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Spatio-Temporal Variability of Lightning, Thunderstorm and Rainfall Occurrences over Nigeria during MAM Season

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Abstract

Lightning (LTG) and thunderstorms (TS) are a significant weather phenomenon in Nigeria, with crucial impacts on local climates, agriculture, energy, and transportation. This study investigates the spatial and temporal variability of lightning and thunderstorm activities in Nigeria by assessing the performance of Worldwide Lightning Location Network (WWLLN) data and the data from the Nigerian Meteorological Agency (NIMET) over time and spatial scales. The study spans four years, from 2020 to 2023. A comprehensive analysis of 37 stations across Nigeria, representing different climatic zones, was conducted for the study. Monthly totals were aggregated to form seasonal datasets for each station, enabling the examination of seasonal variability. The coefficient of correlation was computed, and the use of GIS technology and heat maps provided a visual representation of spatial variations in thunderstorm activities, facilitating the identification of areas with high thunderstorm frequencies. TS activity is more frequent in areas between Lat 4˚N and Lat 8˚N than areas between Lat 8˚N and 14˚N, including a strong correlation between WWLLN and NIMET data. The findings further substantiate that 2022 was a significant flood year in Nigeria, with the Yenagoa station experiencing the most severe impact. This study contributes to the existing body of knowledge on thunderstorm activities in Nigeria, providing insights into the spatial and temporal variability of lightning and thunderstorms. The findings have significant implications for climate resilience strategies, early warning systems, and public awareness in Nigeria, highlighting the need for continued research and monitoring of lightning and thunderstorm activities in the context of climate change.

Keywords

Lightning, Thunderstorms, Rainfall, Strokes

1. Introduction

Thunderstorms are natural meteorological phenomena characterized by the presence of lightning, thunder, heavy rainfall, and sometimes hail and tornadoes [1]. A thunderstorm is a downpour of rain accompanied by thunder. Since lightning produces thunder, all thunderstorms contain lightning. Thunderstorms inflict death and damage worldwide due to lightning and heavy rains [2]. These dynamic occurrences have significant impacts on many industries, including agriculture, transportation, energy, and disaster management, as well as the weather patterns that govern our globe [3]. Nigeria, a large geographic area predisposed to a high frequency of thunderstorm occurrences, is one place where thunderstorms hold great significance [4] [5]. Some areas in Nigeria are more prone to thunderstorms than others, but the frequency of these storms can change across the region [6]. The frequency and intensity of thunderstorms in Nigeria make them the focus of this work.

In Africa where Nigeria is situated, thunderstorm activities over the tropical rainforests reaches their peak during the late afternoon and early evening hours, during the wet or rainy season some areas experience thunderstorms on a daily basis [7]-[9]. Storms are most likely to form shortly after the hottest surface temperatures, which provides warm air packages with the initial buoyancy they require to begin rising. Thunderstorms can last anywhere from an hour to over 12 hours. It is difficult to anticipate the exact time and location of a storm due to its fast growth, relatively small (mesoscale) size, and sensitivity to climatic factors. Despite favourable conditions, forecasters cannot pinpoint exactly, the location of the storm(s) within a region, the precise timing of storm onset, duration, or intensity. This probabilistic approach acknowledges that thunderstorm prediction is not an exact science [10].

Nearly all parts of the planet are known to have thunderstorms, while they are uncommon in the Polar Regions and seldom in latitudes higher than 50˚N and 50˚S. The world's temperate and tropical regions see more thunderstorms [11]. In West Africa, precise estimate and forecasting of thunderstorms is crucial because of the potential damage and disruption they can cause to numerous facets of daily life. Understanding the behaviour and characteristics of these electrical storms can be aided by understanding lightning, a crucial component of thunderstorms.

It is known that strong lightning activity is a signature of convective intensity [12]. It has also been confirmed that the most intense thunderstorms around the world are found in the equatorial Africa region of the Congo Basin [12]. High lightning activity requires a microphysical environment of mixed-phase and strong updrafts. It is therefore natural that deep convection frequently exceeds the tropopause in the Congo Basin [13].

It has long been known that lightning activity has negative societal and environmental effects all around the world. Many people around the world have died or were injured as a result of this electrical weather event. Every year, there are about 2400 human fatalities and 240,000 injuries worldwide. Lightning strikes can potentially disrupt communications and electrical infrastructure. Around the earth, there are about 1800 thunderstorms active at once, with 100 lightning strikes each second [14]. Tropical latitudes are dominated by about 1000 thunderstorms per hour, with tropical Africa having the highest flash rates [15] [16].

