol behavior and its cumulative influence on air pollution in Nigeria.

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