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Analysis Of Rainfall Variability And Its Causal Mechanisms In The Sudano-Sahelian Region Of Nigeria

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ABSTRACT
The Sudano-Sahelian region of Nigeria is bedeviled with frequent rainfall variability on inter-seasonal, inter-annual and inter-decadal time scales partly due to its latitudinal location and other causal mechanisms of rainfall variability such as the Inter-tropical Discontinuity (ITD), Sea Surface Temperature (SST) and El Nino Southern Oscillation (ENSO) episodes. This paper aimed at analyzing the dynamics of rainfall trend and variability in the study area. Monthly rainfall, raindays and dew point temperatures data for thirty years (1994-2023) were obtained from the Nigeria Meteorological Agency (NIMET). However, monthly ENSO and SSTs data were obtained from the National Oceanic Atmosphere Administration (NOAA) Climate Prediction Centre for the same period of study. The data were subjected to different statistical computations such as Mann- Kendall trend test, mean, standard deviation (SD) Coefficient of Variation (CV) and Multiple Linear Regression. The result of the study reveals that the Sudan region obtained above 50% of the annual mean rainfall and raindays, while the Sahel region obtained below 50% of these variables, which was attributed to the influence of ITD, and other climatic indices. Mann-Kendall test reveals a significant rainfall changes in different parts of the region.. The result of regression reveals that global temperature and oceanic indices (Nino 1+2, North Atlantic SST) are key drivers of rainfall variability in the Sudano-Sahelian region. The study recommends among other things, the encouragement on the adoption of drought-resistant crops in drying regions and flood-tolerant varieties in the wetter areas. Proper planning and mitigating strategies are needed to manage changing rainfall patterns effectively.
Keywords: Rainfall Trends, Rainfall Variability, Flood Warning System, Sea Surface Temperature, El-Nino Southern Oscillation, Sudano-Sahelian Region

INTRODUCTION

Sokoto State as a semi-arid belt within the Sudano-Sahelian region of Nigeria relies heavily on seasonal rainfall for agriculture and water resources. Interannual variability in precipitation is strongly influenced by ENSO, a climate phenomenon characterized by periodic warming (El Niño) and cooling (La Niña) of equatorial Pacific SSTs. While ENSO's global impacts are well-documented, its effects on Sokoto rainfall remain complex due to interactions with regional and global climatic drivers. This paper examines the mechanisms linking ENSO to Sokoto state rainfall anomalies, evaluates historical case studies, and discusses implications for climate resilience. ENSO's influence is modulated by SST anomalies in the Atlantic and Indian ceans. For example, warmer Atlantic SSTs during La Niña can amplify monsoon rains, while cooler Atlantic SSTs during El Niño exacerbate aridity. Climate models suggest that ENSO-

driven SST patterns explain ~30–50% of Sokoto rainfall variability, with additional contributions from land-atmosphere feedbacks. Sokoto State is part of the semi-arid region which lies between the Sahara Desert and the Sudanian savannah, is acutely vulnerable to rainfall uncertainty due to its climatic sensitivity and socio-economic reliance on rain-fed agriculture. Rainfall in this region is characterized by high temporal and spatial variability, compounded by climate change, which has intensified uncertainties in seasonal patterns, duration, and distribution. These fluctuations threaten food security, water availability, and livelihoods for millions of agro-pastoral communities, exacerbating risks of desertification, crop failure, and socio-economic instability.

Existing studies on rainfall trends in the region are often fragmented, out-dated, or insufficiently granular to capture localized variability and its socio-ecological impacts. Conflicting findings on historical trends (e.g., declining vs. erratic rainfall) and limited integration of recent climate data hinder the development of context-specific adaptation strategies.

LITERATURE REVIEW

The Intertropical Discontinuity

Recent research has shown that the area where the hot, dry northern air meets the cool, moist southern air is not merely a frontal zone or consistently convergent. Instead, it is characterized by a "Maximum Surface Moisture Gradient," indicating a humidity discontinuity (Adegun and Odunuga, 2022; Matawalli, 2021; Umar and Bako, 2019; Abaje et al., 2012). This region separates the hot, dry northern air, which may have negative dew points, from the cool, moist southern air, often with dew points above 21°C. The World Meteorological Organization (W.M.O.) uses the term "Inter Tropical Discontinuity" (ITD) to describe this moisture boundary on land. It has been suggested that the amount, seasonal distribution, type of rainfall, length of the rainy season, and overall weather conditions in the West African region are largely influenced by the ITD's position and associated weather zones (Odekunle, 2004).

The ITD moves inland up to 22-25°N in August, extending beyond Nigeria's northern border, but it does not move equatorward beyond 4°N during the Harmattan dry season (Olaniran, 2004). It reaches its northernmost position around 20-22°N in August and its southernmost position around 6-7°N in January/February (Ayoade, 2004). The ITD's northward movement in March marks the beginning of the rainy season, advancing gradually before becoming firmly established. Conversely, its southward retreat in September indicates the end of the rainy season. The ITD advances northward at a rate of about 160 km per month and retreats southward at approximately 360 km per month (Umar, 2006). However, the ITD moves north and south with the seasons following the sun. It moves north in the northern hemisphere summer and south in the northern hemisphere winter. Its seasonal migration causes wet and dry seasons in tropical regions. When the ITD moves closer to a region, it brings more precipitation, which leads to cloud formation and storms. The speed of the ITD's migration can affect West African rainfall patterns. A quick migration of ITD leads to an abnormally wet rainy season, while a slow migration can lead to an abnormally dry rainy season. It moves more prominently poleward over land than over water because water has a higher heat capacity than land. The ITD's precipitation is a significant climatic control in many tropical climate zones. Longer term changes in the ITD can lead to severe droughts or flooding. During both ITD advance and retreat, rainfall over Sokoto State is positively related to the ITD's latitude (Ibebuchi and Abu 2023, Umar 2023, Arijaje et-al 2022, Djossou et-al 2017, Emeribe et-al 2017, Odjugo 2015, Lele and Lamb 2010 Otun and Adewumi 2009).