This study investigates the spatial and temporal patterns of lightning and thunderstorm activities across Nigeria using data from the World-Wide Lightning Location Network (WWLLN) and Nigerian Meteorological Agency (NiMET), with a focus on identifying areas with high occurrences (hotspots) and examining how these occurrences vary across different climatic zones and seasons. Additionally, the study seeks to understand the statistical relationship between lightning and thunderstorms through regression and correlation analyses. This investigation will support the accuracy of using lightning data to forecast the occurrence of thunderstorms in Nigeria. The frequency of thunderstorms in Nigeria poses a significant challenge to public safety, infrastructure, and economic activities. However, the lack of comprehensive and localized data on thunderstorm occurrences severely hampers efforts to effectively monitor, predict, and mitigate the impacts of these natural events. Traditional ground-based observation networks in Nigeria suffer from limited coverage and may not adequately capture the full extent and variability of lightning and thunderstorm activity across the diverse climatic zones of the country. This data insufficiency creates critical gaps in understanding the spatial and temporal distribution of lightning and thunderstorms, identifying high-risk areas (lightning hotspots), and developing effective disaster management strategies. Consequently, there is a need to explore and integrate alternative data sources, such as satellite observations and/or advanced lightning detection networks, to obtain a more accurate and comprehensive picture of lightning and thunderstorm activity in Nigeria. Moreover, the relationship between lightning and thunderstorms, as well as their seasonal variations across different climatic zones, remains inadequately quantified due to the fragmented nature of existing data. Addressing these knowledge gaps through data analysis and advanced statistical techniques, such as regression and correlation analysis, is essential for improving weather forecasting, enhancing public safety measures, and informing infrastructure planning and development. Therefore, this study aims to fill these critical gaps by leveraging on two data sources and employing analytical methods to identify lightning and thunderstorm hotspots, analyse their occurrence patterns across different climatic zones and seasons, and uncover the underlying relationships between lightning and thunderstorms in Nigeria.

Nigeria, as shown in **Figure 1**, is a country located in West Africa in the tropics with a diverse terrain that extends from savannahs in the north to tropical rainforests in the south. Nigeria is bordered by several countries, including Benin, Chad, Cameroon, and Niger. It also has a coastline that runs along the Gulf of Guinea. The region is made up of 36 states and the Federal Capital Territory FCT. The physical coordinates of Nigeria are Latitude 4˚N and 14˚N and Longitude 3˚E and 15˚E. Its borders are Niger Republic to the north, Cameroun Republic to the east, Benin Republic to the west, Chad Republic to the northeast and the Atlantic Ocean to the south. The region is known for its different geographical landscapes, which include rainforests, savannas, Sahel and coastal locations. Nigeria is an area with a tropical climate with two major seasons, the rainy and dry season. This region has three distinct climatic zones. In the southern part, we have the tropical monsoon climate and the tropical Savanna climate. In the northern part, there is the Sahelian hot and semi-arid climate. The temperature of Nigeria is influenced by its proximity to the equator, this is characterized by high temperatures ranging from 25˚C to 35˚C (77˚F to 95˚F), Minimal seasonal fluctuations (less than 5˚C/9˚F), High humidity levels, especially in coastal regions, regional variations, with northern regions experiencing slightly cooler temperatures than southern regions [17]. According to [18], West Africa can be divided into three major agro-climatic zones: The Guinea Coast (4˚N-8˚N), Savannah (8˚N-11˚N), and Sahel (11˚N-16˚N). This categorization is based on factors such as land use/land cover, ecosystems, and climate attributes. In this study, the 3 climatic zones are used to divide the 37 stations for easy analysis.

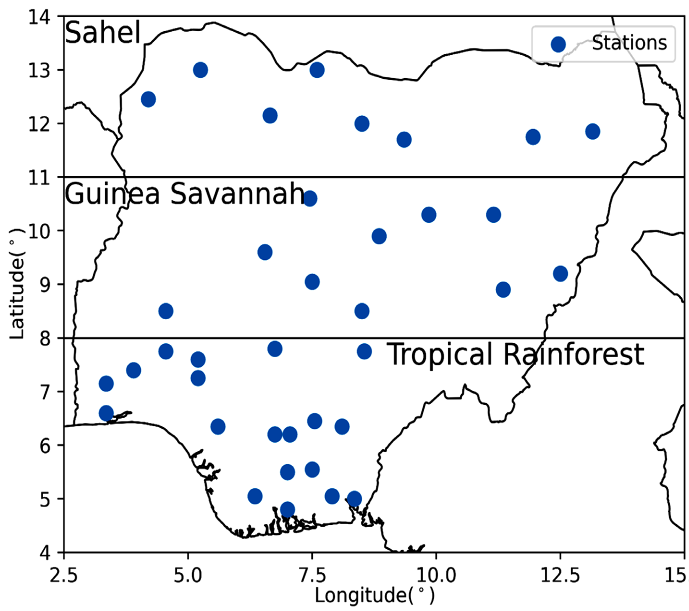

Figure 1. Map of Nigeria showing all 37 stations in their respective climatic zones.

