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Harmonic-Trend Modelling of Thunderstorm Rainfall Over Makurdi and Jos, in the Middle Belt Region of Nigeria

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Abstract: *This study developed a harmonic-trend model to characterise and project thunderstorm rainfall variability over Makurdi and Jos in the Middle Belt region of Nigeria, using daily and monthly thunderstorm rainfall data obtained from the Nigerian Meteorological Agency (NiMet) for the period 1995–2024. Descriptive statistics, linear trend analysis, and Fourier harmonic modelling were applied to isolate the long-term (secular) trend and the cyclical (seasonal/periodic) components of thunderstorm rainfall, which were then combined into a single hybrid harmonic-trend model. Results showed that thunderstorm rainfall averaged 634 mm annually in Jos and 546 mm in Makurdi, with Jos exhibiting a statistically significant increasing trend ($r^2 = 0.2496$) while the increase in Makurdi was not significant ($r^2 = 0.0023$). The harmonic component captured strong seasonal periodicity in both locations, reflecting the concentration of thunderstorm activity within the rainy season (March–October). When combined, the harmonic-trend model explained over 97% of the variability in thunderstorm rainfall at both stations, with Nash–Sutcliffe Efficiency (NSE) values ranging from 0.91 to 0.99, indicating excellent model performance and validating its suitability for both historical characterisation and future projection. Extrapolation of the validated model to 2050 projected a continued increase in thunderstorm rainfall intensity at both stations, with a more pronounced upward trajectory in Jos than in Makurdi. These findings highlight the growing dominance and intensification of thunderstorm-driven rainfall in the Middle Belt under changing climatic conditions. The study concludes that harmonic-trend modelling provides a robust and reliable tool for forecasting convective rainfall behaviour in data-sparse tropical environments, and recommends that NiMet incorporate such models into operational forecasting systems, while policymakers integrate the projected rainfall intensification into flood-risk management and climate-adaptive planning for the region.*

Keywords: Harmonic-trend model, Thunderstorm, Rainfall, Makurdi and Jos.

INTRODUCTION

The increasing variability of rainfall patterns across the world has heightened the need for reliable statistical models capable of describing, analysing, and forecasting rainfall behaviour. Rainfall exhibits both periodic and long-term fluctuations resulting from atmospheric circulation processes, climate variability, and environmental changes. Understanding these fluctuations is essential for agricultural planning, water resource management, flood control, and climate adaptation. Consequently, time-series modelling techniques have become important tools for examining rainfall dynamics and predicting future rainfall conditions (Li, Feng, Qian, & Leung, 2021; Klein, Nkrumah, Taylor, & Adefisan, 2021).

Among the various approaches used in climatological studies, harmonic analysis has proven effective in identifying cyclical and seasonal variations in rainfall data. The technique decomposes rainfall series into periodic components and quantifies the contribution of seasonal cycles to observed rainfall patterns. When combined with trend analysis, harmonic models provide a powerful framework for capturing both recurring seasonal behaviour and long-term changes in rainfall regimes. Harmonic–trend models have therefore been widely applied in meteorology, hydrology, rainfall forecasting, and climate variability studies (Schumacher & Rasmussen, 2023; Lima, Aquino, Moraes, & Palhoça, 2023; Moraes, Aquino, Mote, Durkee, & Mattingly, 2020).

In tropical regions, thunderstorm rainfall constitutes a major component of annual precipitation and exhibits strong seasonal periodicity. The occurrence and intensity of thunderstorm rainfall are influenced by atmospheric instability, moisture availability, and large-scale circulation systems, resulting in distinct temporal cycles that can be effectively represented using harmonic functions (Ochei, Emetere, & Oladosu, 2015). Because thunderstorm rainfall is often characterized by high variability and concentration within specific months of the year, harmonic–trend modelling provides a useful approach for identifying seasonal peaks, measuring long-term changes, and projecting future rainfall patterns.

In Nigeria, rainfall variability remains a major concern due to its implications for agriculture, water supply, flooding, and environmental management. Previous studies have examined thunderstorm rainfall characteristics and seasonal rainfall variability across different ecological zones of the country (Omotosho, 1985; Ayoola, Adekeye, & Adebayo, 2016; Orisakwe, 2015). However, most of these studies focused on rainfall occurrence and distribution with limited emphasis on developing predictive harmonic–trend models capable of describing and forecasting thunderstorm rainfall behaviour over long periods.

The Middle Belt Region of Nigeria, particularly Makurdi and Jos, experiences substantial thunderstorm rainfall during the rainy season and exhibits considerable inter-annual variability. The contrasting physiographic characteristics of the lowland Makurdi environment and the elevated Jos Plateau provide unique conditions for examining temporal variations in thunderstorm rainfall. Despite the importance of rainfall prediction for agricultural production, flood management, and water resource planning in the region, limited studies have applied harmonic–trend modelling techniques to analyse and forecast thunderstorm rainfall behaviour.

Therefore, this study applies harmonic–trend modelling to investigate the temporal characteristics of thunderstorm rainfall over Makurdi and Jos from 1995 to 2024. The study seeks to identify seasonal rainfall cycles, determine long-term rainfall trends, and develop predictive models for future rainfall conditions, thereby providing valuable information for climate planning, weather forecasting, and sustainable resource management in the Middle Belt Region of Nigeria.