3.0: MATERIALS AND METHODS

3.1: The Study Area

The Sudano-Sahelian region of Nigeria is situated between latitudes 10°15'58"N and 13°40'25"N and longitudes 3°34'18.4"E and 14°46'3"E. Encompassing approximately one-third of the nation's total land area (176,000 km²), it spans from the Sokoto plains in the northwest, across the northern high plains of Hausaland, to the Chad Basins (Odekunle and Eludoyin, 2008, Atidya et al, 2021).

3.2: The Climate of the Study Area

The climate of the Sudano-Sahelian region is governed by three key atmospheric systems: the tropical maritime (mT) and tropical continental (cT) air masses, along with the equatorial easterlies. The mT and cT air masses interact along a sloping boundary called the Inter-tropical Discontinuity (ITD), while the equatorial easterlies consist of cooler, variable air currents flowing eastward in the upper atmosphere near the ITD (Umar 2014, Umar and Bako 2019). The ITD's position shifts seasonally and can vary markedly over short timescales. During the peak of the rainy season (July–August), the ITD migrates northward, enabling the moisture-rich mT air mass to dominate the region. In contrast, from October to May, the ITD moves south, allowing the dry cT air mass to prevail, resulting in arid conditions. Annual rainfall in the region varies significantly, with the northeasternmost areas receiving less than 500 mm and the southern zones experiencing up to 1000 mm (Abaje et al,, 2010). Precipitation is concentrated primarily within a five-month window from May to September, with peak intensity occurring in July and August (Adeyefa &Odekunle 2022, Alhassan et al 2024). Spatially and temporally, rainfall patterns exhibit notable variability, with annual deviations ranging between 15% and 20% (Umar 2014, Umar & Bako 2019). This climatic unpredictability underscores the region's dynamic weather systems.

3.3: Vegetation of the Study Area

Ecologically, the Sudano-Sahelian region is defined by savanna landscapes, blending Sudan and Sahel vegetation zones. Tree density and plant cover gradually thin out from south to north, reflecting the transition from Sudan's wooded grasslands to the Sahel's sparse shrublands. These combined ecological and climatic zones form the distinct Sudano-Sahelian region (Atedhor & Odjugo 2012, Babatolu et al 2013, Bibi et al 2014).