2. Data and Methodology

2.1. Data Sources

2.1.1. CHIRPS (Climate Hazards Centre InfraRed Precipitation with Station)

A daily rainfall data from 2020 to 2023 used in this study were obtained from Climate Hazards Centre InfraRed Precipitation with Station data (CHIRPS), located at the University of California Santa Baith high temperature.

CHIRPS is a quasi-global rainfall data set spanning over 40 years. From 1981 to the near present, CHIRPS has been creating gridded rainfall time series for trend analysis and seasonal drought monitoring by combining in-situ station data with

0.05˚resolution satellite images covering 50˚S-50˚N (and all longitudes) (https://www.chc.ucsb.edu/data).

2.1.2. WWLLN (World Wide Lightning Location Network)

This study covers daily data, from 2020 to 2023 inclusive. The lightning data was obtained from the World-Wide Lightning Location Network (WWLLN). They can be contacted at Earth and Space Sciences, University of Washington. The focus of this project is on Nigeria only, extracting the time and location of the lightning strokes.

It is a worldwide network that tracks lightning strokes across the entire globe. Operated by the University of Washington in Seattle, the World-Wide Lightning Location Network (WWLLN, pronounced "woollen") is a network of very low frequency (VLF) radio lightning sensors. "Sferics", or sudden lightning discharges, are the primary source of impulsive signals that dominate most ground-based observations in the 3 - 30 kHz VLF range. There is a significant amount of electromagnetic power that is radiated, primarily at very low frequencies (VLF), ranging from a few hertz to several hundred megahertz. WWLLN regularly creates maps of lightning activity across the whole earth according to its extensive global network of lightning sensors.

Research by [19] indicates WWLLN detection efficiency for strokes. Given that the VLF signal is less attenuated over oceans than over land during signal propagation, WWLLN may identify strokes with lesser energy across oceans compared to land. Consequently, WWLLN tends to identify more lower-energy strokes over the ocean's regions and higher-energy strokes over land [19]. There is evidence that lightning over the oceans has more energy than lightning over land [20] [21]. WWLLN preferentially detects the more energetic lightning [22].

2.1.3. Thunderstorm Data

Thunderstorm data for Nigeria only from 2021 and 2022, were also obtained from the Nigerian Meteorological Agency (NIMET)-Abuja. The geographical coordinates of each station were also obtained from the same source. Thunderstorm data were used as ground truth performance assessment of the Worldwide Lightning Location Network (WWLLN).

2.2. Methodology

1) Downloading the WWLLN data for the globe from WWLLN online data records for the period of 2020 to 2023.

2) The data initially obtained in a compressed format (zip) and stored in a LOC file, was subsequently extracted.

3) Raw data is converted into comma-separated values (CSV) files using a specifically designed code. This enabled the transformation of the data from its original condensed format into a more accessible and analysable format.

4) This extraction was facilitated through the use of program codes, which applied geospatial coordinates (longitude and latitude) to pinpoint and isolate data points associated with individual stations within the Nigerian territory.

5) Aggregate daily data to yield monthly totals, which are combined to for MAM seasonal dataset for each station, to enable the examination of seasonal variability and trends.

6) Compute the coefficient of correlation.

2.2.1. Thunderstorm Analysis

For further analysis, with the aid of Geographic Information Systems (GIS) technology, was used as tools to show imageries of the yearly spatial variations of the thunderstorm and lightning data using heat maps. The data analysis was carried out and plotted with the use of MS Excel.

Thirty-seven (37) stations across Nigeria were considered for this study. The locations of study were specifically selected to have adequate representation of the various climatic zones and for comparisons among stations down south and up in the north. A comprehensive list of the 37 stations for this study is shown below in Table 1 according to their climatic zones. The longitude and latitude are approximate values.

Table 1. Stations across Nigeria for the Rainforest, Savannah, and Sahel zones.