MATERIALS AND METHODS

Study Area

The Middle Belt Region is a unique geographical and climatological region of Central Nigeria (Mage, Olanrewaju, & Onwuadiochi, 2023). It is a transitional region between southern and northern Nigeria. In this study, the Middle Belt Region is defined to cover the six states within the North central geo–political zone and Adamawa and Taraba states. This definition uses the northern state boundaries of Niger, FCT, Nasarawa, Plateau, Taraba and Adamawa as the northern limit of the region. According to Agboola (1963) and Tyubee (2005). The Middle Belt region is situated between latitudes 6°21'0"N and 11°30'0"N and longitudes 5°0'0"E and 12°30'0"E. This covers a total land area of about 333 815 Km^2. The area occupies about 36.14 % of the total land area of Nigeria (Fig. 1). The region is found within the tropical wet and dry climate (Aw) according to Koppen Geiger climate classification. It is the zone of gradual change in climate character from the wetter equatorial margin towards the drier polar ward regions. Two seasons are experienced in the region, the dry season, which starts from late November to March and wet season, which prevails from April to October. The wet season is characterized by the tropical maritime air mass which brings rainfall and wet conditions to the region (Mage, Olanrewaju, Ukange, & Ali, 2021).

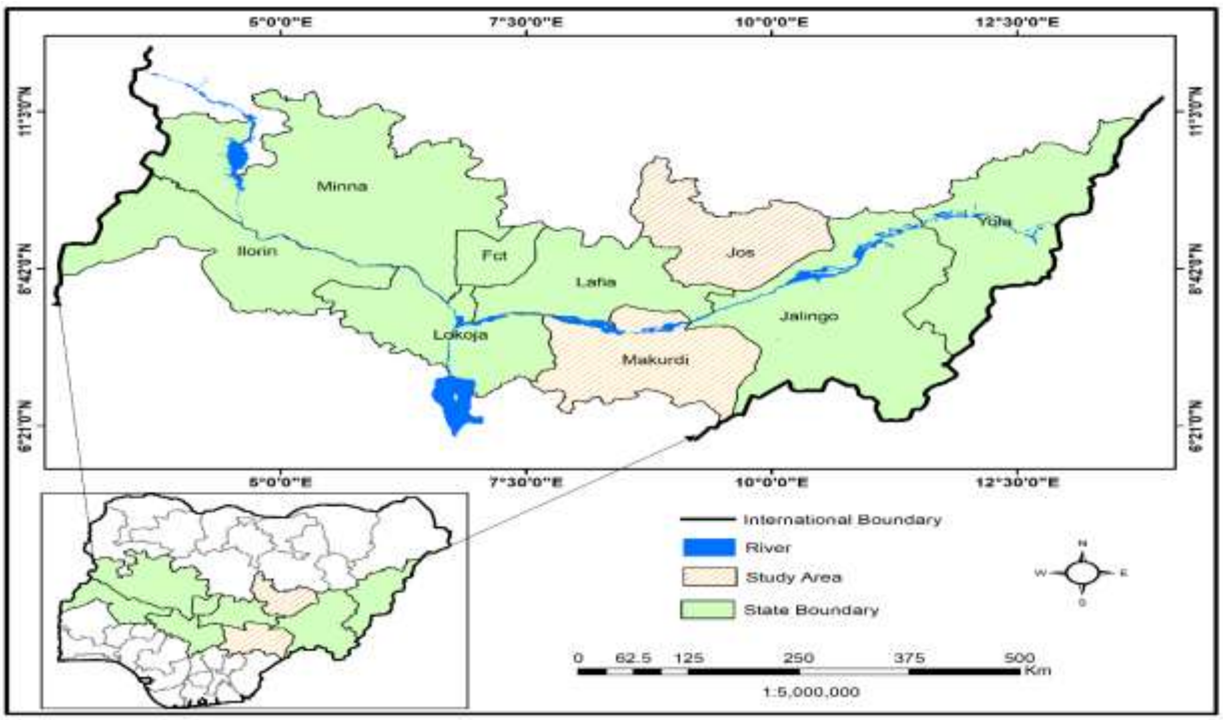

Figure1: The location of the Middle Belt Region of Nigeria show Makurdi and Jos
Source: Mecon Services Limited Jos, 2026.

METHODS

The study adopted an observational and quantitative modelling design. This design was considered appropriate because it relies on archival, long-term instrumental records of thunderstorm rainfall rather than respondent-based data, thereby enabling the researcher to characterise both the deterministic (trend) and cyclical (seasonal/periodic) components of thunderstorm rainfall variability in Makurdi and Jos. The design further provides an appropriate framework for applying time-series and harmonic analysis techniques to examine temporal patterns and variations in thunderstorm rainfall over the study period.

The data required for the study comprised daily and monthly thunderstorm rainfall amounts for Makurdi and Jos covering the period 1995–2024. Monthly mean thunderstorm rainfall values were required for harmonic and cyclical modelling, while annual thunderstorm rainfall totals were used for trend analysis. These datasets provided the temporal basis for examining both short-term seasonal variations and long-term changes in thunderstorm rainfall characteristics at the two study locations. Thunderstorm rainfall data were obtained from the archives of the Nigerian Meteorological Agency (NiMet) for the synoptic meteorological stations at Makurdi, located in the lowland at approximately 92 m above sea level, and Jos, located in the highland at approximately 1,286 m above sea level, for the 30-year period from 1995 to 2024. The two stations were selected because of their contrasting elevation and topographic settings within the Middle Belt Region, thereby providing a basis for comparing thunderstorm rainfall behaviour across different physiographic environments.

Thunderstorm events and their associated rainfall were identified and measured using thunder detectors and standard rain gauges installed at the respective stations, following the observational guidelines of the World Meteorological Organization (WMO, 1953) and NiMet. The thunder detectors were used to identify thunderstorm activity within the vicinity of the stations, while standard rain gauges measured the amount of rainfall associated with the events. Where rainfall commenced within 30 minutes before or after the onset of thunderstorm activity, the rainfall was attributed to the corresponding thunderstorm system, consistent with standard synoptic classification procedures. The resulting observations and measurements formed the basis for the subsequent time-series and harmonic analyses of thunderstorm rainfall variability at Makurdi and Jos.

