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Spatial Variability of Key Climate and Air Quality Parameters Across Some Nigerian Cities

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Abstract: *This study explores the spatial variability of key climate and air quality parameters across Nigerian cities from 1979 to 2024, emphasizing the significance of regional fluctuations in environmental stability. Spatial variability serves as a vital tool for identifying areas of climatic and air quality instability, offering critical insights for environmental management and policy formulation amidst escalating climate change and urbanization. Through comprehensive analysis of rainfall, air temperature, and PM2.5 concentration data, the research highlights distinct patterns of inter-annual fluctuations and their underlying drivers. Regions such as Sokoto and Kano demonstrate high rainfall and temperature variability, posing challenges for agriculture and water resource management. Conversely, coastal cities like Port Harcourt and Uyo exhibit more stable rainfall and air quality patterns, supporting sustainable livelihoods. The variability in PM2.5 levels underscores the influence of industrial activities, traffic emissions, and seasonal winds, with Port Harcourt and Kano experiencing significant fluctuations. These findings underscore the importance of high-resolution data, advanced analytical techniques, and interdisciplinary approaches in addressing environmental variability. Understanding these spatial patterns is essential for developing resilient and adaptive strategies that safeguard ecological and human health in Nigeria's dynamic climate landscape.*

Keyword*: Spatial Variability, Air Quality, PM2.5 Concentrations, Climate Change*

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1.0 Introduction

Understanding the complex patterns and fluctuations within our environment is crucial for addressing the pressing issues of climate change and air quality management (Ofremu *et al.*,2024). One of the key concepts in environmental science is 'spatial variability', which refers to the uneven distribution of climatic and air quality parameters across different geographic regions (Vardoulakis *et al.*,2005). This variability can be influenced by a multitude of factors, including natural processes, human activities, topography, and urbanization (Tuoku *et al.*, 2024). By examining how these factors fluctuate across space, researchers can identify vulnerable areas, develop targeted mitigation strategies, and better predict future environmental changes (Zhai and Lee 2024).

Spatial variability plays a vital role in revealing the dynamic nature of our atmosphere and climate systems. For instance, temperature and precipitation patterns are not uniform across a continent or even a city (Bojago 2024). Some regions may experience extreme heatwaves while neighboring areas remain relatively mild (Pérez-García *et al.*, 2025). Similarly, air pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), and ozone often display significant spatial heterogeneity (Paralovo *et al.*, 2019). These fluctuations are not random; they are driven by specific local sources, geographic features, and meteorological conditions (Girlamo *et al.,* 2023). Recognizing and quantifying these fluctuations help scientists and policymakers understand where environmental conditions are most unstable and potentially harmful (Thornton *et al.*, 2014).

The importance of studying spatial variability extends beyond academic interest it has practical implications for public health, urban planning, and environmental policy (Schindler and Dionisio 2024) . Regions with high fluctuations in air quality often correspond to higher incidences of respiratory and cardiovascular diseases. Urban areas, with dense traffic and industrial activities, tend to show greater variability compared to rural regions. Similarly, climatic instability, such as sudden temperature swings or irregular rainfall, can cause droughts, floods, and other extreme weather events, impacting agriculture and water resources. By mapping and analyzing these variations, stakeholders can implement more effective strategies to protect communities and manage resources sustainably (Adom, 2024.).

Advances in remote sensing technology and geographic information systems (GIS) have enhanced our ability to monitor spatial variability at finer scales. Satellite data, ground-based sensors, and modeling tools now enable detailed mapping of environmental parameters over large regions (Matyukira and Mhangara 2024). These tools help identify hotspots of instability, monitor changes over time, and evaluate the effectiveness of policy interventions. For example, satellite imagery can reveal urban heat islands areas within cities that experience higher temperatures due to dense construction and limited vegetation highlighting the need for urban greening initiatives (Zargari *et al.,* 2024).

