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Analysis of the Percentage Contribution of Squall Lines and Thunderstorms to Annual Rainfall Amount Over the Middle Belt Region of Nigeria

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Abstract: *This study examined the percentage contribution of squall lines and thunderstorms to annual rainfall amount over the Middle Belt region of Nigeria, using Jos and Makurdi as representative stations, based on daily records obtained from the Nigerian Meteorological Agency (NiMet) covering 1995–2024. Mean, Standard of Deviation, Coefficient of Variation, percentage Students t-test and trend analysis were employed in data analysis. The results indicate that both squall lines and thunderstorms were largely confined to the rainy season (March–October), with thunderstorms occurring far more frequently than squall lines at both stations. Thunderstorms accounted for the dominant share of annual rainfall, contributing 48.69% in Jos and 42.17% in Makurdi, while squall lines contributed a comparatively smaller proportion of 17.53% and 14.47%, respectively. The combined contribution of both systems therefore accounted for the majority of annual rainfall in the region, underscoring their central role in the Middle Belt's hydro-climatic regime. Trend analysis revealed that the percentage contribution of squall lines declined significantly over the study period in Jos and marginally in Makurdi, while the contribution of thunderstorms also declined significantly in Jos but showed no significant trend in Makurdi. Despite these declines in relative contribution, total annual rainfall at both stations exhibited no significant long-term trend, suggesting a shifting balance in the convective mechanisms sustaining regional rainfall. The study concludes that squall lines and thunderstorms remain the principal drivers of annual rainfall over the Middle Belt, but their relative contributions are undergoing measurable change consistent with broader climate variability. The study recommended that NiMet enhance convective-system monitoring and that findings be incorporated into climate-smart agricultural planning and flood-risk management strategies for the region.*

Keywords: Thunderstorms, squall lines, rainfall contribution, Middle Belt region, Jos, Makurdi, climate variability.

INTRODUCTION

Rainfall is one of the most important climatic elements influencing water resources, agriculture, transportation, ecosystem functioning, and socio-economic development worldwide. A substantial proportion of global rainfall, particularly in tropical regions, is generated by mesoscale convective systems (MCSs), including thunderstorms and squall lines. These weather systems are characterized by intense convection, strong winds, lightning activity, and heavy precipitation, making them major contributors to annual rainfall totals and extreme weather events (Mathon & Laurent, 2001; Schumacher & Rasmussen, 2023). Studies have shown that MCSs are responsible for a significant proportion of rainfall across tropical regions and are increasingly linked to flooding, soil erosion, and other hydro-meteorological hazards under changing climatic conditions (Klein, Nkrumah, Taylor, & Adefisan, 2021; Lima, Aquino, Moraes, & Palhoça, 2023).

In West Africa, thunderstorms and squall lines constitute the dominant rainfall-producing systems during the rainy season. Research indicates that these systems contribute between 50% and 90% of annual rainfall across different ecological zones, with their influence increasing northward from the coastal regions to the Sahel (Fink, Vincent, & Ermert, 2006; Laurent, D'Amato, Lebel, & Vischel, 1998; Mathon & Laurent, 2001). Beyond rainfall generation, squall lines and thunderstorms play critical roles in atmospheric circulation and are responsible for many extreme rainfall events that often result in flooding and environmental degradation across the region (Huang, Luo, Zhou, Gong, & Li, 2017).

Nigeria experiences rainfall mainly through three synoptic weather systems: monsoonal rainfall, local convective thunderstorms, and squall lines (Ramara, 1986; Debois, 1988). Previous studies have shown that the contribution of these systems varies spatially across the country. Omotosho (1985) reported that thunderstorm rainfall decreases with increasing latitude, while squall-line rainfall reaches its maximum contribution around latitude 9°N. Similarly, Orisakwe (2015) found that mesoscale convective systems contribute approximately 72.5% of total annual rainfall in Nigeria, with thunderstorms accounting for about 45.7% and squall lines contributing about 26.8%. These findings highlight the significant role of convective weather systems in shaping Nigeria's rainfall regime.

The Middle Belt Region of Nigeria, particularly Makurdi and Jos, occupies a transitional climatic zone between the humid southern region and the semi-arid northern region. This location makes the area highly sensitive to variations in convective rainfall systems. Makurdi, located within the Benue Valley around latitude 7°44'N, and Jos, situated on the Jos Plateau around latitude 9°56'N, experience substantial rainfall generated by thunderstorms and squall lines during the wet season. The region's dependence on rain-fed agriculture, coupled with increasing urbanization, makes it vulnerable to rainfall variability, flooding, soil erosion, and environmental degradation. Recent climate variability has further intensified the frequency and magnitude of extreme rainfall events across the Middle Belt, resulting in recurrent flooding and significant socio-economic losses (Adelekan, 2005; Oke, Akinyemi, Ayanlade, Adeyeri, & Olanrewaju, 2023).

Although several studies have investigated thunderstorms, squall lines, and rainfall characteristics in different parts of Nigeria (Omotosho, 1985; Nwodu, 1983; Ayoola, Adekeye, & Adebayo, 2016; Ochei, Emetere, & Oladosu, 2015), limited attention has been given to their percentage contribution to annual rainfall over the Middle Belt Region over a long-term period. Furthermore, there is inadequate information on the temporal and spatial variability of these weather systems, their rainfall contributions and long-term trends in Makurdi and Jos. Therefore, this study seeks to assess the percentage contribution of squall lines and thunderstorms to annual rainfall amounts over the Middle Belt Region of Nigeria from 1995 to 2024, with a view to improving understanding of regional rainfall dynamics and providing information useful for climate adaptation, flood management, agricultural planning, and environmental sustainability.

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).