Rainforest Zone			Savannah Zone			Sahel		
Stations	Longitude	Latitude	Abuja	10.00˚E	9.00˚N	Stations	Longitude	Latitude
Abakaliki	8.10˚E	6.33˚N	Bauchi	9.83˚E	10.32˚N	Damaturu	11.95˚E	11.73˚N
Abeokuta	3.33˚E	7.15˚N	Birnin-Kebbi	4.5˚E	11.5˚N	Dutse	9.5˚E	12.0˚N
Ado-Ekiti	5.22˚E	7.62˚N	Gombe	11.17˚E	10.28˚N	Gusau	6.25˚E	12.16˚N
Akure	5.20˚E	7.25˚N	Ilorin	4.55˚E	8.50˚N	Kano	8.5˚E	12.0˚N
Asaba	6.18˚E	6.75˚N	Jalingo	11.37˚E	8.90˚N	Maiduguri	13.15˚E	11.83˚N
Awka	7.73˚E	6.20˚N	Jos	8.90˚E	9.92˚N	Sokoto	5.24˚E	13.05˚N
Benin city	5.60˚E	6.32˚N	Kaduna	7.43˚E	10.50˚N	Katsina	7.62˚E	12.98˚N
Calabar	8.32˚E	4.95˚N	Lafia	8.52˚E	8.48˚N			
Enugu	7.50˚E	6.50˚N	Lokoja	6.82˚E	7.75˚N			
Ibadan	3.90˚E	7.38˚N	Markurdi	8.53˚E	7.73˚N			
Ikeja	3.33˚E	6.58˚N	Minna	6.55˚E	9.62˚N			
Owerri	7.02˚E	5.48˚N	Yola	11.93˚E	9.91˚N			
Oshogbo	4.67˚E	7.77˚N						
Port-harcourt	7.00˚E	4.75˚N						
Umuahia	7.73˚E	6.20˚N						
Uyo	7.93˚E	5.05˚N						
Yenagoa	6.26˚E	4.92˚N						

2.2.2. Statistical Methods: Coefficient of Correlation Variation

The CORREL function in Excel was used to calculate the correlation coefficient between the two sets of data from WWLLN and from NIMET due to its various applications in data analysis, such as:

- Identifying relationships between variables
- Analysing trends and patterns
- Predicting outcomes based on correlations
- Evaluating the strength of relationships between variables

The correlation coefficient, denoted as r, ranges from −1 to 1, indicating the degree of correlation, as shown in Table 2 below.

Table 2. The degree of the correlation coefficient between two variables (for this study TS and LTG).

Perfect positive linear relationship	Perfect negative linear relationship	No linear relationship
+1	−1	0

The CORREL function takes the two ranges of data as inputs and returns the correlation coefficient. The syntax is: CORREL (array1, array2), Where array1 and array2 are the two ranges of data.

3. Results and Discussion

3.1. Annual and Seasonal Variation of Lightning and Thunderstorm

The temporal and seasonal variability of lightning strokes as reflected by the yearly total is shown below. Analysed plots showing this across the Rainforest, Guinea Savana and Sahel are depicted in Figure 2(a). The different colours indicate the four years under study, thereby showing the years of high-frequency of lightning strokes and periods of low frequency. Figures 2(a)-(c). represents the typical variation of LTG frequency across 37 stations in Nigeria, according to their climatic zones. The MAM season, which corresponds to the early part of the rainy season, is significantly characterized by increase in humidity and temperature as well as the onset of rainfall. An observation of the plots from 2020 to 2023 shows year-to-year variability in the values of LTG strokes in the Rainforest, Guinea Savanah and Sahel zone, with the Rainforest zone experiencing more LTG strokes than Guinea Savannah and Sahel zones accordingly. The highest LTG frequency of occurrence was in Calabar station (Rainforest zone) in the year 2023, with a maximum of 401 strokes, minimum LTG was in the Damaturu station (Sahel zone), no stroke was recorded in this station. A careful observation shows an increasing rate in the number of LTG strokes in Calabar station from 2021 to 2023, while no stroke is observed in Damaturu station throughout this period. Yenegoa had the second-highest lightning stroke occurrence. [23] and [24] established that the southern part of the country (where Calabar is situated) enjoys a double maxima rainfall while the northern part of the country (where we have Damaturu) enjoys a single maximum. This suggests that areas with prolonged rainfall seasons are more prone to thunderstorm activity. Longer rainfall seasons increase atmospheric instability, leading to more frequent thunderstorms. Double maxima rainfall patterns which is typical of tropical regions where Calabar is situated, enhance atmospheric instability and moisture content, favoring thunderstorm development. Single maximum rainfall, which is experienced in Damaturu implies shorter rainfall season, reduced atmospheric instability and therefore decrease in chances of lightning and thunderstorms