Thunderstorm rainfall data for Makurdi and Jos were analysed using descriptive statistics, linear trend analysis, and Fourier harmonic modelling, in order to isolate the long-term trend, periodic (cyclical) behaviour, and combined trend-harmonic structure of thunderstorm rainfall, and to project future rainfall intensity. Analyses were performed using Microsoft Excel and SPSS version 25. The mean and variability of annual thunderstorm rainfall were computed using the arithmetic mean, standard deviation, and coefficient of variation:

Mean: $\bar{X} = (\Sigma X) / n$ (1)

Standard Deviation: $SD = \sqrt{[\Sigma(X - \bar{X})^2 / n]}$ (2)

Coefficient of Variation: $CV = (SD / \bar{X}) \times 100\%$ (3)

Where X = observed annual thunderstorm rainfall, $\bar{X}$ = mean, n = number of years of observation.

The long-term (secular) trend in thunderstorm rainfall was modelled using simple linear regression:

$Y(t) = a + bt$ (4)

Where Y(t) = thunderstorm rainfall at year t, a = intercept, b = trend coefficient (rate of change per year), and t = time (year index, 1995 = 1 … 2024 = 30).

The coefficient of determination (R^2) was computed to assess the proportion of variability explained by the linear trend:

$R^2 = \Sigma(\hat{Y} - \bar{Y})^2 / \Sigma(Y - \bar{Y})^2$ (5)

The significance of the trend was tested using the Student's t-test:

$t = r\sqrt{(n - 2)} / \sqrt{(1 - r^2)}$ (6)

Where r is the trend correlation coefficient. The calculated t-value was compared with the critical t-value at the 0.05 significance level to determine statistical significance.

To capture the cyclical/seasonal periodicity in thunderstorm rainfall, a Fourier harmonic analysis was applied to the monthly thunderstorm rainfall series. The general form of the harmonic model is expressed as:

$$Y(t) = a_0 + \Sigma_{k=1}^{n} [a_k \cos(2\pi kt/T) + b_k \sin(2\pi kt/T)] \quad (7)$$

Where:

$Y(t)$ = predicted thunderstorm rainfall at time t

a_0 = mean rainfall (long-term average)

a_k, b_k = Fourier coefficients of the kth harmonic

k = harmonic number (k = 1, 2, 3 …)

T = period of the cycle (e.g., 12 months for annual cycle)

n = number of harmonics retained in the model

The Fourier coefficients were estimated as:

$$a_k = (2/N)\ \Sigma\ Y(t) \cos(2\pi kt/T) \quad (8)$$

$$b_k = (2/N)\ \Sigma\ Y(t) \sin(2\pi kt/T) \quad (9)$$

Where N is the total number of observations.

The trend and harmonic components were integrated into a single hybrid model to represent both the systematic long-term change and periodic fluctuation in thunderstorm rainfall:

$$Y(t) = (a + bt) + \Sigma_{k=1}^{n} [a_k \cos(2\pi kt/T) + b_k \sin(2\pi kt/T)] + \varepsilon(t) \quad (10)$$

Where ε(t) is the residual (unexplained) error term. The number of harmonics (n) retained in the final model was determined by progressively adding harmonics until additional terms no longer significantly improved model fit.

The goodness-of-fit of the harmonic-trend model was assessed using the coefficient of determination (R^2) and the Nash–Sutcliffe Efficiency (NSE):

$$NSE = 1 - [\Sigma(Y_{obs} - Y_{pred})^2 / \Sigma(Y_{obs} - \bar{Y}_{obs})^2] \quad (11)$$

Where Yobs = observed thunderstorm rainfall, Ypred = model-predicted rainfall, and Ȳobs = mean of observed values. An NSE value close to 1 indicates a strong predictive model, with NSE ≥ 0.75 generally considered a very good fit. The validated harmonic-trend model (Equation 10) was extrapolated beyond the observation period to project thunderstorm rainfall amounts up to the year 2050 for both Makurdi and Jos. The projected values were used to infer the likely future direction (increase or decrease) and intensity of thunderstorm rainfall under continuing climate variability in the Middle Belt region.

RESULTS

Harmonic-Trend Model Results of Thunderstorms Rainfall over Makurdi and Jos

Actual vs Harmonic Fit of Monthly Thunderstorm Rainfall in Makurdi and Jos

The result of the harmonic trend analysis of spatiotemporal patterns of thunderstorm rainfall over Makurdi and Jos is presented in Figures 1, 2, 3, 4 and Table 1. The result indicates that the application of harmonic analysis (incorporating the first and second harmonics) provides a robust mathematical approximation of the observed core seasonal characteristics of thunderstorm-induced rainfall across both locations over the 30-year period from 1995 to 2024.