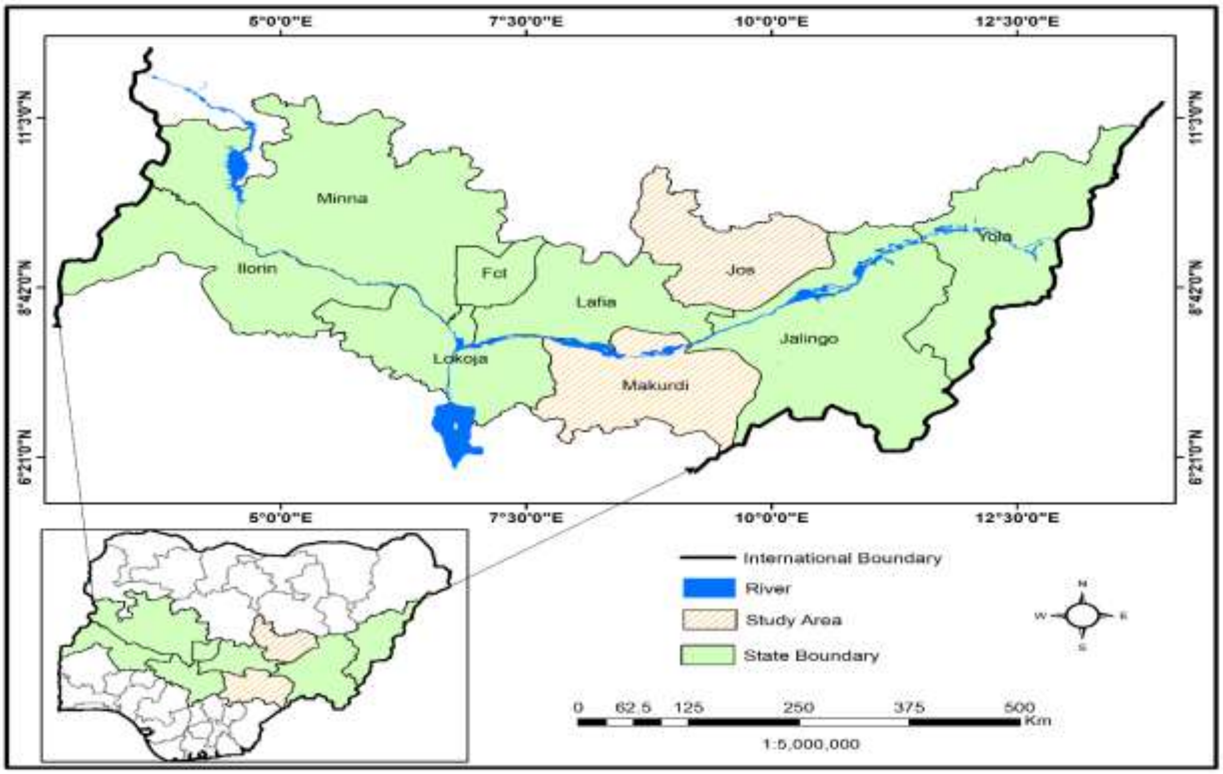

Figure1: The location of the Middle Belt Region of Nigeria show Makurdi and Jos
Source: Mecon Services Limited Jos, 2026.

METHODS

The study adopted an observational research design. This design was considered appropriate because it allows the use of archival data obtained through direct field observation and instrumental measurement over an extended period. The design enabled the researcher to examine long-term trends and variations in the occurrence of thunderstorms, squall lines, and rainfall activities in the Middle Belt Region during the study period. The observational design also eliminates dependence on respondents, whose responses or observations may be influenced by prevailing circumstances, thereby providing a more objective basis for analysing atmospheric phenomena.

The data required for the study comprised daily rainfall amounts, daily occurrences of squall lines and thunderstorms, occurrences of squall lines and thunderstorms associated with rainfall, and occurrences of squall lines and thunderstorms without rainfall. All the data covered a 30-year period from 1995 to 2024. Data on squall lines, thunderstorms, and daily rainfall were obtained from two synoptic meteorological stations, namely 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. The two stations were selected because of their marked difference in elevation and their suitability for examining the occurrence and characteristics of squall lines and thunderstorms, which are important weather phenomena in the region. The 1995–2024 period was selected because the analysis of climate phenomena is generally more meaningful when based on long-term observations. A 30-year period is widely used as a standard reference period for describing and assessing climatic conditions and variability. aConsequently, the 30-year dataset provides an adequate temporal basis for examining variations and trends in thunderstorms, squall lines, and associated rainfall at the two study locations.

The detection and measurement of thunderstorms were based on observations from thunder detectors installed at the synoptic weather stations. A thunder detector is a sensor used to detect thunderstorms within the vicinity of a weather station. It operates by detecting flashes of light and momentary changes in the electric field associated with lightning (WMO, 1953). Where rainfall commenced within 30 minutes before or after the arrival of either of the two systems, the rainfall was recorded as being associated with that system. Squall lines were detected through a combination of visual observations and instrumental measurements in accordance with standard procedures adopted by the Nigerian Meteorological Agency (NiMet). During both daytime and nighttime, observers maintained continuous surveillance of the eastern portion of the station for the development and approach of cumulonimbus cloud formations characterised by a dark appearance and a relatively distinct linear orientation. During the daytime, the cumulonimbus cloud mass could be observed developing progressively and becoming increasingly dark, often accompanied by thunder or other signs of a thunderstorm.