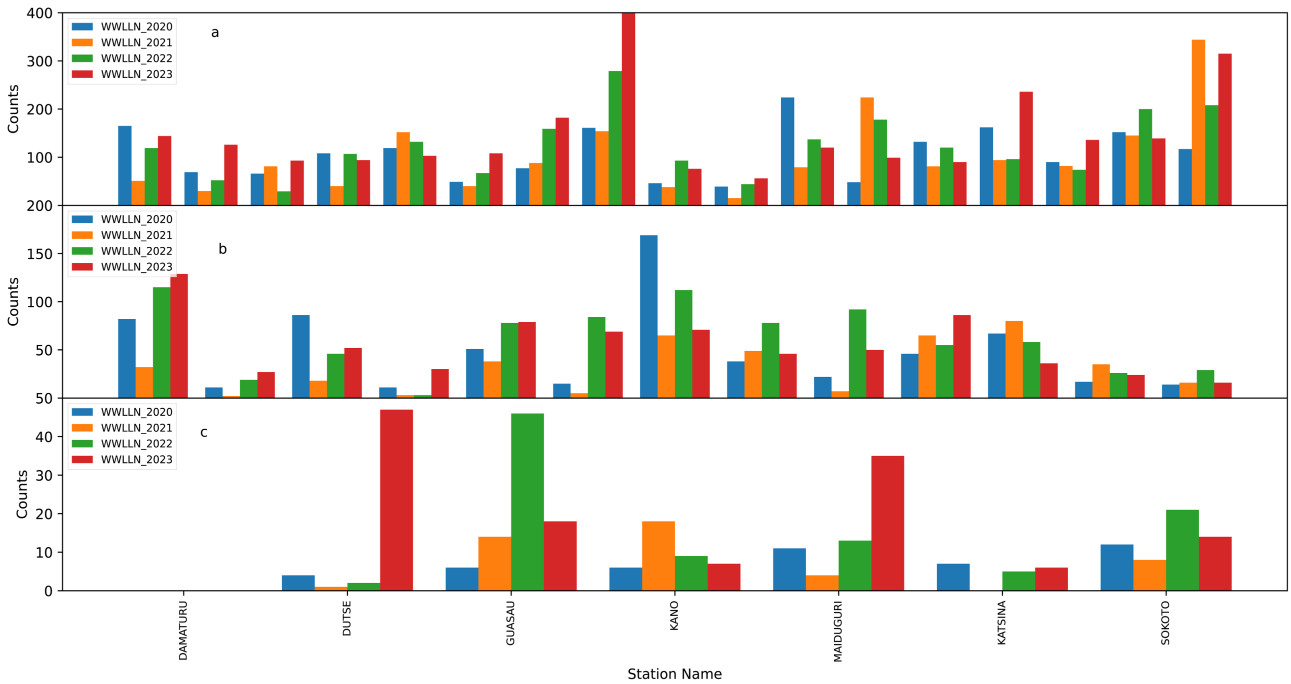

Figure 2. Variability of lightning (LTG) frequency across; (a) The Rainforest, (b) The Savannah, and (c) The Sahel zones based on the WWLLN data set during 2020-2023 for the MAM season.

Figures 3(a)-(c) illustrates the thunderstorm counts for the years 2021 and 2022 as observed over 37 stations in Nigeria. It can be observed that thunderstorm counts from NIMET data has its highest frequency in Yenagoa station and its lowest counts across several stations, Damaturu inclusive. By comparing the thunderstorm (NIMET data) and the lightning (WWLLN data) frequencies, the highest frequency does not correspond with the same station (Calabar), implying that only fewer lightning strokes were produced by the thunderstorms in Yenegoa when compared with Calabar station. The pattern is the same with the rainforest having the most frequent occurrence of lightning and thunderstorms, and the Sahel zone having the least frequent occurrence of lightning and thunderstorms. [25] observe that WWLLN has been capable of detecting almost every thunderstorm since 2005, although this work did not perform thunderstorm extraction from lightning (WWLLN) data.