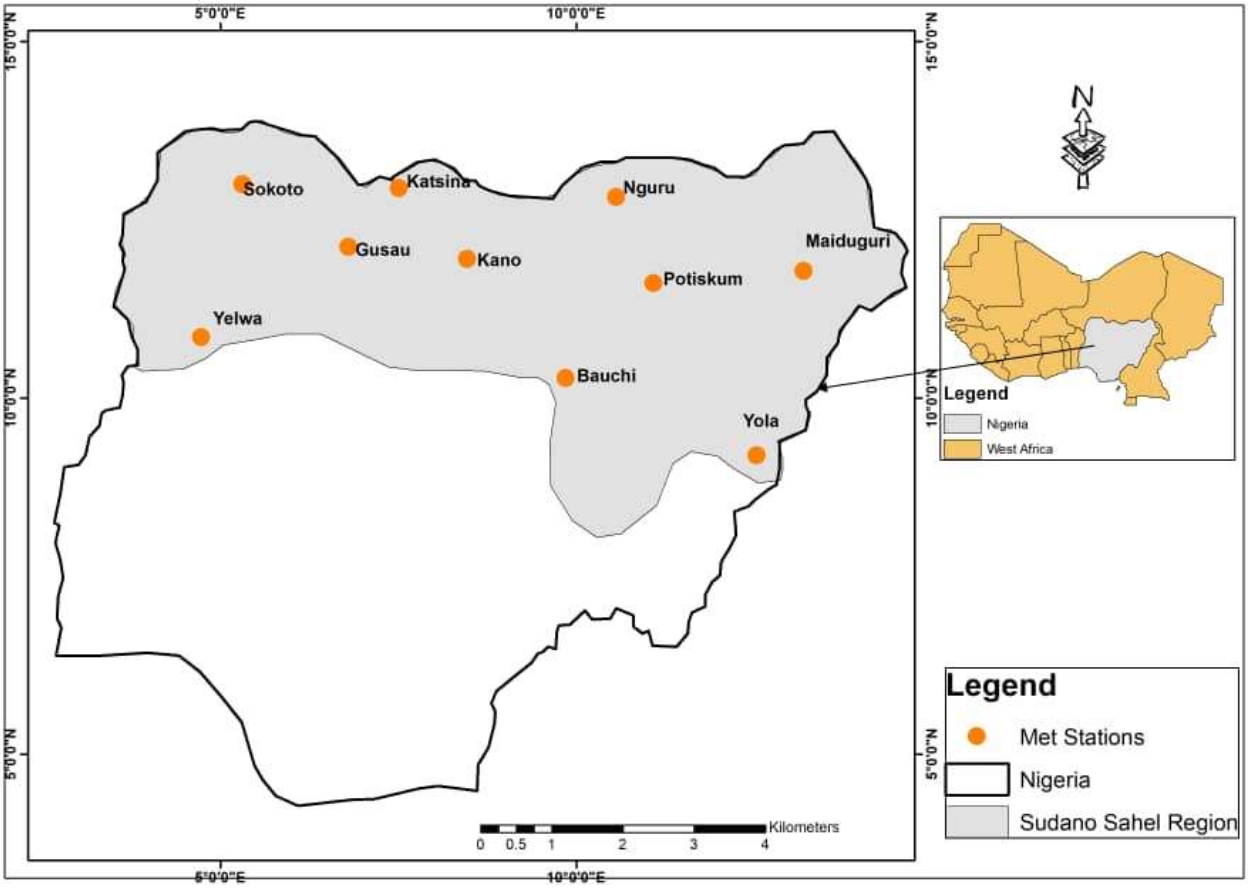

Figure 1: Meteorological Stations in the Sudano-Sahelian Region of Nigeria

3.4: Data Collection

The nature of the data required by this study was mainly the secondary sources which involved monthly rainfall, raindays and dew point temperature record from the Nigeria meteorological Agency (NIMET). The data was obtained from the afore-mentioned body for a period of three decades (1994-2023) equivalent to one complete climatic normal. The selection of thirty year period was based on the World Meteorological Organization (W.M.O.) standard to enable for calculation of climatic normal, whether of temperature or of precipitation (Umar,2014). However, monthly data on SSTs for the four Nino regions were obtained from the Climate Prediction Centre (CPC) covering:

- North Atlantic (Lat. 5-20^{0}North, Long. 60-30^{0}West),
- South Atlantic (Lat. 0-20^{0}South, Long. 30^{0}West-10^{0}East), and
- Global Tropics (Lat. 10^{0}South, 10^{0}North, Long. 0-360^0).

3.5: Data Analysis

The collected monthly rainfall and rain-days data were analyzed for trend analysis using Mann-Kendall tau test, by calculating the mean annual figure for each of the station in the study area in order to identify the long-term temporal trends and understand the direction and rate of changes in rainfall and rain-days patterns in the following categories:

- Rainfall trend for each state in the study area
- Rainfall trend for each state in the Sahel region (Lat. 10-11^{0}N)
- Rainfall trend for each state in the Sudan region (Lat. 12-13^{0}N)

The mean, standard deviation and coefficient of variation were also calculated for determining the extent of rainfall variability in the study area. The standard deviation formula is $\sigma = \sqrt{[\Sigma(x - \mu)^2 / N]}$, where σ is the population standard deviation, Σ is the sum, x is each data point, μ is the population mean, and N is the total number of data points. For a sample, the formula is $s = \sqrt{[\Sigma(x - \bar{x})^2 / (n - 1)]}$, where s is the sample standard deviation, $\bar{x}$ is the sample mean, and n is the sample size.

The standard formula for calculating the coefficient of variation is as follows: Coefficient of Variation (CV) = (Standard Deviation/Mean) × 100

Mann-Kendall (M-K) test is a non-parametric statistical test use to analyze trend in climatology and hydrologic time series mainly because it takes care of outliers in the very large values associated with climatology (Data 2015).

The Mann-Kendall test has two primary formulas: one for the S statistic and one for the Z statistic, which is a standardized version of S used for large sample sizes.

The S Statistic Formula

The S statistic quantifies the number of pairs of data points (x_i, x_j) where x_j is greater than x_i, for all $j > i$.$S = \sum \sum \text{sgn}(x_j - x_i)$ (for n-1 pairs) where: n is the total number of data points.

x_i and x_j are sequential data values, with $j > i$. sgn() is the sign function, which returns 1 if $(x_j - x_i)$ is positive, -1 if it's negative, and 0 if it's zero.

The Z Statistic Formula

For larger sample sizes, the S statistic is converted into a standardized normal test statistic, ZMK, using the following formula: $ZMK = S - 1 / \sqrt{VAR(S)}$ (if $S > 0$) $ZMK = 0$ (if $S = 0$) $ZMK = S + 1 / \sqrt{VAR(S)}$ (if $S < 0$)

where:

VAR(S) is the variance of S, which accounts for ties in the data.

VAR(S) has a complex formula that includes the number of tied groups (p) and the size of each tied group (q_k).

What the Formulas Mean

A positive value of S (and therefore ZMK) indicates an upward trend in the data.

A negative value of S (and therefore ZMK) indicates a downward trend.

A value of S or ZMK equal to zero indicates no trend.

A very high positive value of S shows that there is an increase trend while the very low negative value is an indicator of a decreasing trend.

The Multiple Linear Regression Model was employed to determine the relationship between the rainfall and the three causal mechanisms for rainfall variability in the study area. It is a statistical technique that uses several explanatory variables to predict the outcome of a response variable. It is used to predict the occurrence of a variable, trend or value based on the value of two or more variables; determine the relationship between two or more variables; and understand how one variable changes when another changes (Data 2012, Jäntschi et al 2015, Darlington & Hayes 2016,). But for the purpose of this study, multiple linear regression was applied to determine the relationship between the dependent variables which are the annual and annual rainfall data for each station in the study area denoted as y-variables and the independent variables which are mean monthly records of Nino 1+2, Nino 3, Nino 3.4, Nino 4, North Atlantic SST, South Atlantic SST, Global SST and Dew Point Temperature values denoted as x-variables. The formula for multiple linear regression is $Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + ... + \beta_pX_p + \varepsilon$, where Y is the dependent variable, X_1, X_2, ..., X_p are the independent variables, β_0 is the intercept, β_1, β_2, ..., β_p are the slope coefficients for each independent variable, and ε is the error term. This equation represents the linear relationship between one dependent variable and multiple independent variables, allowing you to predict Y based on the values of the X variables.