Despite these technological advancements, understanding the underlying drivers of spatial variability remains a complex challenge. Factors such as topography, land use, population density, and meteorological conditions interact in intricate ways to produce the observed patterns (Verburg *et al.,* 2011). For example, mountainous regions may experience temperature fluctuations greater than flat plains, while industrial zones may show persistent high levels of pollutants with sharp spatial gradients. Disentangling these influences requires sophisticated statistical and computational approaches, as well as comprehensive datasets (Mo *et al.,* 2025). However, for Nigerian cities, there remains a paucity of high-resolution, long-term analyses that simultaneously examine both climatic and air quality parameters, leaving gaps in our understanding of how these variables co-vary across different ecological zones.

Therefore, this study aims to investigate the spatial variability of key climate (rainfall and temperature) and air quality ($PM_{2.5}$ concentrations) parameters across selected Nigerian cities from 1979 to 2024, with the goal of identifying regions of environmental instability and potential vulnerability. By addressing this gap, the research will provide evidence-based insights to inform climate adaptation, air quality management, and sustainable urban planning in Nigeria.

2.0 Materials and Methods

Nigeria, located in West Africa, has a population of approximately 229.5 million according to the 2024 census. The country lies between latitudes 4°N and 14°N and longitudes 3°E and 14°E, bordered by Niger to the north, Chad and Cameroon to the east, the Gulf of Guinea to the south, and Benin to the west. Covering an area of approximately

923,769 square kilometers, Nigeria is the most populous country in Africa and the sixth most populous in the world. The nation exhibits diverse geography and climate, ranging from arid regions in the north to humid equatorial climates in the south. Nigeria is endowed with abundant natural resources, including significant petroleum and natural gas reserves.

The climate in Nigeria is predominantly tropical, characterized by distinct rainy and dry seasons that vary by location. The southern region is the most economically developed, with extensive exploitation of forest resources. This region also hosts the majority of Nigeria's major industrial activities, oil fields, and seaports (Omaliko et al., 2025). The northern regions, particularly Sokoto and Kano, are among the most densely populated areas (Koko et al., 2023). Lagos, a cosmopolitan city consisting of islands and mainland, has experienced remarkable economic and population growth in recent decades. Approximately one-fifth of Nigerians derive their livelihood from agriculture (Koko & Bello, 2023).

For this study, ten locations were selected across Nigeria (Fig. 1) based on their distinct geographical and economic characteristics: Ilorin, Ikeja, Sokoto, Uyo, Kano, Owerri, Enugu, Abuja, Port Harcourt, and Gombe (see Figure 1). These cities represent diverse climatic zones and urbanization levels, which are important for analyzing spatial variability in climate and air quality parameters (Reddingy, 2008). The locations were plotted using QGIS software (version X.X) to visualize their spatial distribution.

2.1 Data Analysis

Descriptive statistical methods were used to analyze the datasets, including calculations of mean and standard deviation, as well as the generation of scatter plots to visualize trends.

a) **Mean**: The mean (arithmetic average) of a dataset is calculated by summing all individual data points and dividing by the total number of observations. It is given by:

$$\mu = (\Sigma x) / n \quad (1)$$

Where: 'x' represents individual data points, 'Σ' denotes the sum, 'n' is the number of data points

b) **Standard Deviation**: Standard deviation measures the amount of variation or dispersion of data points relative to the mean. It is calculated as:

$$\sigma = \sqrt{[(\Sigma(x - \mu)^2) / (n - 1)]^2) / (n - 1)]} \quad (2)$$

where symbols have their usual meanings.