The approach and passage of a squall line were identified from several characteristic meteorological signatures. These included a brief period of calm surface wind, typically lasting about 2–3 minutes, followed by a sudden and substantial increase in wind speed, generally ranging from 16 to 22 knots. The passage was also associated with a rapid increase in atmospheric pressure, a noticeable decrease in temperature, and the occurrence of thunder and lightning. In terms of pressure behaviour, the pressure generally remained relatively stable before the arrival of the squall line, increased rapidly as the system passed directly over the station, and subsequently returned towards its normal level after passage. Rainfall associated with squall lines was measured using a standard rain gauge, which recorded the amount of precipitation occurring during and immediately following the passage of the gust front. At manned stations, observers also recorded the sudden onset and intensification of rainfall associated with the system. The integration of visual observations with instrumental measurements of wind, temperature, atmospheric pressure, and rainfall provided a basis for identifying the occurrence of squall lines and thunderstorms and determining their associated rainfall contributions at the study locations.
The contribution of squall lines and thunderstorms to annual rainfall totals was determined using percentage analysis.
For squall lines:

$$PSC = RSL/TR \times 100 \tag{1}$$

For thunderstorms:

$$PTS = RTS/TR \times 100 \tag{2}$$

Where:
PSC = Percentage Contribution of Squall Line to Rainfall
PTS = Percentage Contribution of Thunderstorm to Rainfall
RSL = Percentage Contribution of Squall Line to Rainfall

RTS = Percentage Contribution of Thunderstorm to Rainfall
TR = Total Annual Rainfall
The temporal behaviour of the percentage contributions was subsequently analysed using trend analysis and graphical presentation. Temporal trends in the percentage contributions were determined using simple linear regression expressed as:

$$Y = a + bX \quad (3)$$

Where:
Y = Percentage Contribution (Rainfall Variable)
a = Intercept (Constant)
b = Gradient
X = Year
The coefficient of determination (R^2) was used to assess the proportion of variation in the percentage contribution explained by the trend.

$$R^2 = (\sum(\hat{Y} - \bar{Y})^2)/(\sum(Y - \bar{Y})^2) \quad (4)$$

The significance of the trend in percentage contribution was tested using Student's t-test, expressed as:

$$t = (r\sqrt{(n - 2)})/\sqrt{(1 - r^2)} \quad (5)$$

Where:
t = Student's t-test
r = Trend (Correlation Coefficient)
n = Number of observations
The calculated t-value was compared with the critical t-value at the 0.05 significance level. A trend in the percentage contribution of squall lines and thunderstorms to annual rainfall was considered significant when the calculated t-value exceeded the critical value.

RESULTS AND DISCUSSION

Percentage Contribution of Squall Lines to Annual Rainfall in Jos

The results of the percentage contribution of squall lines (SL) and thunderstorms (TS) to annual total rainfall amount in Jos and Makurdi are presented in Tables 1-3 and Figures 2-5.

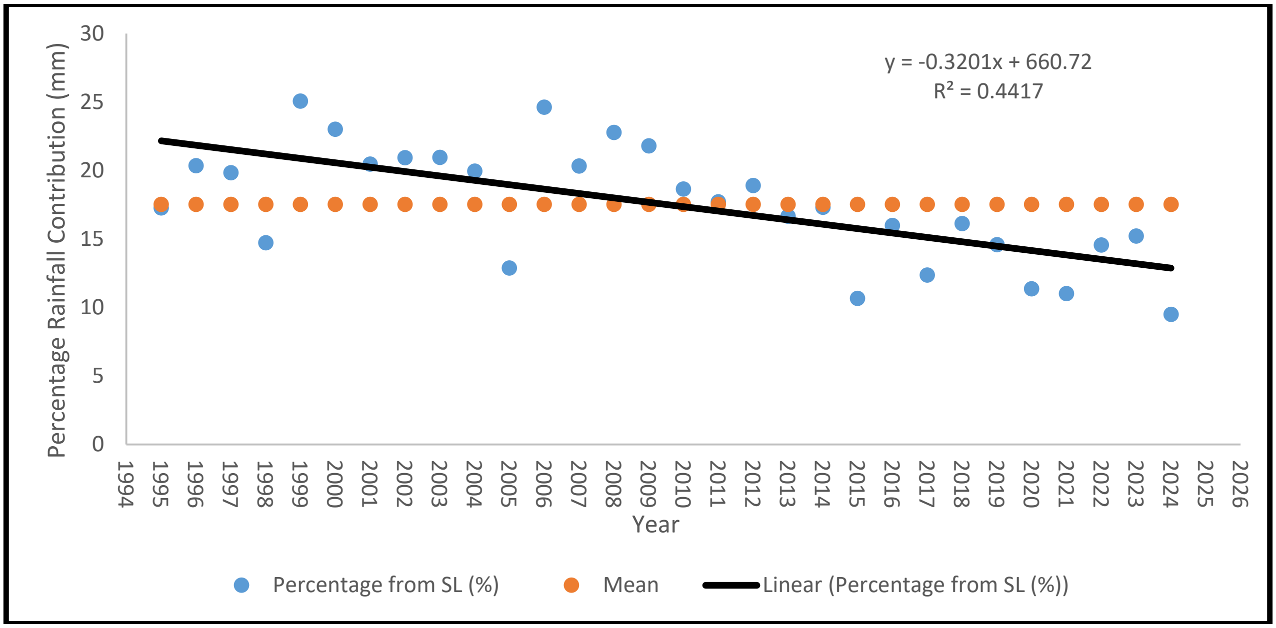

Figure 2: Yearly Variability in Percentage (%) Contribution of Squall Lines to Annual Rainfall Total over Jos

Table 1: Percentage (%) Rainfall Contribution of Squall Line (SL) to Annual Total Rainfall Amount in Jos

Year	SL Rainfall	Total Annual Rainfall	Percentage Contribution of Rains from SL (%)
1995	140.7	814.7	17.27
1996	281.3	1382	20.35
1997	263.9	1329.3	19.85
1998	274.2	1861.7	14.73
1999	287.9	1148.2	25.07
2000	266.9	1159.6	23.02
2001	255.4	1247.5	20.47
2002	275.75	1316.7	20.94
2003	274.05	1308.4	20.95
2004	241.7	1211.7	19.95
2005	155.4	1206.4	12.88
2006	309.6	1257.1	24.63
2007	276.3	1359	20.33
2008	287.1	1259.8	22.79
2009	256.9	1178.5	21.80