Components of the Formula

Y: The predicted or expected value of the dependent variable.

β_0 (Beta-zero): The y-intercept, which is the value of Y when all independent variables (X_1, X_2, etc.) are equal to zero.

β_1, β_2, ..., β_p (Beta-one, Beta-two, etc.): These are the regression coefficients (slopes).

Each coefficient (β_1) represents the change in the dependent variable (Y) for a one-unit increase in its corresponding independent variable (X_1).

X_1, X_2, ..., X_p: These are the independent or predictor variables.

ε (Epsilon): The error term, also known as the residuals. It accounts for the variability in the dependent variable that is not explained by the independent variables in the model.

4.0: RESULTS

4.1: Rainfall Variability

The mean annual rainfall and raindays for each station for thirty-year period of study were computed and presented in the table 1 below.

Table 2: Mean Annual Rainfall and Raindays for the Ten Stations

S/No	Station	Rainfall	Raindays
1	Bauchi	1,287.0	67.9
2	Gusau	927.2	64.1
3	Kano	1,095.7	52.2
4	Katsina	607.4	44.6
5	Maiduguri	761.4	45.5
6	Nguru	524.6	33.4
7	Potiskum	688.5	49.1
8	Sokoto	741.5	49.8
9	Yelwa	1.104.8	70.9
10	Yola	871.3	68.9

In the table 2 above, Bauchi station has the highest mean annual rainfall record (1,287mm), followed by Yelwa (1,104.8mm) and Kano (1,095.7mm). On the other hand, Yelwa recorded the highest mean annual raindays (70.9), followed by Yola 968.9) and then Bauchi (67.9) as the third station. From this result, it can be seen vividly that rainfall and raindays records do not always correlate with each other, since Bauchi with the highest rainfall did not record highest raindays. The tables 3 and 4 below however, reveal the results of standard deviation and coefficient of variation for each station in the study area for both rainfall and raindays records. For rainfall SD, Bauchi, Kano, Yelwa and Gusau have the highest values, while Nguru and Katsina have the lowest values; but for CV record, Nguru, Maiduguri, Katsina and Potiskum have the highest values. The same trend applies to mean annual raindays records in table 4. The figures 2 and 3 below also depict this result diagrammatically.

Table 3: Mean Annual Rainfall, Standard Deviation and Coefficient of Variation (1994-2023)

Station	Mean Annual Rainfall	SD (in mm)	CV (in %)
Bauchi	1287	137.8	10.71
Gusau	927.2	101.3	10.93
Kano	1095.7	131.3	11.98.
Katsina	607.4	73.8	12.15
Maiduguri	761.4	94.0	12.35
Nguru	524.6	71.1	13.55
Potiskum	688.5	82.7	12.01
Sokoto	741.5	87.1	11.75
Yelwa	1104.8	108.0	9.78.
Yola	871.3	82.3	9.45

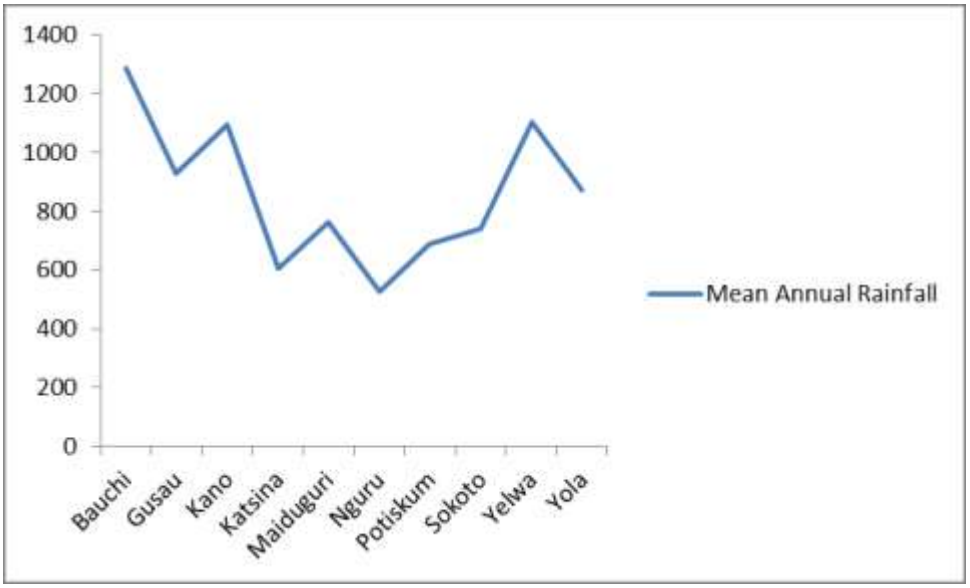

Figure 2: Mean Annual Rainfall for Ten Stations for Thirty Years (1994-2023)

From table 3 above, it can be seen that Bauchi station records mean annual rainfall of 1287 mm per year, while Nguru averaged only 524.6 mm per year. SD (Standard Deviation) (in mm) measures how much the annual rainfall typically varied from the long-term average (mean). A higher SD means the year-to-year rainfall amounts were more spread out (more variable). Also, Bauchi's rainfall varied by about ±137.8 mm from its average (1287 mm). Nguru's varied by ±71.1 mm from its average (524.6 mm). While Nguru's SD is lower, its relative variability is much higher. CV (Coefficient of Variation) (in %) is the key indicator of rainfall reliability or predictability. It shows the size of the variation relative to the average. A higher CV % means rainfall is more variable and less predictable year-to-year relative to its average. A lower CV % means rainfall is more consistent and predictable year-to-year relative to its average. Yola (CV = 9.45%) has relatively more consistent rainfall from year to year compared to its average than Nguru (CV = 13.55%), which has highly erratic rainfall relative to its much lower average.