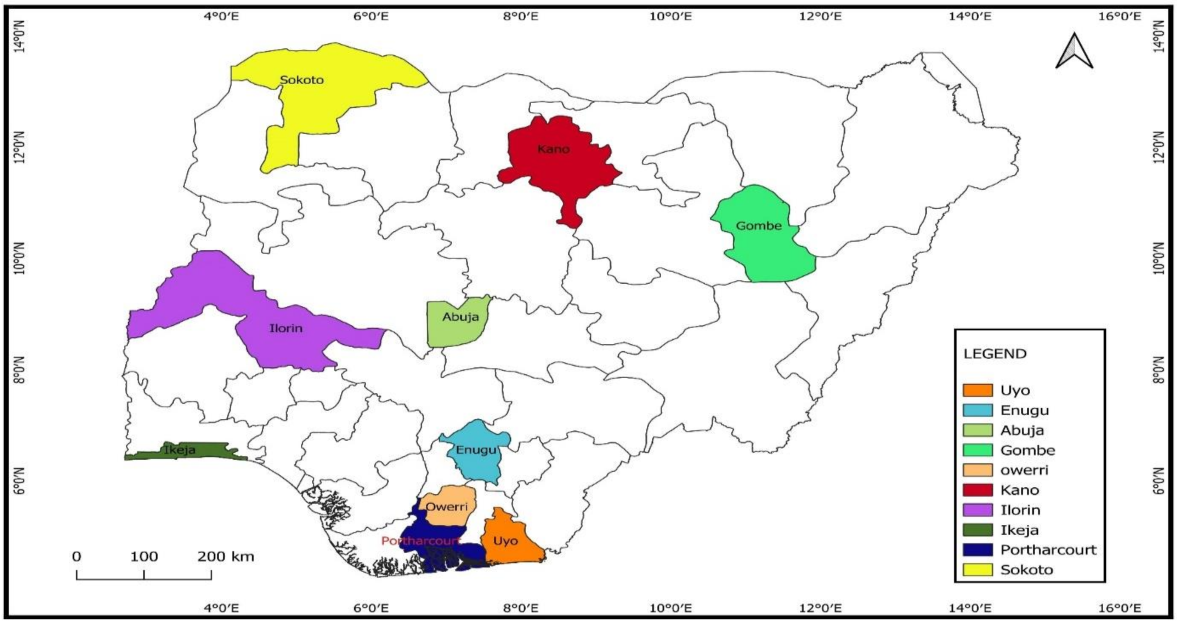

Fig. 1: Map of Nigeria showing the selected study locations.

2.2 Atmospheric Parameters Analyzed

The datasets used in this study were obtained primarily from satellite retrievals and meteorological records for the selected cities:

- Particulate Matter (PM2.5) concentrations from NASA Giovanni (1980–2024).
- Air temperature data from NASA Giovanni (1980–2024).Rainfall data obtained from the Nigerian Meteorological Agency (NiMet) (1979–2023).

QGIS software was utilized for spatial mapping and calculation of standard deviations across the locations.

3.0 Results and Discussion

The spatial patterns for inter-annual variability of key climate and air quality parameters revealed provide insight into regional environmental stability and potential vulnerabilities.

3.1 Rainfall Variability Across Nigerian Cities

Fig. 2 depicts the spatial distribution of the standard deviation of annual rainfall across the study locations for the period 1979 to 2023. The standard deviation is widely recognized in meteorology as a robust measure of rainfall variability: higher SD values indicate greater inconsistency in annual precipitation, while lower values correspond to more stable and predictable rainfall regimes.

Analysis of Fig. 2 reveals pronounced spatial heterogeneity in rainfall variability across Nigeria. The northern city of Sokoto exhibits the highest SD, signifying highly erratic rainfall patterns. Such variability poses significant challenges to rainfed agriculture and water resource management, potentially exacerbating drought and food security risks in this semi-arid zone. Gombe follows closely, also demonstrating elevated rainfall variability, reflective of its position within the Sudanian climatic belt.

Kano shows substantial variability, though slightly less than Sokoto and Gombe, indicating somewhat more reliable but still unpredictable rainfall. Moving towards central Nigeria, Abuja presents moderate SD values, consistent with its transitional climate that bridges northern arid and southern humid zones. Ilorin, located within a similar transitional zone, experiences seasonal rainfall fluctuations typical of regions where wet and dry seasons alternate distinctly.