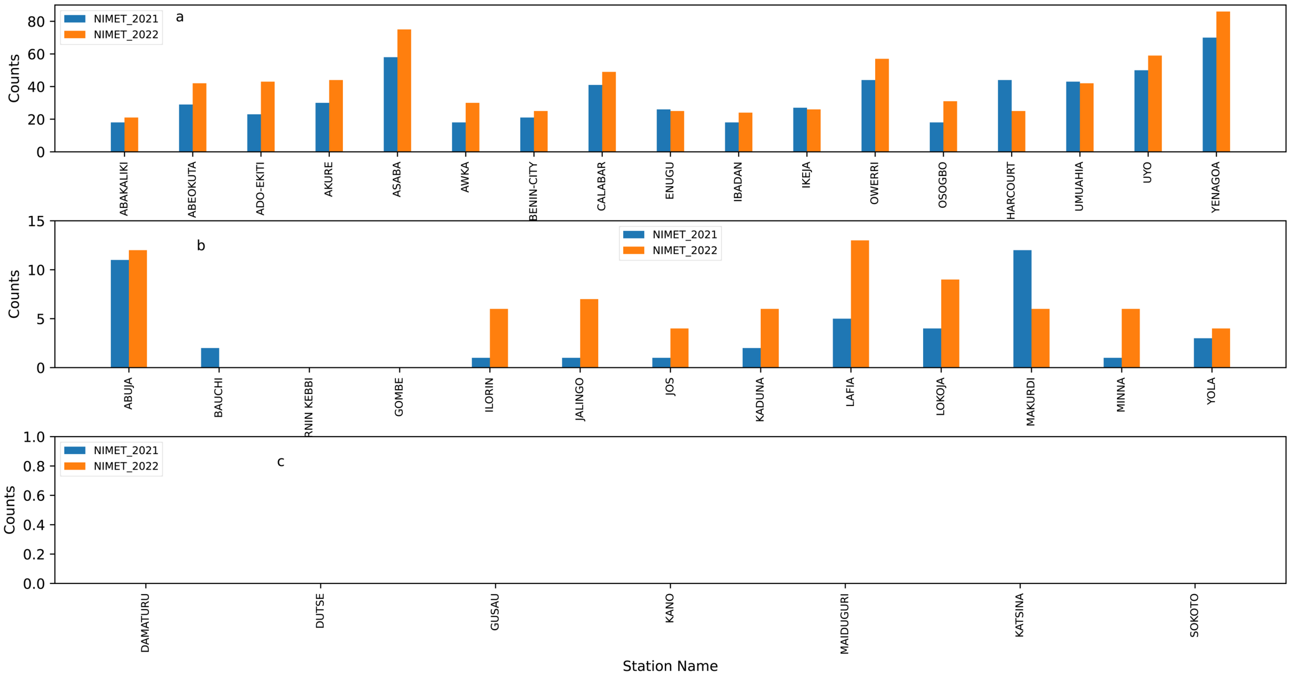

Figure 3. Variability of thunderstorms (TS) counts across; (a) Rainforest, (b) Savannah, and (c) The Sahel zones based on the NIMET data set during 2021-2022 for MAM season.

3.2. Spatial and Seasonal Variation of Lightning and Thunderstorm Occurrence

Figures 4(a)-(f) shows the TS and LTG distribution across stations in Nigeria from latitude 4˚ N to latitude 14˚N in the MAM season. the areas with the highest frequencies of thunderstorms (TS) are located between latitudes 4˚and 8˚N, which corresponds to the coastal plains in southern Nigeria. Specifically, Calabar, Asaba, and Yenagoa stations recorded the highest number of thunderstorm events. Calabar station which is one of the stations with peak in TS activities can be related to the study by [26], the study showed more lightning flashes were predominant in the Nigeria-Cameroon rainforest zone than other zones. Calabar shares boundary with Cameroon, which is a mountainous area with consistently high lightning activities. Convective systems are more frequent in the location because of the topography [26]. Not all of these convective systems will develop into thunderstorms, or some may not be recognized as thunderstorms by observers. In contrast, areas with low frequencies of thunderstorms are situated between latitudes 12˚and 14˚N, covering the northern savanna and Sahel regions of Nigeria. Damaturu station did not record any thunderstorm events throughout the study period. The data from NIMET and WWLLN follows this same pattern.

The correlation value r, in the **Table 3** was gotten from the square root of R^2 in the scatter plot (not shown) and regression analysis of WWLLN and NIMET. The general implication of the result in **Table 3** is that rainforest zone shows consistent positive correlations, while Savana and Sahel zones show weaker or inconsistent correlations.