2010	275.2	1475.2	18.66
2011	208.5	1176.8	17.72
2012	277.3	1467.2	18.90
2013	197.7	1185.9	16.67
2014	216.6	1249.7	17.33
2015	129.5	1214.3	10.66
2016	157.15	983.7	15.98
2017	173.9	1405.2	12.38
2018	248.8	1541.7	16.14
2019	206.8	1416.8	14.60
2020	182.8	1608.4	11.37
2021	120.4	1093.4	11.01
2022	248.4	1706.5	14.56
2023	196.1	1287.8	15.23
2024	172.1	1810.2	9.51

Source: Researchers Fieldwork, 2024

Table 2: Summary of Statistical Values of (%) Rainfall Contribution of Squall Line (SL) to Annual Total Rainfall Amount in Jos

Variable	Value/Status
Mean	17.53
Standard of Deviation	4.24
Coefficient of Variation	24.19
Maximum	25.07
Minimum	9.51
r^2	0.4417
r	0.665
Computed t-value	4.707
Critical t-value	1.70
Significance Decision	Significant
Direction of the trend line *($y = -0.320x + 660.72$)*	Negative

Source: Researchers Fieldwork, 2024

The result presented in Table 2 and Figure 2 shows that squall lines contributed substantially to annual rainfall totals in Jos during the study period. The percentage contribution ranged from a minimum value of 9.51% in 2024 to a maximum of 25.07% in 1999, with a mean contribution of 17.53% (Table 16). This

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implies that, on average, nearly one-fifth of the annual rainfall received in Jos was associated with squall line activities.

The temporal pattern indicates marked inter-annual fluctuations in the contribution of squall lines. Relatively high contributions were recorded during the late 1990s and early 2000s. For instance, values above 20% occurred in 1996 (20.35%), 1997 (19.85%), 1999 (25.07%), 2000 (23.02%), 2002 (20.94%), 2003 (20.95%), 2006 (24.63%), 2008 (22.79%), and 2009 (21.80%). These years correspond to periods of enhanced convective activity and stronger mesoscale atmospheric disturbances capable of generating organised squall systems over the Jos Plateau region. Conversely, lower contributions were observed in more recent years, particularly after 2015. The percentage contribution declined to 10.66% in 2015, 11.37% in 2020, 11.01% in 2021, and eventually 9.51% in 2024. This persistent reduction suggests a weakening influence of squall-line-related rainfall over time.

The coefficient of variation (24.19%) indicates moderate variability in the contribution of squall lines to annual rainfall in Jos. The relatively high standard deviation of 4.24 further confirms substantial year-to-year fluctuations in squall-line rainfall contribution. Trend analysis reveals a statistically significant declining trend in the contribution of squall lines to annual rainfall in Jos. The trend equation, ($y = -0.320x + 660.72$), shows a negative slope, indicating a gradual decrease over time. The coefficient of determination ($r^2 = 0.4417$) implies that approximately 44.17% of the observed variation in squall-line rainfall contribution is explained by time. Similarly, the correlation coefficient ($r = 0.665$) indicates a strong relationship between time and the declining trend. The computed t-value (4.707) exceeded the critical t-value (1.70), confirming that the trend is statistically significant at 0.05 (95%) confidence level.

The declining contribution of squall lines may be linked to changes in atmospheric circulation patterns, weakening moisture convergence, increasing atmospheric instability irregularities, or broader manifestations of climate variability and climate change affecting convective systems over the region. Since squall lines are major contributors to intense rainfall events in northern and central Nigeria, the observed decline could have implications for rainfall intensity patterns, water availability, agricultural productivity, and hydrological processes in Jos and surrounding environments.

Percentage Contribution of Thunderstorms to Annual Rainfall in Jos

The result presented in Table 3 and Figure 3 indicates that thunderstorms contributed a much larger proportion of annual rainfall in Jos compared to squall lines. The percentage contribution ranged between 26.89% in 2015 and 76.48% in 2000, with a mean value of 48.69% (Table 3). This suggests that nearly half of the annual rainfall in Jos during the study period originated from thunderstorm activities.

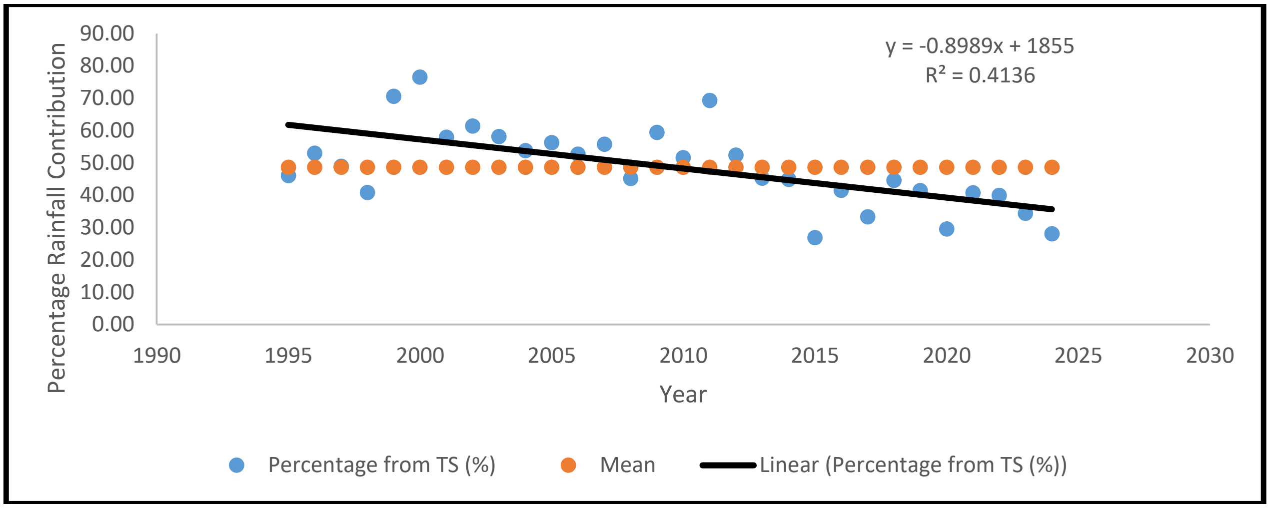

Figure 3: Yearly Variability in Percentage (%) Contribution of thunderstorms to Annual Rainfall Total over Jos