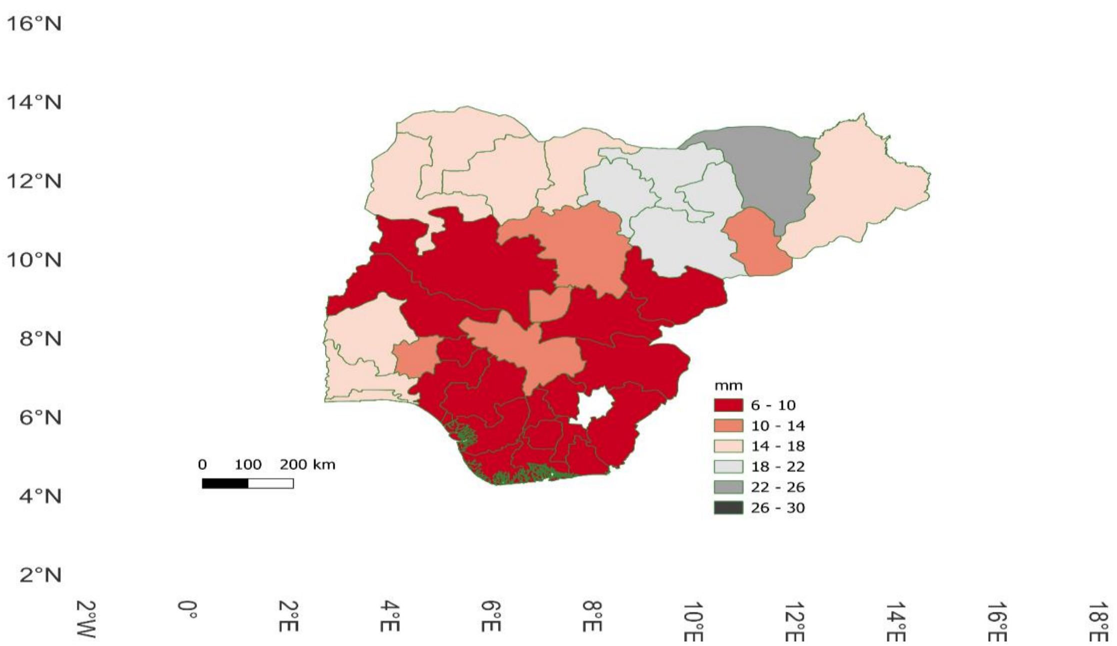

Fig. 2: illustrates the Variability in rainfall across various regions in Nigeria (1979-2023)

In contrast, southern and coastal cities such as Ikeja (Lagos), Port Harcourt, Uyo, Enugu, and Owerri exhibit low rainfall standard deviations, indicative of consistent and reliable precipitation patterns. Port Harcourt stands out with one of the lowest SD values, reflecting stable rainfall that supports robust agricultural systems and reliable water supply. Uyo, Enugu, and Owerri mirror these stable patterns, further underlining the climatic stability characteristic of the humid tropics and equatorial coastal environments.

3.2 Air Temperature Variability Across Nigerian Cities

Fig. 3 illustrates the spatial distribution of the standard deviation of annual mean air temperature for the period 1980 to 2024, highlighting the influence of geographic location and climate zones on temperature stability.

Southern cities, including Uyo, Port Harcourt, Owerri, and Ikeja, consistently show low temperature variability. This stability is attributable to the moderating effects of their equatorial location and proximity to the Atlantic Ocean, which buffer extreme temperature fluctuations and result in relatively constant, mild thermal conditions throughout the year.

Conversely, central Nigerian cities such as Abuja, Ilorin, and Gombe exhibit moderate temperature variability. These cities experience transitional climatic influences characterized by pronounced wet and dry seasons, leading to moderate seasonal temperature swings.

The highest temperature variability is observed in northern cities, particularly Sokoto and Kano. These regions endure severe temperature contrasts between scorching dry seasons, marked by intense solar radiation and elevated daytime temperatures, and cooler nights or harmattan periods influenced by dry, dusty winds from the Sahara Desert. This wide range of daily and annual temperature fluctuations complicates agricultural planning, energy demand forecasting, and health management, underscoring the need for region-specific climate adaptation strategies.