Table 4: Mean Annual Raindays, Standard Deviation and Coefficient of Variation (1994-2023)

Station	Mean Annual Rain Days	SD (in mm)	CV (in %)
Bauchi	67.9	6.2	9.13
Gusau	64.1	6.2	9.67
Kano	52.2	5.5	10.54
Katsina	44.6	4.9	10.99
Maiduguri	45.5	4.8	10.55
Nguru	33.4	3.9	11.68
Potiskum	49.1	5.2	10.60
Sokoto	49.8	5.0	10.04
Yelwa	70.9	6.2	8.74
Yola	68.9	5.7	8.27

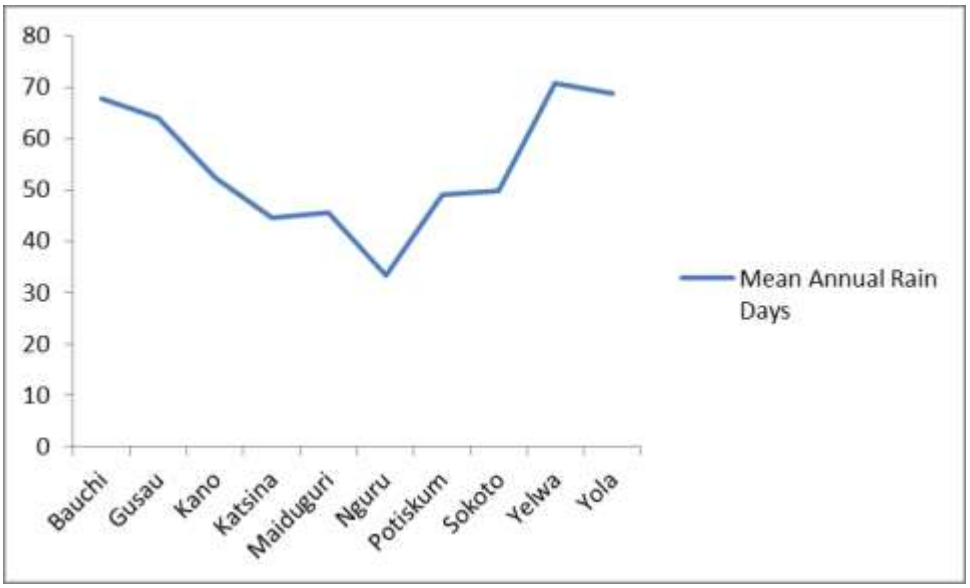

Figure 3: Mean Annual Raindays for Ten Stations for Thirty Years (1994-2023)

From table 4 above, Bauchi's SD is 6.2 days. This means in many years, the actual number of rainy days was about 6.2 days higher or lower than its average of 67.9 days. Bauchi's CV is 109.8%. This means the typical year-to-year variation (±6.2 days) is equivalent to 109.8% of its average (67.9 days), indicating relatively high variability. Yelwa has the highest average annual rain days (70.9), followed closely by Yola (68.9) and Bauchi (67.9). Nguru has the lowest average (33.4 days), followed by Katsina (44.6) and Maiduguri (45.5). This shows a general gradient, with stations further south (like Yelwa, Yola, Bauchi, and Gusau) having more frequent rainy days on average than those further north/northeast (like Nguru, Katsina, and Maiduguri).

Absolute Variability (SD):

The SD values across stations ranges from 3.9 days (Nguru) to 6.2 days (Bauchi, Gusau, and Yelwa). Stations with higher *average* rain days generally have slightly higher SDs. This is common as there's more "scope" for variation around a larger mean. The CV values range from 8.27% (Yola) to 11.68% (Nguru).

Relationship between Rainfall and Raindays

Higher rainfall does not always correlate with higher raindays. For example, Yelwa has the highest number of raindays but does not have the highest annual rainfall. Bauchi has the highest annual rainfall but slightly fewer raindays suggesting that rainfall intensity per rain event is higher in Bauchi than in Yelwa. Nguru and Katsina, with the lowest raindays, also record the lowest annual rainfall, confirming their semi-arid nature.

Agricultural Implications:

Bauchi, Yelwa, and Yola stations are more favorable for crop farming (maize, rice, vegetables, and tubers) due to sufficient rainfall. Kano, Sokoto, and Maiduguri stations with moderate rainfall allow for mixed farming (grains, legumes, and livestock rearing). Katsina, Nguru, and Potiskum stations require irrigation-based agriculture due to low and erratic rainfall.

Water Resource Management:

Higher rainfall zones (e.g. Bauchi and Yelwa) may have better water availability for domestic, industrial, and irrigation use. Lower rainfall zones (e.g. Nguru and Katsina) require rainwater harvesting, boreholes, and reservoir construction to ensure water security.