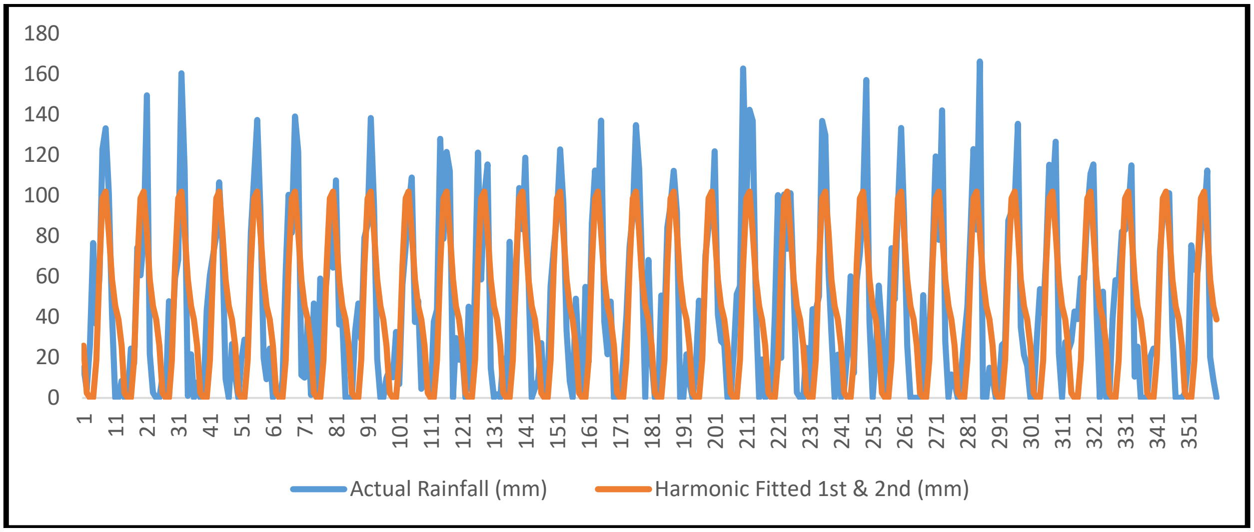

Figure 2: Actual vs Harmonic Fit of Monthly Thunderstorm Rainfall in Makurdi (1995-2024)
Source: Researchers Fieldwork, 2024

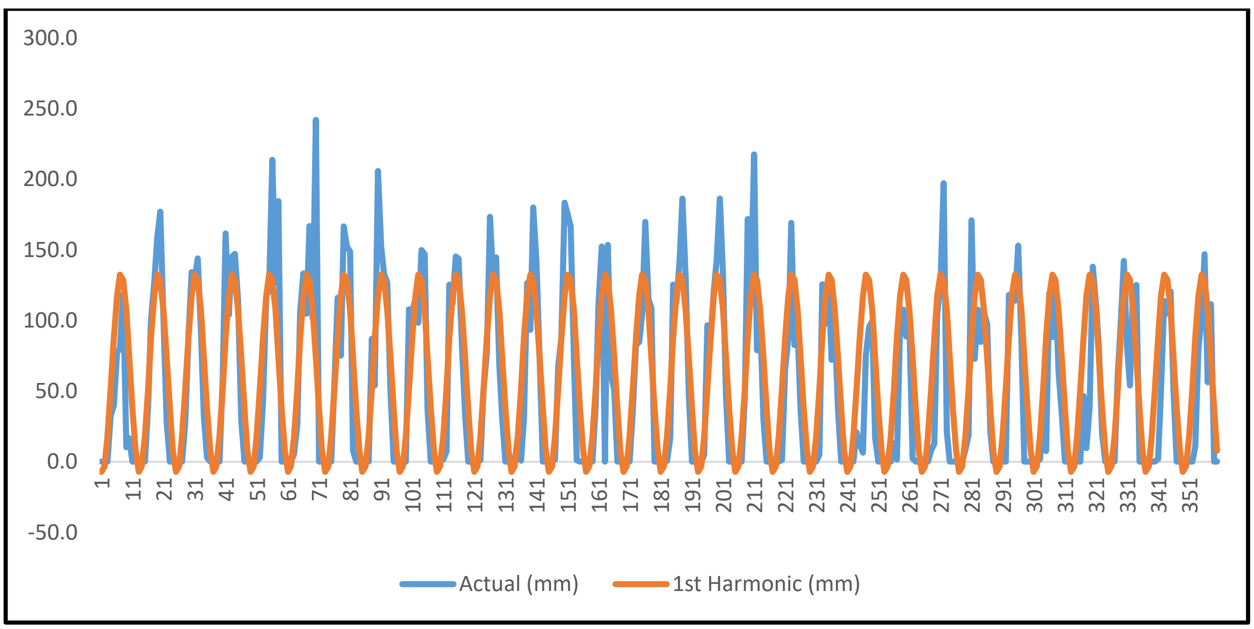

Figure 3: Actual vs Harmonic Fit of Monthly Thunderstorm Rainfall in Jos (1995-2024)
Source: Researchers Fieldwork, 2024

Figure 1 displays the unbroken time-series sequence of monthly actual thunderstorm rainfall against the modeled first and second harmonic fitted cycles across the entire 360-month investigation matrix (1995–2024). The actual thunderstorms rainfall shows highly cyclical synoptic behavior as evident in the repetitive, regular annual oscillations, though it exhibits significant interannual variability in peak magnitudes, with some extreme convective seasons pushing actual mothly totals above 160mm around months 34, 210, and 287. The Harmonic Fit smooths these stochastic, high-frequency fluctuations into a consistent, idealized periodic wave pattern. It systematically bounds the peak outputs at a regularized maximum near 100 mm across the successive multi-decadal cycles, showing that while the model captures the stable thermodynamic forcing mechanisms of the area, it naturally dampens localized, extreme annual convective anomalies.

The Figure 2 compares the actual monthly thunderstorms rainfall in Jos with the 1st harmonic model estimates over the study period (1995-2024). The result shows that actual rainfall series exhibits a strong seasonal pattern characterized by alternating periods of low and high rainfall. Rainfall values remain close to zero during the dry months and rise sharply during the wet season, reflecting the typical tropical rainfall regime of the study area. The 1st harmonic model also reproduces this cyclical behaviour, generating smooth sinusoidal waves that correspond to the annual rainfall cycle.