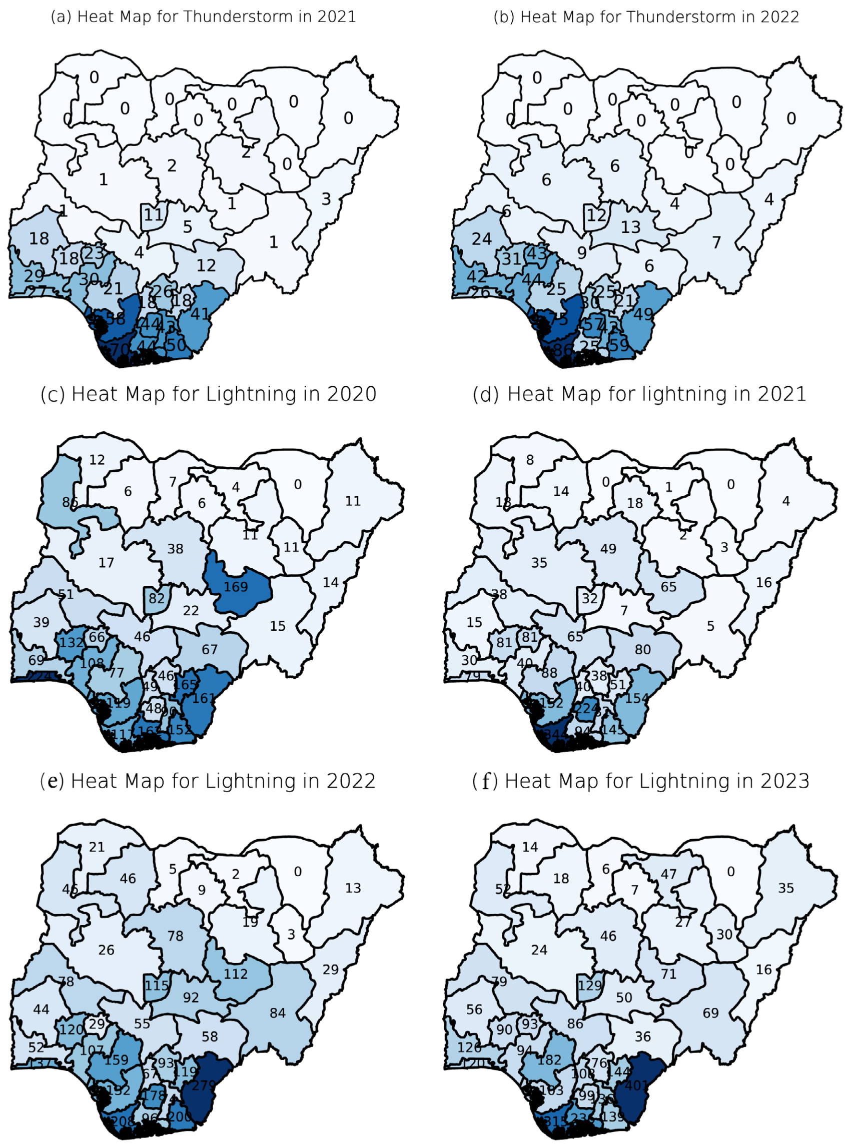

Figure 4. (a) (b) Heat map of spatial variation of Thunderstorm frequency over Nigeria from NIMET data for the MAM season for (a) 2021 and (b) 2022; (c)-(f) Heat map of Spatial Variation of Lightning frequency over Nigeria from WWLLN Data for the MAM season; (c) 2020, (d) 2021, (e) 2022, (f) 2023.

Table 3. Correlation, r of TS and LTG across the three climatic zones at different season.

Season	Zone	Year	Correlation, r
MAM	Rainforest	2021	0.826
MAM	Rainforest	2022	0.474
MAM	Savana	2021	0.427
MAM	Savana	2022	0.669
MAM	Sahel	2021	0
MAM	Sahel	2022	0

3.3. Spatial Distribution of Rainfall During the MAM Season

Rainfall distribution during the MAM season in **Figures 5(a)-(d)** show a clear gradient from south to north. The southern region experiences high and relatively consistent rainfall due to their proximity to the coast and the influence of the ITCZ. The central region (Lat. 9 - 12) has moderate rainfall with higher variability, marking a transition zone. The northern region receives low and highly variable rainfall, with a later onset of the rainy season, which reflects the semi-arid climate of the Sahel. Although rainfall is consistent in the southern region, it can be observed that there's annual variation in some stations. From 2021 to 2023 there's decrease in rainfall in Calabar station while there's increase in Jos station from 2020 to 2022.