Drought and Flood Risks:

Drought-Prone Areas: Nguru, Katsina, Maiduguri, and Potiskum are prone to drought due to their low rainfall record and therefore require climate adaptation measures like drought-resistant crops and efficient irrigation systems. Flood-Prone Areas: Bauchi, Yelwa, and Yola, with high rainfall may be at risk of seasonal flooding, requiring flood control measures like drainage systems and embankments.

Table 5: Mean Annual Rainfall for Regions in the Study Area

Region	Annual Rainfall for the Region	Mean for the Region	Standard Deviation	Coefficient of Variation
Sudan	4694.0	938.8	100.9	10.75
Sahel	3882.3	776.5	92.9	11.96
Sudano-Sahelian	8576.4	857.6	96.9	11.30

From table 5 above, the *total* rainfall recorded across *all* measurement stations in that region stands as 8576.4mm (Sudano-Sahelian). The standard deviation measures how much variation exists from the mean. A higher number means rainfall amounts are more spread out (some stations have much wetter/drier than the average). The Coefficient of Variation (CV) expresses variability *relative* to the mean. Higher CV means greater relative variability/unpredictability of year-to-year variation.

Sahel Region (Extreme North) including Sokoto, Gusau, Kano, Katsina and Nguru stations are the driest region with the lowest mean rainfall (776.5 mm). The region's highest CV (11.96%) indicates the *greatest relative year-to-year variability* in rainfall. This translates to frequent droughts and occasional floods. The low Mean (776.5 mm) reflects its aridity. The high Standard Deviation (92.9 mm) and highest CV (11.96%) highlight its climatic instability. Rainfall is highly unpredictable, posing significant challenges for rain-fed agriculture and water resources.

Table 6: Mean Annual Raindays for Regions in the Study Area

Region	Annual Raindays for the Region	Mean for the Region	Standard Deviation	Coefficient of Variation
Sudan	302.3	60.5	5.6	9.26
Sahel	243.6	48.6	5.1	10.49
Sudano-Sahelian	545.4	54.5	5.5	10.09

From the table 4 above, the raindays mean value for all the stations stands as (54.5 days) .This value represents the average number of days in a year when measurable rainfall (typically >0.1mm or >0.2mm) occurs at locations *within* the Sudano-Sahelian region of the study area. Residents and agricultural activities in Sudano-Sahelian zone can *expect* roughly 55 days of rain per year, on average, over the long term. These figures are the sum of the "Annual Raindays" for the Sudan (302.3) and Sahel (243.6) regions listed above it (302.3 + 243.6 = 545.9, close enough to 545.4. The Sudano-Sahelian region represents a combined zone encompassing both the Sudan and Sahel regions within the study area. The standard deviation measures how much the actual annual raindays typically vary from the long-term mean (54.5 days). A value of 5.5 days indicates moderate year-to-year variability. In roughly 68% of years, the actual number of raindays in the Sudano-Sahelian zone will fall between 49.0 and 60.0 days (54.5 ± 5.5). In about 95% of years, it will fall between 43.5 and 65.5 days (54.5 ± 11.0). This variability is significant for rain-fed agriculture and water resource planning. Farmers must be prepared for seasons that might have ~10 days less or more rain than average. Relative Variability (Coefficient of Variation = 10.09%): The CV expresses the standard deviation (5.5) as a percentage of the mean (54.5). It allows comparison of variability between regions with different mean values.

Comparison:
Sudan (Wetter)**:** CV = 9.26% (Lower relative variability)
Sahel (Drier)**:** CV = 10.49% (Higher relative variability)
Sudano-Sahelian**:** CV = 10.09% (Intermediate relative variability)
Significance for Nigeria**:** The Sudano-Sahelian region exhibits moderate to high relative variability in annual raindays compared to the wetter Sudan region but slightly less than the drier Sahel. This reflects its transitional nature, where rainfall is inherently less predictable than in the consistently wetter south but slightly more reliable than in the consistently drier north.

4.3: Relationship of ENSO and SST to Rainfall Variability in the Study Area

The summary of multiple linear regression results for each of the ten stations which indicate the relation of ENSO and SST to rainfall variability in the study area were presented in tables 9-18 below. In table 9 for instance, it reveals that only the global tropical shows a significant positive relationship with rainfall in Bauchi station, while Nino 1+2 and North Atlantic have negative relationship with rainfall in Bauchi but not significant. The rest of the five variables indicate no relationship. This trend applies to all the remaining nine stations.

Table 9: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Bauchi

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	-12340.583	7588.890		-1.626	.119
NINO 1+2	-682.888	272.577	-1.688	-2.505	.021
NINO 3	1031.202	889.248	1.793	1.160	.259
NINO 3.4	-298.428	947.574	-.503	-.315	.756
NINO 4	-695.099	615.191	-1.040	-1.130	.271
North Atl.	-453.281	237.886	-.436	-1.905	.071
South Atl.	-232.972	410.979	-.178	-.567	.577
Global	1765.671	831.620	1.309	2.123	.046
DP TEMP	-30.508	32.481	-.170	-.939	.358

a. Dependent Variable: Annual Rainfall

Table 10: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Gusau

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	-3449.814	4806.774		-.718	.481
NINO 1+2	37.865	167.446	.166	.226	.823
NINO 3	-772.123	542.768	-2.382	-1.423	.170
NINO 3.4	1253.846	573.320	3.747	2.187	.040
NINO 4	-768.993	379.143	-2.041	-2.028	.055
North Atl.	-342.020	146.642	-.583	-2.332	.030
South Atl.	411.330	255.143	.558	1.612	.122
Global	386.837	511.650	.509	.756	.458
DP TEMP	-18.737	22.318	-.180	-.840	.411