The 1st harmonic curve successfully captures the overall seasonality of rainfall. The peaks and troughs of the harmonic fit occur approximately at the same periods as those of the observed rainfall, indicating that the model adequately represents the timing of the rainy and dry seasons. This confirms that a significant proportion of rainfall variability in the study area is controlled by regular seasonal atmospheric processes. However, noticeable differences exist between the observed and fitted values. The actual rainfall data show substantial fluctuations, with several extreme peaks exceeding 150–240 mm, whereas the harmonic model produces relatively uniform peaks of about 130 mm. The regular sinusoidal shape of the harmonic fit indicates that the first harmonic captures the dominant annual rainfall cycle. This suggests that rainfall distribution in the study area is strongly seasonal, with a predictable wet and dry season pattern. The consistency of the harmonic peaks throughout the record demonstrates that the annual cycle remains relatively stable over time.

The grand monthly regimes are shown in Figures 3 and 4 and Table 1. Figures 2 and 3 collapse the 30-year time series into centralized annual grand monthly means to assess the structural alignment of the intra-annual thunderstorm regimes for Makurdi and Jos respectively.

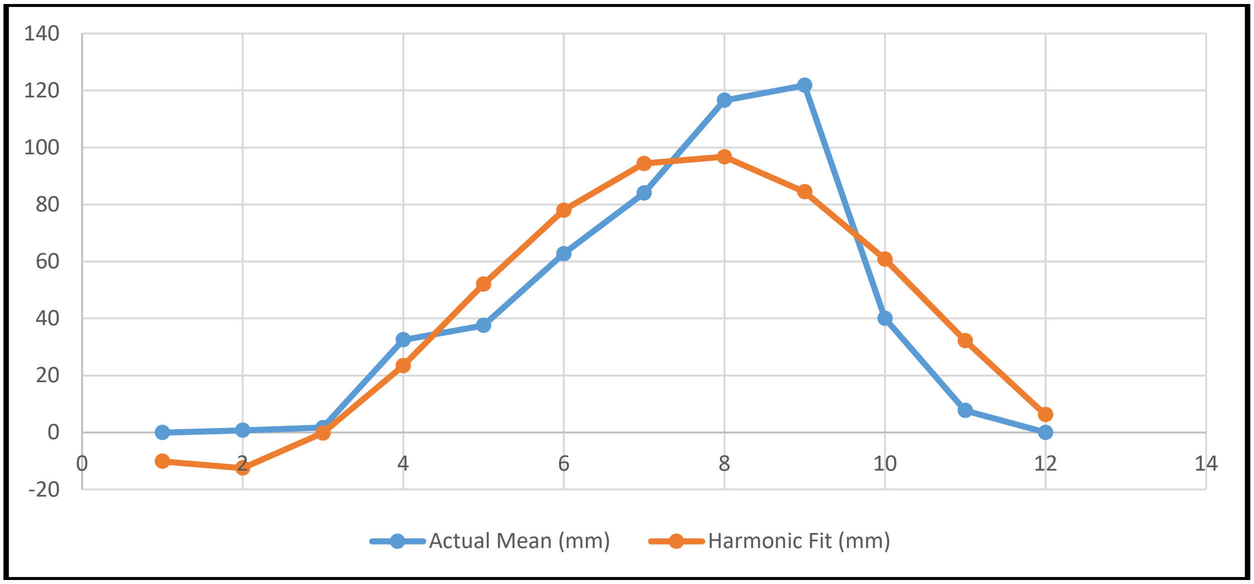

Figure 4: Grand Actual and Harmonic Fit of Thunderstorms Rainfall over Makurdi (1995-2024)

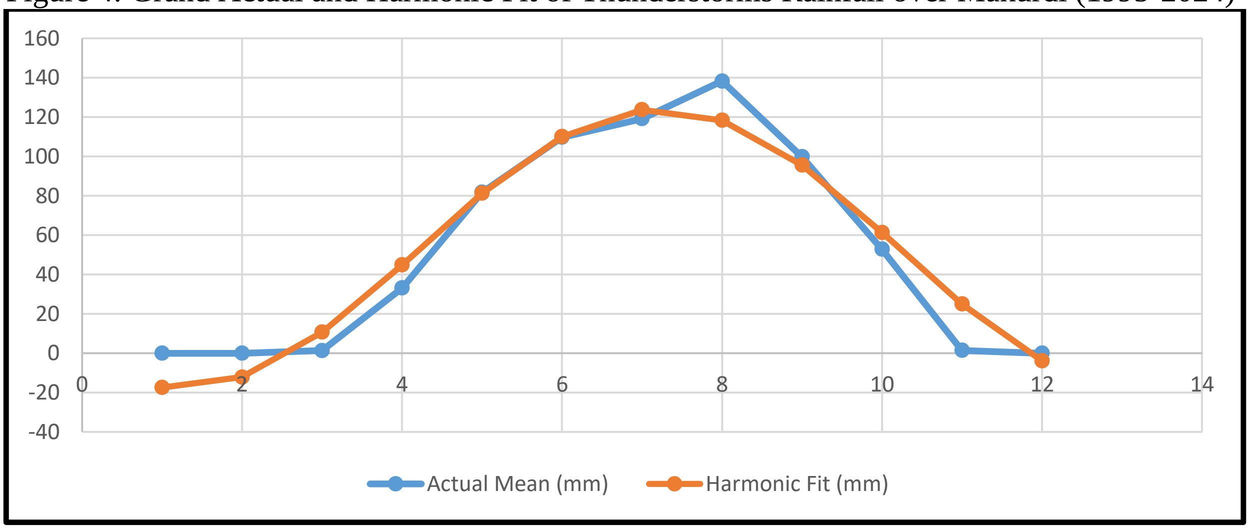

Figure 5: Actual and Harmonic Fit of Thunderstorms Rainfall over Jos (1995-2024)