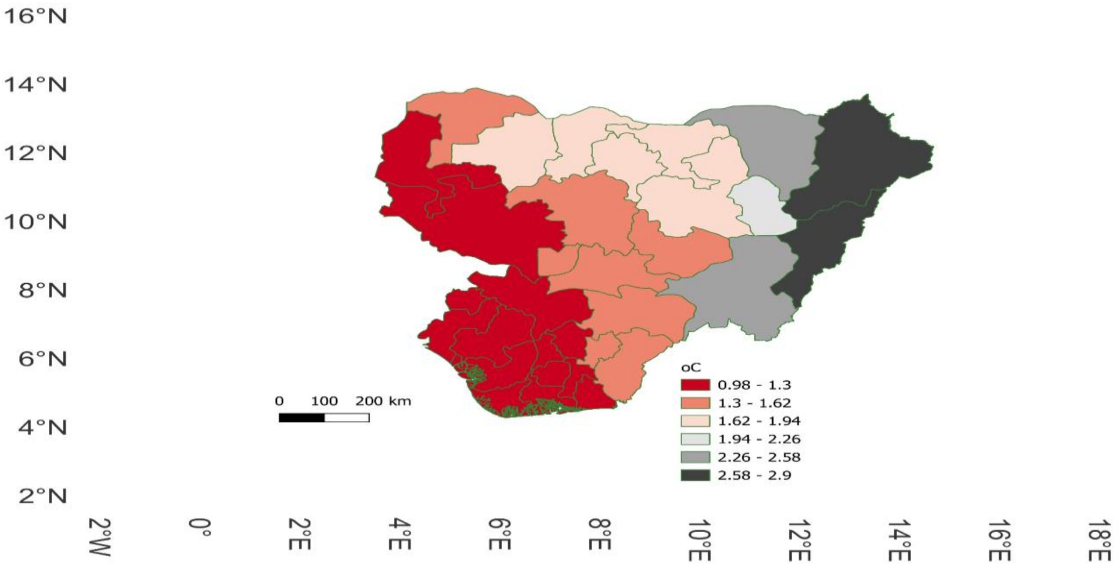

Fig. 3: Spatial distribution of the standard deviation of air temperature across Nigeria (1980-2024)

3.3 $PM_{2.5}$ Concentration Variability Across Nigerian Cities

Fig. 4 presents the spatial distribution of the standard deviation of $PM_{2.5}$ concentrations from 1980 to 2024, revealing distinct pollution dynamics across the cities studied.

Port Harcourt exhibits the highest variability in $PM_{2.5}$ concentrations, reflecting episodic pollution events primarily driven by gas flaring, oil refinery operations, and other industrial activities concentrated in the Niger Delta region. These frequent pollution surges pose serious environmental and public health risks, particularly respiratory diseases.

Similarly, Lagos (Ikeja) and Kano demonstrate significant $PM_{2.5}$ fluctuations. In Lagos, high vehicular traffic, urban congestion, and biomass burning contribute to this variability. Kano's variability is influenced by dust storms and biomass combustion, particularly during dry seasons, coupled with increasing urban emissions.

Cities such as Ilorin, Enugu, Owerri, Gombe, and Sokoto show moderate $PM_{2.5}$ variability, largely affected by seasonal phenomena including harmattan winds, agricultural burning, and windborne dust transport. These natural and anthropogenic factors create fluctuations in air quality that vary seasonally but are less extreme than those in highly industrialized or densely urbanized centers.

Notably, Uyo and Abuja exhibit the lowest $PM_{2.5}$ variability, indicating relatively stable air quality over time. However, it is important to highlight that even these stable concentrations often exceed World Health Organization (WHO) recommended limits, signaling ongoing health concerns that warrant continued air quality monitoring and management.

The spatial variability patterns across rainfall, temperature, and $PM_{2.5}$ concentrations collectively illustrate Nigeria's diverse climatic and environmental landscape. Northern cities face compounded risks from highly variable rainfall and temperature regimes, alongside moderate air pollution influenced by natural dust and urban emissions. These factors contribute to vulnerabilities in agriculture, water resources, and public health.

Southern and coastal cities benefit from stable rainfall and temperature but confront significant air pollution challenges tied to industrialization and dense urban activity. Central cities fall between these extremes, exhibiting moderate variability in all three parameters.