b. Dependent Variable: Annual Rainfall

Table 11: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Kano

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	17474.186	6956.272		2.512	.020
NINO 1+2	-228.214	260.332	-.612	-.877	.391
NINO 3	1145.774	837.471	2.161	1.368	.186
NINO 3.4	-831.783	884.015	-1.520	-.941	.357
NINO 4	-148.958	593.197	-.242	-.251	.804
North Atl.	184.076	225.972	.192	.815	.424
South Atl.	-479.955	381.106	-.398	-1.259	.222
Global	-263.958	792.027	-.212	-.333	.742
DP TEMP	18.820	49.358	.075	.381	.707

c. Dependent Variable: Annual Rainfall

Table 12: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Katsina

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	-12394.981	4043.012		-3.066	.006
NINO 1+2	-200.440	143.827	-.956	-1.394	.178
NINO 3	410.877	455.026	1.379	.903	.377
NINO 3.4	-306.411	463.772	-.996	-.661	.516
NINO 4	164.382	300.796	.475	.546	.590
North Atl.	314.683	119.342	.584	2.637	.015
South Atl.	15.926	198.955	.024	.080	.937
Global	65.432	413.149	.094	.158	.876
DP TEMP	-8.155	18.987	-.089	-.429	.672

d. Dependent Variable: Annual Rainfall

Table 13: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Maiduguri

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	-14254.995	4444.521		-3.207	.004
NINO 1+2	-40.247	177.712	-.136	-.226	.823
NINO 3	-596.386	569.708	-1.413	-1.047	.307
NINO 3.4	205.649	604.915	.472	.340	.737
NINO 4	-364.893	402.277	-.744	-.907	.375
North Atl.	-159.762	153.682	-.209	-1.040	.310
South Atl.	-413.533	269.492	-.431	-1.534	.140
Global	1814.468	544.078	1.833	3.335	.003
DP TEMP	40.627	28.828	.216	1.409	.173

e. Dependent Variable: Annual Rainfall

Table 14: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Nguru

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	-10636.000	4323.448		-2.460	.023
NINO 1+2	55.309	184.303	.229	.300	.767
NINO 3	-600.538	563.689	-1.749	-1.065	.299
NINO 3.4	205.222	573.511	.579	.358	.724
NINO 4	-275.686	393.033	-.691	-.701	.491
North Atl.	-369.022	156.475	-.594	-2.358	.028
South Atl.	-455.876	245.688	-.584	-1.856	.078
Global	1765.352	511.319	2.193	3.453	.002
DP TEMP	6.785	34.168	.040	.199	.844

f. Dependent Variable: Annual Rainfall

Table 15: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Potiskum

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	3132.886	3965.914		.790	.438
NINO 1+2	-84.393	124.525	-.576	-.678	.505
NINO 3	52.938	403.692	.254	.131	.897
NINO 3.4	115.837	425.378	.539	.272	.788
NINO 4	-292.449	280.013	-1.209	-1.044	.308
North Atl.	-69.688	109.946	-.185	-.634	.533
South Atl.	-256.488	189.035	-.542	-1.357	.189
Global	412.723	386.045	.846	1.069	.297
DP TEMP	19.799	18.786	.286	1.054	.304

g. Dependent Variable: Annual Rainfall

Table 16: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Sokoto

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	-5362.042	4433.675		-1.209	.240
NINO 1+2	-426.650	183.166	-1.740	-2.329	.030
NINO 3	635.682	579.751	1.824	1.096	.285
NINO 3.4	419.572	594.928	1.166	.705	.488
NINO 4	-785.999	394.172	-1.940	-1.994	.059
North Atl.	50.358	152.433	.080	.330	.744
South Atl.	130.541	259.320	.165	.503	.620
Global	187.883	529.524	.230	.355	.726
DP TEMP	54.384	23.010	.443	2.363	.028

h. Dependent Variable: Annual Rainfall

Table 17: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Yelwa

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	4549.585	5268.938		.863	.398
NINO 1+2	-.836	220.959	-.003	-.004	.997
NINO 3	2.846	711.744	.008	.004	.997
NINO 3.4	-.392	722.823	-.001	-.001	1.000
NINO 4	30.365	477.710	.075	.064	.950
North Atl.	-212.302	189.622	-.336	-1.120	.276
South Atl.	316.984	324.780	.399	.976	.340
Global	-242.976	693.274	-.296	-.350	.729
DP TEMP	11.548	24.663	.111	.468	.644

i. Dependent Variable: Annual Rainfall

Table 18: Summary of the Multiple Linear Regression between Annual Rainfall and Predictors for Yola

Coefficients

Model	Unstandardized Coefficient B	Std. Error	Standardized Coefficient Beta	T	Sig.
1 (Constant)	2961.781	3807.511		.778	.445
NINO 1+2	294.762	147.880	1.446	1.993	.059
NINO 3	-807.159	481.662	-2.786	-1.676	.109
NINO 3.4	196.728	516.307	.658	.381	.707
NINO 4	248.417	336.372	.738	.739	.468
North Atl.	-200.337	132.033	-.382	-1.517	.144
South Atl.	-143.473	217.686	-.218	-.659	.517
Global	283.541	451.755	.417	.628	.537
DP TEMP	41.768	18.491	.430	2.259	.035

j. Dependent Variable: Annual Rainfall

4.4: DISCUSSION

From the results of both Mann-Kendall and Multiple Linear Regression explained earlier, there is strong evidence that the mean annual rainfall decreases significantly from south (Bauchi: 1287 mm, Yelwa: 1104.8 mm) to north (Nguru: 524.6 mm, Katsina: 607.4 mm). This reflects the transition from the wetter Sudan Savanna to the drier Sahel Savanna. This is in line with the outcome of Olaniran and Sumner (1989), which in their study of climate variability in Nigeria based on the onset, retreat and length of the rainy season found out that there was a progressive early decline of rainfall over the country. All stations with exception of Yelwa and Yola have very high CV values (>10%), indicating high year-to-year rainfall variability as the norm across this entire region of Nigeria. Droughts and very wet years are common occurrences.