Table 3: Percentage (%) Rainfall Contribution of Thunderstorms to Annual Total Rainfall Amount in Jos

Year	Total (R/F) from TS	Total Annual Rainfall	Percentage from TS (%)
1995	375	814.7	46.03
1996	731.9	1382	52.96
1997	650.7	1329.3	48.95
1998	760.45	1861.7	40.85
1999	810.2	1148.2	70.56
2000	886.9	1159.6	76.48
2001	722.3	1247.5	57.90
2002	808.9	1316.7	61.43
2003	760.5	1308.4	58.12
2004	652.27	1211.7	53.83
2005	678.7	1206.4	56.26
2006	662.95	1257.1	52.74
2007	757.2	1359	55.72
2008	569.8	1259.8	45.23
2009	700.5	1178.5	59.44
2010	761.9	1475.2	51.65
2011	816.1	1176.8	69.35

2012	769.4	1467.2	52.44
2013	537.15	1185.9	45.29
2014	561.32	1249.7	44.92
2015	326.5	1214.3	26.89
2016	408.8	983.7	41.56
2017	468.2	1405.2	33.32
2018	687.4	1541.7	44.59
2019	587.45	1416.8	41.46
2020	476.2	1608.4	29.61
2021	445.3	1093.4	40.73
2022	682	1706.5	39.96
2023	443.1	1287.8	34.41
2024	508	1810.2	28.06

Source: Researchers Fieldwork, 2024

Table 4: Summary of Statistical Values of (%) Rainfall Contribution of Thunderstorms to Annual Total Rainfall Amount in Jos

Variable	Value/Status
Mean	48.69
Standard of Deviation	12.30
Coefficient of Variation	25.27
Maximum	76.48
Minimum	26.89
r^2	0.4136
r	0.643
Computed (t)-value	4.444
Critical (t)-value	1.70
Significance Decision	Significant
Direct of the trend line *($y = -0.8989x + 1855$)*	Negative

Source: Researchers Fieldwork, 2024

The result further reveals substantial inter-annual variability in thunderstorm rainfall contribution. Exceptionally high contributions were observed in 1999 (70.56%), 2000 (76.48%), and 2011 (69.35%). These years were characterised by very active convective storm systems, leading to enhanced rainfall generation through thunderstorm mechanisms. In contrast, relatively low contributions occurred in 2015 (26.89%), 2020 (29.61%), and 2024 (28.06%). The decline in recent years suggests that thunderstorm-related rainfall may be reducing in relative importance within the annual rainfall regime of Jos.

The coefficient of variation (25.27%) indicates moderate variability in thunderstorm rainfall contribution, while the standard deviation (12.30) confirms significant temporal fluctuations. Compared with squall lines, thunderstorms exhibited wider variability due to their stronger dependence on local atmospheric instability and convective dynamics. Trend analysis indicates a statistically significant negative trend in thunderstorm rainfall contribution over the study period. The regression equation (y = -0.8989x + 1855) shows a pronounced declining slope. The coefficient of determination (r^2 = 0.4136) suggests that about 41.36% of the temporal variation is attributable to time-related changes. The correlation coefficient (r = 0.643) indicates a moderately strong relationship between time and declining thunderstorm contribution.

The computed t-value (4.444) is greater than the critical t-value (1.70), indicating that the decreasing trend is statistically significant. This implies that the reduction in thunderstorm contribution is not due to random chance but reflects a systematic temporal change. The decreasing role of thunderstorms in annual rainfall generation may have important environmental implications. Thunderstorms are major sources of short-duration, high-intensity rainfall capable of triggering flooding, soil erosion, and runoff generation. Therefore, changes in their contribution may influence hydrological extremes, agricultural water supply, and urban flood dynamics in Jos.

Percentage Contribution of Squall Lines to Annual Rainfall in Makurdi

The result presented in Table 4 and Figure 4 shows that the contribution of squall lines to annual rainfall in Makurdi varied considerably throughout the study period.

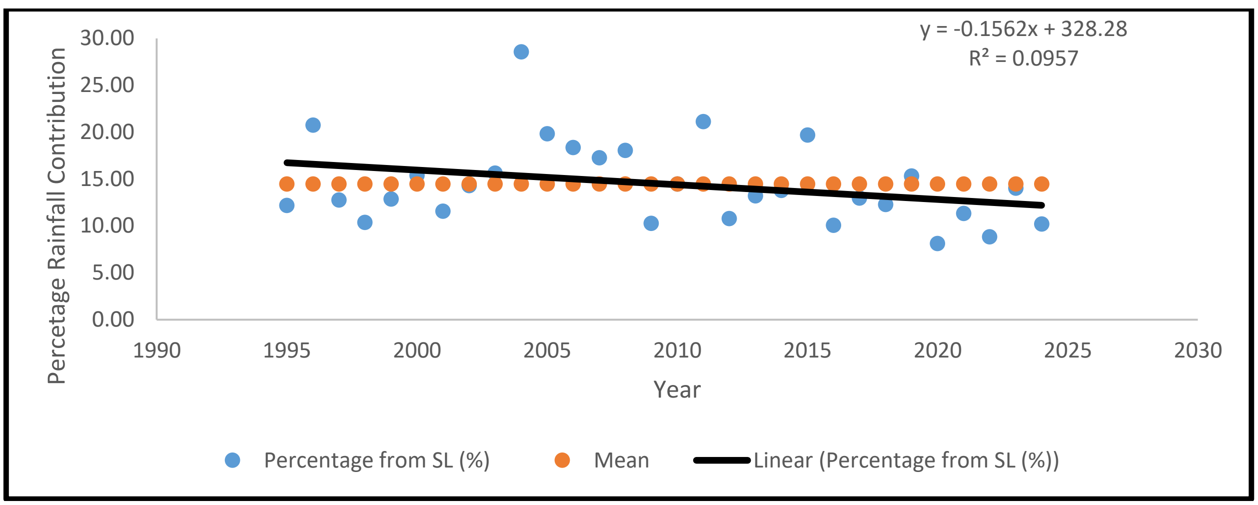

Figure 4: Yearly Variability in Percentage (%) Contribution of Squall Lines to Annual Rainfall Total over Makurdi.