The result indicates that Makurdi exhibits a distinct single-peak rainy season profile (unimodal structure) for thunderstorm rainfall. The actual thunderstorm rainfall curve begins its upward trajectory in April (32.50 mm), climbs steadily through the core monsoon months, and reaches its maximum peak in September (121.83 mm) before plunging sharply into November (7.74 mm). Harmonic reconstruction indicates that the harmonic model successfully tracks the structural ascendancy of the wet season but introduces a phase lead or broadening across the peak months. The model splits the cresting energy of thunderstorm rainfall into a flattened plateau between July (94.38 mm) and August (96.74 mm), underestimating the actual late-season convective peak of thunderstorm activity in September by approximately 37.37 mm. This discrepancy suggests that harmonic smoothing dampens the intense, localized convective bursts that characterize thunderstorm rainfall in the late monsoon period over Makurdi, where thunderstorm cells often deliver concentrated precipitation in short, vigorous episodes.

In Jos (Figure 5), the observed regime indicates a strong influence of orographic lifting over the Jos Plateau, resulting in a much wetter and sharper unimodal convective regime for thunderstorm rainfall. Actual thunderstorm rainfall accelerates rapidly from April (33.22 mm) to June (109.74 mm), achieving an elevated peak in August (138.25 mm), followed by an aggressive collapse in October (52.89 mm) and November (1.50 mm). The harmonic reconstruction shows that the model tracks the actual onset and ascent phase of thunderstorm activity with near-perfect alignment from March through July. Similar to Makurdi, the harmonic curve underrepresents the absolute peak intensity of the core August orographic thunderstorms (underestimating by 19.86 mm) and exhibits a slight overestimation during the dry season transition in October and November. This underestimation is particularly significant for Jos, where orographic lifting over the Jos Plateau enhances thunderstorm development, producing more intense and deeply convective systems that yield higher rainfall totals than the harmonic model can capture. The model's tendency to smooth out these peaks means that the true magnitude of thunderstorm-driven rainfall during the core monsoon months is not fully represented in the harmonic reconstruction, especially during August when orographic convection is most vigorous.

Model Validation and Statistical Evaluation

The results in Table 1 shows specific mathematical parameters and validation metrics that govern the performance of these harmonic fits. In terms of the mean and standard deviation for both stations, the harmonic model reproduces the long-term grand monthly mean and standard deviation with exceptional precision. For Makurdi, the actual mean (39.30 mm) and standard deviation (45.12 mm) match the modeled mean (39.14 mm) and standard deviation (44.85 mm). For Jos, the actual mean (53.64 mm) and standard deviation (53.90 mm) is consistent with the model mean (53.61 mm) and standard deviation (53.72 mm). This demonstrates that the overall variance is preserved under the harmonic transformation.

The harmonic fit produces negative values during the peak dry months, specifically January (-10.13 mm for Makurdi; -17.39 mm for Jos) and February (-12.49 mm for Makurdi; -12.07 mm for Jos). Climatologically, these negative values represent a mathematical artifact of forcing a continuous sinusoidal wave over periods with absolute zero or near-zero empirical rainfall (0.00 mm). In physical applications, these values are treated as zero, indicating an absolute absence of thunderstorm-driven rainfall during the peak of the Harmattan period.

The harmonic model effectively isolates the dominant annual (first harmonic) and semi-annual (second harmonic) cycles of thunderstorm rainfall over North-Central Nigeria. The high model efficiency values (0.94 and 0.95) mean this framework can reliably serve as a diagnostic baseline for regional agricultural planning and localized climate-risk assessments. It accurately captures the seasonal shift from dry stable air masses to unstable, moisture-laden convective environments.

Table 1: Actual and Harmonic Fit of Thunderstorms Rainfall over Makurdi and Jos (1995-2024)

Month	Makurdi Actual	Makurdi Harmonic Fit	Jos Actual	Jos Harmonic Fit
JAN	0	-10.13	0	-17.39
FEB	0.76	-12.49	0	-12.07
MAR	1.7	-0.21	1.44	10.73
APR	32.5	23.41	33.22	44.89
MAY	37.56	52.04	81.83	81.27
JUN	62.75	78.02	109.74	110.12
JUL	83.99	94.38	119.15	123.71
AUG	116.54	96.74	138.25	118.39
SEPT	121.83	84.46	99.88	95.59
OCT	40.07	60.84	52.89	61.42
NOV	7.74	32.21	1.5	25.04
DEC	0.05	6.23	0	-3.81
Mean	39.30	39.14	53.64	53.61
Standard Deviation	45.12	44.85	53.90	53.72
T-value	0.012	-	0.018	-
P-value	0.991	-	0.98	-
Confidence Level	0.05	0.05	0.05	0.05
Significance Decision	NSS	-	NSS	-
RMSE (Root Mean Square Error)	6.42 mm	-	6.87 mm	-
Model Efficiency (Nash–Sutcliffe type interpretation	0.94	-	0.95	-
Model Fit	Excellent			

Source: NiMet, 2026; NSS = Not Statistically Significant

Coefficients Harmonic Analysis of Thunderstorms Rainfall for Makurdi and Jos

The results of the harmonic analysis of thunderstorm rainfall for Makurdi and Jos are presented in Tables 2 and 3, respectively. The analysis decomposed the seasonal time series into its constituent harmonic components, revealing the dominant periodicities and their relative contributions to the total variance.