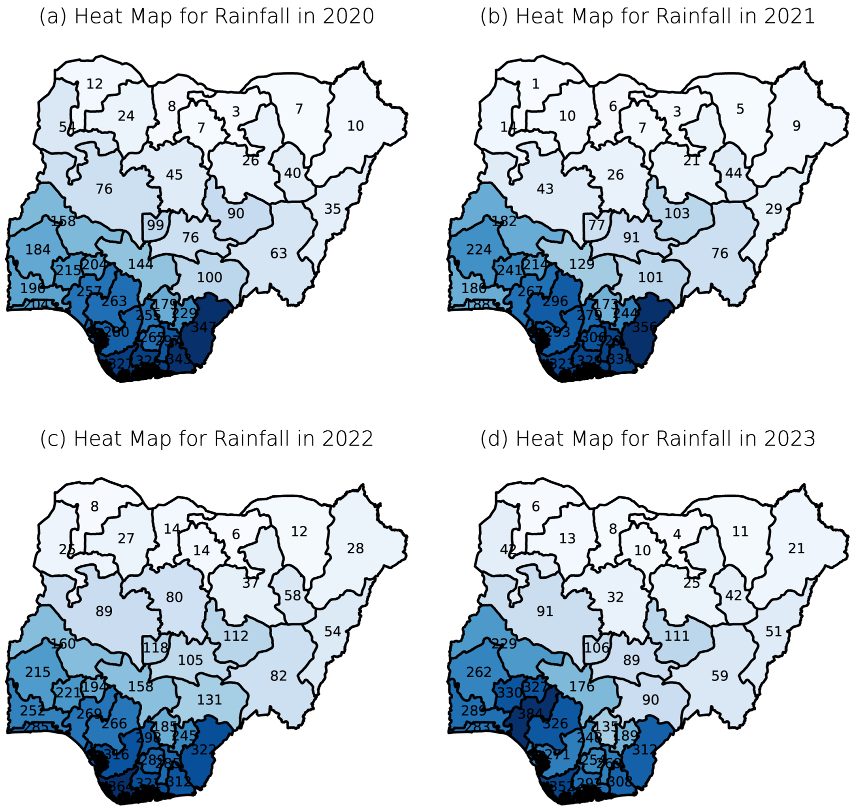

Figure 5. Rainfall Distribution Heat Map for MAM: (a) 2020; (b) 2021; (c) 2022; (d) 2023.

Comparing this result to the result on thunderstorms in previous section it can be seen that just as Calabar and Yenagoa regions experienced more thunderstorms these stations also experienced the highest amount of rainfall during the MAM season. In 2022 Yenagoa had the highest number of TS Counts which is 86 and the highest amount of rainfall (364.5 mm), although MAM is the onset of the rainy season these peak numbers recorded in Yenagoa station account for one of the reasons why there was severe flood in Yenagoa that year.

In the MAM period, as shown in **Table 4**, the correlations in the rainforest, savanna, and Sahel zones show moderate positive correlations, indicating that during this season, rainfall and lightning activities are moderately related.

Table 4. Correlation, r of rainfall and LTG across the three climatic zones at different season, for the year 2022.

Season	Zone	Correlation, r
MAM	Rainforest	0.63
MAM	Savana	0.49
MAM	Sahel	0.57

4. Conclusion

This study investigated the spatial and temporal variability of thunderstorms over Nigeria, utilizing a two-year record of thunderstorm data from NIMET, four-year lightning data from WWLLN and rainfall data from CHIRPS. ArcGIS proved instrumental in analyzing essential meteorological data. The analysis revealed significant patterns in thunderstorms and their variation, and establishing the potential of WWLLN data for monitoring thunderstorm dynamics and changes. The research has provided invaluable insights into the complex dynamics of thunderstorm activities in Nigeria under different climate scenarios. The study's results demonstrate the critical importance of proactive climate resilience strategies and the necessity for continued research and monitoring of thunderstorm dynamics. Temporal analysis showed yearly variations across climatological zones and stations, while spatial analysis identified areas of frequent thunderstorms. Correlation analysis between WWLLN and meteorological data revealed a positive relationship between thunderstorms and lightning activity. Seasonal variations in thunderstorm patterns were observed, influenced by prevailing meteorological conditions and topographical features.

The observed fluctuations in thunderstorm patterns across climatic zones and time frames have significant implications for agriculture, water resources, and transportation. The positive correlation between thunderstorms and lightning activity emphasizes the need for integrated early warning systems. Also, the correlations between rainfall and lightning over a one-year period, year 2022 showed that their relationship varies across zones and seasons. The wet seasons tend to show moderate to weak correlations, while in the dry seasons, correlations in some zones become stronger. Further research is warranted to confirm these findings and establish long-term trends. Expanding the dataset to include multiple years would provide a more comprehensive understanding of the relationships between rainfall and LTG and account for potential annual variability. This would enable researchers to identify more robust patterns.

To address the growing threat of thunderstorm occurrences, policymakers, scientists, and communities must collaborate to develop and implement effective climate adaptation and mitigation measures. Future research should focus on investigating thunderstorm electrification processes, developing predictive models for lightning strikes, and analyzing rainfall variability impacts on agriculture. Ultimately, this study contributes to the understanding of lightning and thunderstorm dynamics in Nigeria, informing evidence-based decision-making and climate resilience strategies. Conclusively, in light of this research on thunderstorm occurrence in Nigeria, further in-depth investigation is required to further understand the role of climatic factors in the development of thunderstorms and lightning as well as early warning systems over Nigeria.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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