Table 5: Percentage (%) Rainfall Contribution of Squall Line to Annual Total Rainfall Amount in Makurdi

Year	SL Rainfall	Total Annual Rainfall	Percentage from SL (%)
1995	142.6	1172.1	12.17
1996	274.5	1323.9	20.73
1997	173.2	1359.4	12.74
1998	152.3	1471.4	10.35
1999	213.6	1664	12.84
2000	169.3	1099.8	15.39
2001	123.9	1071.9	11.56
2002	184	1287.5	14.29
2003	117.4	751.8	15.62
2004	247.5	867.3	28.54
2005	171.5	864.9	19.83
2006	246.3	1343	18.34
2007	229.2	1328.2	17.26
2008	180.5	1000.6	18.04
2009	147.3	1435.1	10.26
2010	153.9	1065.3	14.45
2011	212.5	1007.1	21.10
2012	160.6	1492.8	10.76
2013	166.4	1260.8	13.20
2014	171.1	1242.5	13.77
2015	198.3	1007	19.69
2016	129.6	1290.5	10.04
2017	122.3	944	12.96
2018	117.8	961.1	12.26
2019	242.4	1583.9	15.30
2020	104.9	1294.3	8.10
2021	156.66	1383.5	11.32
2022	133.7	1512.5	8.84
2023	195.2	1392.4	14.02
2024	143.1	1402.2	10.21

Source: Researchers Fieldwork, 2024

Table 6: Summary of Statistical Values of (%) Rainfall Contribution of Squall Line to Annual Total Rainfall Amount in Makurdi

Variable	Value/Status
Mean	14.47
Standard of Deviation	4.44
Coefficient of Variation	30.72
Maximum	28.54
Minimum	8.10
r^2	0.0957
R	0.309
Computed (t)-value	1.721
Critical (t)-value	1.70
Significance Decision	Significant (marginal)
Direction of the Trend line *(y = -0.1562 + 328.28)*	Negative

Sources: From Table 19 and Figure 44

The percentage contribution ranged from 8.10% in 2020 to 28.54% in 2004, with a mean contribution of 14.47% (Table 4). This average is lower than the corresponding value recorded in Jos, indicating that squall lines contributed less to annual rainfall generation in Makurdi. This is because squall line is formed in the North Eastern of Nigerian and traverse down South. So the influence moves in Jos closer to their formation and many dissipate as they move down south Makurdi. The temporal pattern shows alternating periods of increase and decrease. Higher contributions occurred in 2004 (28.54%), 2011 (21.10%), 1996 (20.73%), and 2005 (19.83%). Conversely, very low contributions were recorded in 2020 (8.10%), 2022 (8.84%), and 2016 (10.04%).

The coefficient of variation (30.72%) indicates relatively high variability in squall-line contribution in Makurdi compared with Jos. This suggests that the occurrence and rainfall-producing efficiency of squall lines are more unstable in Makurdi. The higher variability may be associated with Makurdi's transitional climatic location within the Guinea Savannah belt, where rainfall systems are influenced by both tropical maritime and continental air masses. Trend analysis reveals a negative trend represented by the regression equation ($y = -0.1562x + 328.28$). Although the slope is negative, the decline is weaker than that observed in Jos. The coefficient of determination ($r^2 = 0.0957$) indicates that only 9.57% of the variation in squall-line contribution is explained by time, suggesting a relatively weak temporal relationship.

The computed t-value (1.721) is only slightly greater than the critical t-value (1.70), indicating marginal statistical significance. This suggests that while there is evidence of declining squall-line contribution in Makurdi, the trend is weak and less pronounced compared to Jos. The relatively lower and weakly declining contribution of squall lines in Makurdi may imply that other rainfall-generating mechanisms, particularly localised thunderstorms and monsoonal rainfall processes, play a more dominant role in annual rainfall generation within the area.

Percentage Contribution of Thunderstorms to Annual Rainfall in Makurdi

The result presented in Table 7 and Figure 5 reveals that thunderstorms constitute a major source of rainfall in Makurdi. The percentage contribution ranged between 27.11% in 2001 and an exceptionally high value of 91.12% in 2011, with an average contribution of 42.17%.