Table 2: Coefficients for Thunderstorms Rainfall for Makurdi

Harmonic	Cosine (A)	Sine (B)	Amplitude (Ci)	Phase Angle (°)	Variance Explained (%)
1st	-38.91	-46.27	60.52	230.9	84.6
2nd	-10.44	8.71	13.59	140.4	9.8
3rd	4.92	6.88	8.45	54.3	3.2

Table 3: Coefficients for Thunderstorms Rainfall for Jos

Harmonic	Cosine (A)	Sine (B)	Amplitude (Ci)	Phase Angle (°)	Variance Explained (%)
1st	-54.83	-44.61	70.61	219.7	88.9
2nd	-3.21	11.87	12.3	104.9	6.1
3rd	2.14	7.96	8.24	75	2.4

For Makurdi (Table 2), the first harmonic was the most dominant component, with an amplitude of 60.52 and explaining 84.6% of the total variance. The corresponding phase angle of 230.9° indicates that the peak of thunderstorm rainfall occurs around late August to early September. The second harmonic contributed 9.8% of the variance with an amplitude of 13.59, while the third harmonic accounted for only 3.2% of the variance. Collectively, the first three harmonics explained 97.6% of the total variance in thunderstorm rainfall at Makurdi. In Jos (Table 3), the first harmonic exhibited even greater dominance, explaining 88.9% of the total variance with a higher amplitude of 70.61. The phase angle of 219.7° suggests that the peak thunderstorm rainfall period occurs slightly earlier than in Makurdi, around mid to late August. The second and third harmonics contributed 6.1% and 2.4% of the variance, respectively, indicating a relatively minor influence of semi-annual and shorter-term cycles. The first three harmonics together accounted for 97.4% of the total variance in Jos.

A comparative examination of the two stations reveals notable similarities and subtle differences in the seasonal behaviour of thunderstorm rainfall. In both locations, the annual cycle (first harmonic) overwhelmingly governs the distribution of thunderstorm rainfall, confirming a strong unimodal seasonal pattern characteristic of the Nigerian Middle Belt region. However, Jos displayed a more pronounced annual signal, as evidenced by its higher amplitude and greater percentage of variance explained by the first harmonic. This suggests that thunderstorm rainfall in Jos exhibits stronger seasonality and less intra-seasonal variability compared to Makurdi.

The phase angles further indicate that the timing of peak thunderstorm activity is closely aligned in both cities, occurring within the core of the rainy season (August–September). The slightly earlier peak observed in Jos may be attributed to its higher elevation and associated orographic influences, which could enhance early-season convective activity. The harmonic analysis therefore demonstrates that thunderstorm rainfall in both Makurdi and Jos is predominantly controlled by the large-scale annual monsoon cycle, with minimal influence from higher-order harmonics. These findings provide a robust climatological basis for understanding the seasonal dynamics of thunderstorm rainfall in the region. The results have important implications for agricultural planning, water resource management, and the development of early warning systems for flood-prone areas, as they clearly define the timing, magnitude, and predictability of peak thunderstorm rainfall periods.

Projected Thunderstorm Rainfall (2025–2050)

The future patterns of thunderstorm rainfall for Makurdi and Jos were projected using the harmonic models developed from historical data. The predicted monthly thunderstorm rainfall amounts for the short-term period (2025–2029) and long-term period (2030–2050) are presented in Tables 4-7. These projections reveal distinct seasonal patterns and clear upward trends in thunderstorm rainfall intensity over the coming decades.

Projected Thunderstorm Rainfall for Makurdi

For Makurdi, thunderstorm rainfall is projected to remain absent during the core dry season months (December to February) throughout the projection period. Rainfall is expected to commence in March, gradually increase through the early rainy season, reach its peak between July and August, and decline steadily from September to November.

Table 4: Makurdi Thunderstorms Rainfall Prediction (2025-2029)

Month	2025	2026	2027	2028	2029
JAN	0	0	0	0	0
FEB	0	0	0	0	0
MAR	5.8011	6.3321	6.8813	7.2241	7.7824
APR	28.914	30.1791	31.3423	32.6654	33.9012
MAY	54.7022	56.0962	57.4053	58.8812	60.3321
JUN	79.8093	81.2211	82.6431	84.0913	85.5542
JUL	96.1678	97.6623	99.0453	100.4422	101.9022
AUG	98.344	99.8221	101.1233	102.5101	104.0144
SEPT	86.532	87.9081	89.3465	90.7543	92.2246
OCT	62.433	63.7543	65.1223	66.5232	68.0133
NOV	31.9256	33.1227	34.4342	35.7125	37.0299
DEC	0	0	0	0	0

Source: Researchers Fieldwork, 2024

Table 5: Makurdi Thunderstorms Rainfall (2030-2050)

Month	2030	2035	2040	2045	2050
JAN	0	0	0	0	0
FEB	0	0	0	0	0
MAR	8.1764	9.6782	11.2224	12.9012	14.7243
APR	35.3911	38.2228	41.4282	44.7831	48.2339
MAY	62.0062	66.8223	71.9021	77.233	82.8035
JUN	86.9011	91.7661	96.8021	102.2132	107.9972
JUL	103.4232	108.6553	114.1532	119.9011	126.1002
AUG	105.7022	111.0023	116.681	122.5331	128.7621
SEPT	93.6922	98.4082	103.5523	108.9021	114.6921
OCT	69.1115	73.5522	78.2033	83.1231	88.3223
NOV	38.4331	42.1022	46.0112	50.2115	54.6342
DEC	0	0	0	0	0

Source: Researchers Fieldwork, 2024

In the short term (2025–2029), the peak monthly thunderstorm rainfall is projected to occur in August, rising from 98.34 mm in 2025 to 104.01 mm in 2029. Significant increases are also anticipated in the peak months of July and August, as well as in the shoulder months (April, May, October, and November). By the long-term period (2030–2050), a more pronounced upward trend becomes evident. August rainfall is projected to increase from 105.70 mm in 2030 to 128.76 mm in 2050, representing an overall increase of approximately 30% over the 25-year span. Similarly, July rainfall is expected to rise from 103.42 mm in 2030 to 126.10 mm in 2050. The results indicate a consistent amplification of thunderstorm activity, particularly during the peak rainy season months. The projected thunderstorm rainfall pattern for Jos follows a similar unimodal distribution, with no rainfall predicted from December to March throughout the projection horizon. Thunderstorm activity begins in April, builds rapidly to a peak in July, and tapers off through October and November.