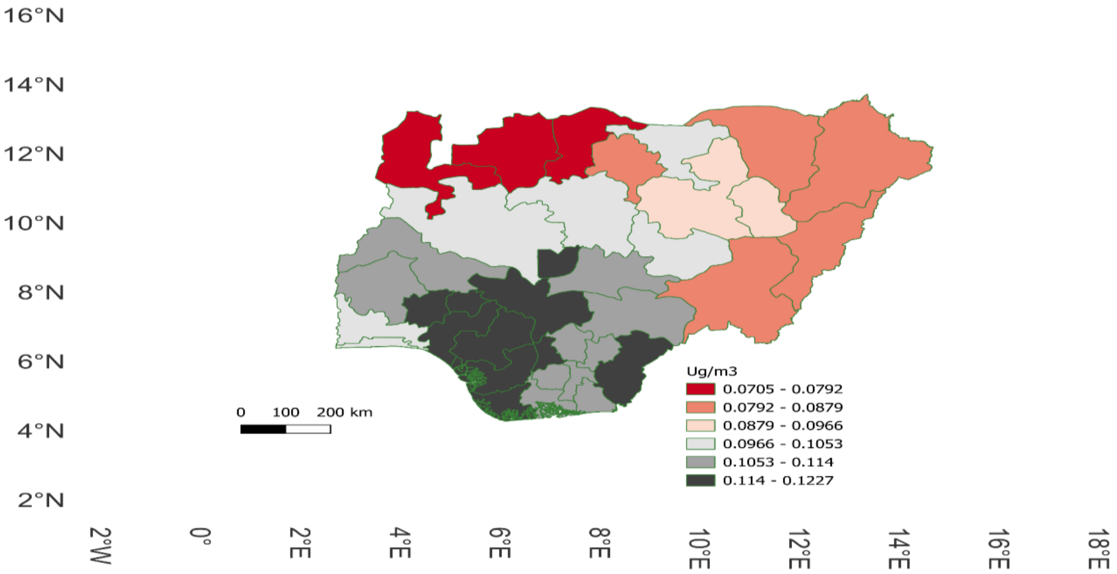

Fig. 4: Spatial distribution of the standard deviation of PM2.5 concentrations across Nigeria cities (1980-2024).

These findings emphasize the necessity for geographically tailored policies: adaptive water and agricultural management to mitigate rainfall and temperature extremes in the north, intensified pollution control and urban planning in southern industrial centers, and integrated climate-health interventions nationwide. Additionally, the observed $PM_{2.5}$ variability highlights the urgent need for targeted air quality regulations to reduce episodic pollution peaks with acute health impacts.

4.0 Conclusion

This study highlights the importance of spatial variability in assessing environmental and climatic stability across Nigerian cities. The findings demonstrate considerable regional differences in rainfall, air temperature, and PM2.5 concentrations, with northern cities such as Sokoto and Kano experiencing significant fluctuations that present challenges to agriculture, water resource management, and public health. In contrast, coastal cities like Port Harcourt and Uyo show more consistent environmental conditions, supporting greater stability in these sectors. These results emphasize the need for the use of high-resolution data and advanced analytical techniques combined with interdisciplinary approaches to accurately monitor and address environmental changes. Given the ongoing pressures of climate change and rapid urbanization in Nigeria, effectively understanding and managing spatial variability is crucial for developing adaptive and resilient strategies that safeguard ecosystems and foster sustainable development across diverse regions of the country.

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Compliance with Ethical Standards Declarations

The authors declare that they have no conflict of interest.

Data availability

All data used in this study will be readily available to the public

Availability of data and materials

The publisher has the right to make the data public.

Competing interests

The authors declared no conflict of interest.

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Author Contribution

Conceptualization, methodology, Formal analysis, and writing original draft preparation; Augustus Onyemauchechukwu Obioha; Supervision, Software and writing-review and editing; Chidiezie Chineke, Validation and Project administration while Obinwanne Okafor consulted for us.

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