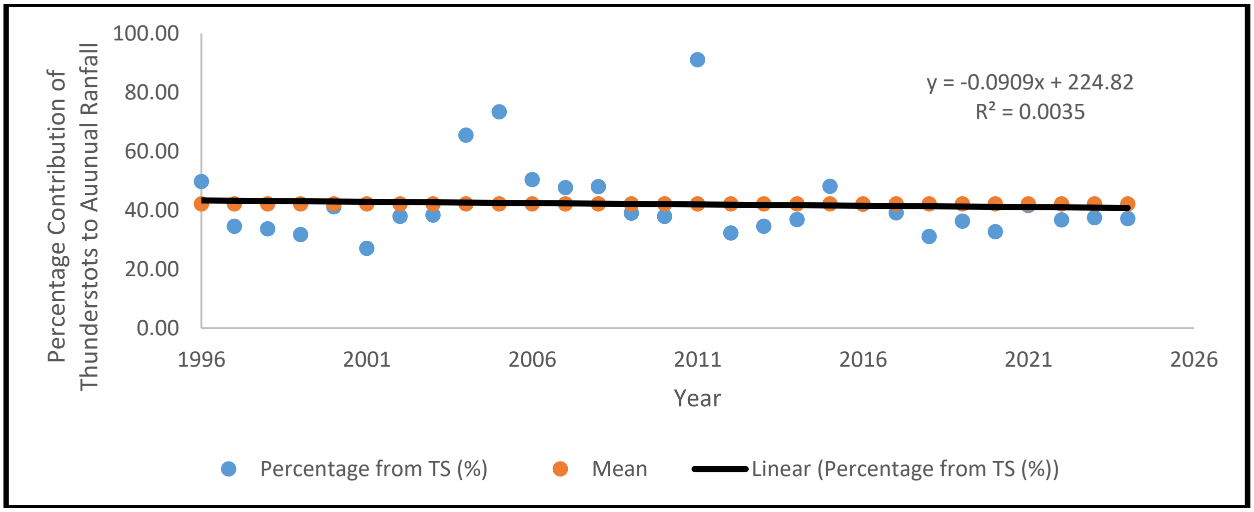

Figure 5: Yearly Variability in Percentage (%) Contribution of Thunderstorms to Annual Rainfall Total Over Makurdi

Table 8: Percentage (%) Rainfall Contribution of Thunderstorms to Annual Total Rainfall Amount in Makurdi

Year	Total (R/F from TS	Total Annual Rainfall	Percentage from TS (%)
1995	355.4	1172.1	30.32
1996	658.5	1323.9	49.74
1997	471	1359.4	34.65
1998	496.4	1471.4	33.74
1999	529.7	1664	31.83
2000	453.8	1099.8	41.26
2001	290.6	1071.9	27.11
2002	488.7	1287.5	37.96
2003	289.1	751.8	38.45
2004	568.1	867.3	65.50
2005	634.9	864.9	73.41
2006	676.8	1343	50.39
2007	633.8	1328.2	47.72
2008	480.6	1000.6	48.03
2009	560.3	1435.1	39.04
2010	404.7	1065.3	37.99
2011	917.7	1007.1	91.12
2012	483.2	1492.8	32.37
2013	436.8	1260.8	34.64
2014	457.9	1242.5	36.85
2015	485	1007	48.16
2016	543.7	1290.5	42.13
2017	369.8	944	39.17
2018	299.7	961.1	31.18
2019	576.6	1583.9	36.40
2020	424.7	1294.3	32.81
2021	577.1	1383.5	41.71
2022	555.7	1512.5	36.74
2023	523	1392.4	37.56
2024	521.6	1402.2	37.20

Source: Researchers Fieldwork, 2024

Table 9: Summary of Statistical Values of (%) Rainfall Contribution of Thunderstorms to Annual Total Rainfall Amount in Makurdi.

Variable	Value/Status
Mean	42.17
Standard of Deviation	13.53
Coefficient of Variation	32.09
Maximum	91.12
Minimum	27.11
r^2	0.0035
R	0.059
Computed (t)-value	0.314
Critical (t)-value	1.70
Significance Decision	Not Significant
Direction of the Trend line *(y = -.0.0909x + 224.82)*	Negative

Sources: Researchers Fieldwork, 2024

The extremely high contribution recorded in 2011 suggests that thunderstorm activities overwhelmingly dominated rainfall production during that year. Other years with relatively high contributions include 2004 (65.50%), 2005 (73.41%), 2006 (50.39%), and 2007 (47.72%). Conversely, lower values were recorded in 2001 (27.11%), 1995 (30.32%), and 2018 (31.18%).

The coefficient of variation (32.09%) indicates high variability in thunderstorm rainfall contribution, suggesting strong fluctuations in convective storm activities over Makurdi. The standard deviation of 13.53 further confirms pronounced year-to-year differences. Trend analysis reveals a very weak negative trend represented by the regression equation (y = -0.0909x + 224.82). The coefficient of determination (r^2 = 0.0035) indicates that only 0.35% of the variation is explained by time, showing an extremely weak relationship. Similarly, the correlation coefficient (r = 0.059) suggests almost no correlation between time and thunderstorm rainfall contribution. The computed t-value (0.314) is far lower than the critical t-value (1.70), indicating that the trend is not statistically significant. This means that the observed fluctuations in thunderstorm contribution are largely random and do not reflect any meaningful long-term decline. The absence of a statistically significant trend suggests relative stability in the role of thunderstorms in rainfall generation over Makurdi despite annual fluctuations. This may imply that local convective mechanisms remain consistently active in the area, sustaining thunderstorm rainfall production over time.

Comparative Interpretation of Contribution of Rainfall by Meso Scale Systems over Jos and Makurdi

Comparatively, thunderstorms contributed a larger proportion of annual rainfall than squall lines in both Jos and Makurdi throughout the study period. However, Jos recorded higher average contributions from both squall lines (17.53%) and thunderstorms (48.69%) compared with Makurdi, where mean contributions were 14.47% and 42.17% respectively. The results further reveal stronger and more statistically significant declining trends in Jos than in Makurdi. Both squall-line and thunderstorm contributions in Jos exhibited significant negative trends, whereas Makurdi showed only a marginally significant decline for squall lines and a non-significant trend for thunderstorms. This spatial contrast may be attributed to differences in topography, atmospheric circulation, altitude, and local climatic controls. Jos, being a highland environment, is more sensitive to changes in convective atmospheric processes and mesoscale systems. In contrast, Makurdi's lower-altitude tropical setting may support more stable convective rainfall generation over time.

The findings therefore, suggest that convective rainfall systems, especially thunderstorms, remain dominant contributors to annual rainfall in both locations. However, the observed declining trends, particularly in Jos, may indicate evolving rainfall characteristics associated with regional climate variability and climate change, with possible implications for agriculture, flood occurrence, water resources management, and environmental sustainability in north-central Nigeria. The observed decline in the percentage contribution of squall lines to annual rainfall in both Jos (mean = 17.53%) and Makurdi (mean = 14.47%) indicates a gradual reduction in the dominance of organised mesoscale convective systems in the rainfall climatology of North-Central Nigeria. The statistically significant negative trend in Jos further suggests that squall-line systems are becoming less structurally important in rainfall generation despite their continued occurrence.