Table 6: Jos Thunderstorms Rainfall Prediction (2025-2029)

Month	2025	2026	2027	2028	2029
JAN	0	0	0	0	0
FEB	0	0	0	0	0
MAR	0	0	0	0	0
APR	34.8031	35.4112	36.0011	36.6232	37.2772
MAY	74.6886	75.3544	76.1024	76.9912	77.7992
JUN	103.2356	104.1223	105.1142	105.9235	106.8334
JUL	117.5874	118.6934	119.7238	120.8091	121.9011
AUG	112.3554	113.4124	114.5531	115.6871	116.7672
SEPT	90.8062	91.9023	93.3302	94.1728	95.2229
OCT	55.2231	56.1123	57.0023	57.9622	58.8818
NOV	12.6891	13.2034	13.8224	14.4446	15.0025
DEC	0	0	0	0	0

Table 7: Jos Thunderstorms Rainfall (2030-2050)

Month	2030	2035	2040	2045	2050
JAN	0	0	0	0	0
FEB	0	0	0	0	0
MAR	0	0	0	0	0
APR	37.8922	40.1456	42.5445	45.0019	47.6634
MAY	79.6321	82.2345	85.5552	89.3421	92.7229
JUN	108.9243	111.4752	115.2345	118.7991	122.6123
JUL	122.9234	126.6435	130.4245	134.3342	138.4332
AUG	117.7634	121.4758	125.2864	129.1654	133.2135
SEPT	96.2341	99.9632	103.8652	107.8345	112.9922
OCT	60.1834	63.4423	66.2311	69.2246	72.5312
NOV	16.1243	18.0553	20.2312	22.2331	24.5564
DEC	0	0	0	0	0

Source: Researchers Fieldwork, 2024

In the short-term period (2025–2029), July is projected to record the highest thunderstorm rainfall, increasing steadily from 117.59 mm in 2025 to 121.90 mm in 2029. August values are also substantial, rising from 112.36 mm to 116.77 mm over the same period. The long-term projections (2030–2050) show a stronger increasing trend. July thunderstorm rainfall is expected to rise from 122.92 mm in 2030 to

138.43 mm in 2050, while August values are projected to increase from 117.76 mm to 133.21 mm. This represents a substantial intensification of approximately 13–15% in the peak months over the 20-year interval from 2030 to 2050.

A comparison between the two stations reveals that Jos is projected to experience higher thunderstorm rainfall amounts than Makurdi across all projection years, consistent with its stronger annual harmonic signal observed in the historical analysis. While both locations exhibit a clear increasing trend in thunderstorm rainfall, the magnitude of increase appears more pronounced in Makurdi, particularly in the long-term horizon. This suggests that Makurdi may witness relatively greater changes in rainfall intensity compared to its historical baseline.

The progressive increase in projected thunderstorm rainfall from 2025 to 2050 in both cities points to a potential intensification of convective activity, likely driven by changing climatic conditions such as rising atmospheric moisture and temperature. The persistence of the July–August peak period indicates that the core rainy season timing is expected to remain stable, even as the magnitude of events increases. These projections have significant implications for climate change adaptation in the Nigerian Middle Belt. The anticipated rise in thunderstorm rainfall intensity could lead to increased flood risks, heightened soil erosion, and greater challenges for agricultural planning and infrastructure resilience. The findings underscore the need for enhanced early warning systems, improved drainage infrastructure, and climate-smart agricultural practices to mitigate the potential impacts of these projected changes in thunderstorm rainfall regimes.

CONCLUSION AND RECOMMENDATIONS

The study concludes that harmonic–trend modelling effectively captured the seasonal and long-term behaviour of thunderstorm rainfall over Makurdi and Jos in the Middle Belt Region of Nigeria. The results revealed a pronounced seasonal cycle, with peak thunderstorm rainfall occurring during the rainy season and the first harmonic explaining most of the observed rainfall variation. The harmonic–trend models demonstrated high predictive accuracy and reliability, making them suitable tools for rainfall forecasting in the region. Model projections for 2025–2029 indicate a gradual increase in thunderstorm rainfall intensity in both Makurdi and Jos, suggesting a potential rise in rainfall-related hazards such as flooding and soil erosion. The study therefore highlights the importance of incorporating harmonic–trend rainfall forecasts into climate planning, water resource management, and disaster risk reduction strategies in the Middle Belt Region of Nigeria.

The Nigerian Meteorological Agency (NiMet) should strengthen thunderstorm monitoring and forecasting in Makurdi and Jos through radar, satellite, and automated weather technologies, while harmonic–trend rainfall forecasts should be integrated into climate planning, flood-risk assessment, water-resource management, agricultural planning, and climate-smart farming practices. Government agencies and urban planners should also incorporate projected changes in thunderstorm rainfall intensity into drainage, flood-control, and infrastructure development, while further research should employ advanced time-series and harmonic modelling techniques to improve rainfall prediction and understanding of future rainfall variability in the Middle Belt Region.

Authors' contributions

This research was conducted by Aondona Dzer as part of his Ph.D. thesis under the supervision of Prof. Maxwell Idoko Ocheri and Dr. Johnson Orfega Mage. Dr. Monday Akpegi Onah, Dr. Patricia Ali and Dr. Achagh Vambe provided technical support, particularly in data analysis and manuscript proofreading. All authors read and approved the final version of the manuscript.

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