This finding is consistent with classical and contemporary empirical evidence on rainfall partitioning in Nigeria. Omotosho (1985) established that squall lines historically contributed the largest share of rainfall in northern Nigeria (often exceeding thunderstorms and monsoon rainfall), but also noted their high spatial and temporal variability. The present results suggest a departure from this earlier climatological dominance, implying a long-term redistribution of rainfall contributions among convective systems.

More recent Nigerian-based studies reinforce this interpretation. Mamman et al. (2021), in a national rainfall exceedance analysis, reported increasing irregularity in rainfall systems across North-Central Nigeria, with reduced persistence of organised convective rainfall events. Similarly, Morrison et al. (2023) found that rainfall variability across Nigeria (1901–2021) is increasingly characterised by episodic extremes rather than structured storm systems, indicating a weakening of classical squall-line dominance. In addition, Usman and Mamman (2022) observed strong spatio-temporal variability of rainfall in North-Central Nigeria using dry-spell analysis, noting that rainfall events are becoming more fragmented and less associated with sustained mesoscale organisation. This provides a strong explanatory basis for the declining contribution of squall lines observed in both Jos and Makurdi.

Thunderstorms remain the dominant rainfall-producing system in both Jos (48.69%) and Makurdi (42.17%), but their proportional contribution shows a statistically significant decline in Jos and a non-significant decline in Makurdi. This suggests that while thunderstorms remain frequent, their relative importance in annual rainfall totals is decreasing due to increasing contributions from non-convective or mixed rainfall processes. This pattern aligns with findings from Dada (2019), who showed that convective systems in selected Nigerian cities are strongly influenced by local temperature maxima and atmospheric instability, but their rainfall efficiency varies significantly over time. The implication is that thunderstorms may be occurring under increasingly unstable but less moisture-organised atmospheric conditions, reducing their proportional rainfall contribution. Similarly, Omotosho (1985) reported that thunderstorms contribute substantially to rainfall in southern and central Nigeria, but their contribution varies widely depending on latitude and seasonal moisture flux. The current findings suggest that this latitudinal structure is now being modified by changing atmospheric conditions.

More recent regional studies further support this shift. Morrison et al. (2023) observed that rainfall in Nigeria is becoming more concentrated in fewer high-intensity events, even where overall rainfall totals remain relatively stable. This implies that thunderstorms are becoming more episodic and intense, but not necessarily more dominant in annual rainfall budgets. The declining proportional contribution of both squall lines and thunderstorms suggests a broader restructuring of rainfall systems in North-Central Nigeria. Rather than a reduction in rainfall generation, the results indicate a shift toward increased contributions from non-convective rainfall processes and mixed atmospheric systems.

This interpretation is strongly supported by rainfall variability studies across Nigeria. Morrison et al. (2023) demonstrated that rainfall variability in Nigeria is increasingly driven by atmospheric circulation anomalies rather than structured convective systems, with stronger interannual fluctuations in rainfall composition. Similarly, Usman et al. (2022) found that North-Central Nigeria is experiencing increasing dry spell intensity and irregular rainfall distribution, reflecting reduced persistence of organised convective rainfall systems. At a broader scale, rainfall distribution analysis by Ifeanyi et al. (2023) shows that rainfall in Nigeria has become more spatially heterogeneous, with increasing variability in seasonal rainfall distribution across the Guinea Savannah zone. This supports the observed instability in squall-line and thunderstorm contributions in both Jos and Makurdi.

These findings collectively suggest that rainfall systems are becoming less governed by classical mesoscale organisation and more influenced by transient atmospheric instability, moisture variability, and synoptic-scale circulation changes. The observed spatial differences between Jos and Makurdi reflect contrasting atmospheric and physiographic controls. Jos, due to its elevated terrain, enhances convective initiation but is also more sensitive to disruptions in moisture transport and atmospheric stability, leading to a more pronounced decline in organised convective rainfall contributions.

Makurdi, by contrast, lies within the Guinea Savannah transition zone, where rainfall systems are influenced by both maritime and continental air masses. This supports more sustained thunderstorm activity but reduces sensitivity to long-term structural change, explaining the weaker trend in thunderstorm contribution. Recent studies of West African rainfall dynamics (Omotosho, 1985) show that squall lines are strongly modulated by African Easterly Waves and West African Monsoon variability. Any weakening or increased irregularity in these systems directly affects squall-line organisation and longevity, which is consistent with the declining contributions observed in this study.

CONCLUSION AND RECOMMENDATIONS

The study concludes that thunderstorms and squall lines are the principal contributors to annual rainfall in the Middle Belt Region of Nigeria**,** accounting for a substantial proportion of rainfall in both Jos and Makurdi between 1995 and 2024. Thunderstorms contributed a larger share of annual rainfall than squall lines, highlighting their dominant role in regional rainfall generation. The findings further indicate a gradual decline in the percentage contribution of both rainfall systems, suggesting changes in rainfall dynamics within the region. While thunderstorms are projected to increase in intensity, squall-line rainfall is expected to decline in the future. These changes have important implications for flood management, agriculture, water resources, and climate adaptation planning in the Middle Belt Region of Nigeria.

The Nigerian Meteorological Agency (NiMet) should strengthen the monitoring and forecasting of thunderstorms and squall lines in the Middle Belt Region to improve rainfall prediction, early warning systems, and preparedness for weather-related hazards, while government agencies and planners should integrate the dominant contribution of thunderstorms and the changing role of squall lines into flood-risk management, agricultural planning, and water-resource development. Climate-smart agricultural practices should also be promoted to enhance farmers' resilience to increasing rainfall intensity, flooding, and soil erosion, while further research should investigate the long-term effects of climate change on thunderstorm and squall-line activities to support sustainable environmental management and development planning.

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 and Dr. Patricia Ali 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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