The driest stations (Nguru, Katsina, Potiskum and Maiduguri) generally have the highest CV values. Nguru (524.6 mm average, CV 13.55%) has the most unreliable rainfall relative to its average. The result has supported the findings of Abaje et al (2012), who in their study of recent trends and fluctuations of annual rainfall in the Sudano-Sahelian Ecological Zone of Nigeria: Risks and Opportunities revealed that Nguru and Katsina were significantly drier than the long-term mean. The outcome of this study also supported the findings of Emeribe et al (2017) in their study of inter-decadal nature of rainfall character in Sudano-Sahel, north-west, Nigeria which revealed that there is significant decrease in the annual rainfall in the region from late 1980 onwards. Also, Mamman et al (2018), who conducted the analysis of rainfall

variation over northern parts of Nigeria attributed that Nguru recorded the lowest amount of rainfall (470.2mm) over the years, and also has the minimum rainfall variability with 12% CV. It also supported the findings of Sidi (2022), who in his study of rainfall found out that the CV for the annual rainfall in Nguru revealed a moderate inter-annual variability (25%) which indicated a considerable and high variability in total rainfall received. This is characteristic of semi-arid and Sahelian climates where rainfall is often concentrated in a few intense events. This is however corroborated by Tano et al (2023) findings, that the long-term variability of rainfall is characterized by a decrease in the amount of rainfall all over West African Countries.

The wetter stations (Yelwa, Bauchi, and Yola) generally have the lowest CV values (though still very high by global standards). Yola (871.3 mm average CV 9.45%) and Yelwa (1104.8 mm average, CV 9.78%) have the most predictable rainfall within this highly variable region. This however corroborated the findings of Atedhor (2014) in his study of the growing season rainfall trends and drought intensities in the Sudano-Sahelian region of Nigeria which indicated downward trends of growing season rainfall in all the synoptic stations investigated in the study area with the exception of Kano which showed positive. It also supported the findings of Otun and Adewumi (2009) which in their study of rainfall variability and drought inference in Sudano-Sahelian region of Nigeria that there was temporal variability in the amount and distribution of rainfall and number of rain days in the study area.

For the multiple linear regression result, the explanatory power and significance of the regression models vary drastically across the ten stations. Only Katsina and Maiduguri showed statistically significant overall models. Bauchi, Gusau, Nguru, Sokoto, and Yola had significant individual predictors despite non-significant overall models. Kano, Potiskum, and Yelwa showed no significant predictors. The result of this study confirmed the findings of Hashidu and Badaru (2021) in their study of the relationship between ENSO and rainfall in the Sudano-Sahelian of Northern Nigeria which revealed significant relationship for Potiskum, Maiduguri and Katsina with CV of 0.25, 0.26 and 0.27 respectively while Kano, Gusau, Nguru and Sokoto and show no significant relationship.

For Dominant Predictors, the Global SST emerged as a significant positive driver in Bauchi, Maiduguri, and Nguru. Showed positive trends elsewhere (Potiskum, Yelwa) but not always significant. Nino 1+2 has significant negative effect in Bauchi and Sokoto. Near-significant positive in Yola, effects are location-dependent. Nino 3.4: Significant positive effect only in Gusau. North Atlantic SST: Significant negative effects in Gusau and Nguru, but a significant positive effect in Katsina. Near-significant negative in Bauchi, effects are complex and location-specific. Dew Point Temperature: Significant positive effects in Sokoto and Yola. Nino 4: Near-significant negative effects in Gusau and Sokoto. South Atlantic SST: Near-significant positive effect in Nguru. No single climate index was a consistently significant predictor across all or even most stations. The influence of ENSO (Nino) regions and Atlantic SSTs is highly localized within the Sudano-Sahelian region of Nigeria. Only Katsina and Maiduguri had statistically significant overall regression models ($p < 0.05$), indicating a reliable combined effect of the predictors for these stations. All other stations lacked overall model significance. Despite often lacking overall model significance, several individual predictors showed statistically significant effects at specific stations. The result of this study supported the findings of Umar and Kehinde (2020) in their study of the relationship El Nino Southern oscillation to rainfall patterns in Nigeria, which revealed that annual rainfall totals, growing season rainfall and annual raindays series exhibited a downward trend at most of the stations over the period of the study.

Nino 1+2: Significant negative impact in Bauchi and Sokoto; borderline positive in Yola.

Nino 3.4: Significant positive impact in Gusau.

Nino 4: Borderline negative impact in Gusau and Sokoto.

North Atlantic SST: Significant negative impact in Gusau; significant positive impact in Katsina; borderline negative in Nguru.

Global SST/Temperature: Significant positive impact in Bauchi, Maiduguri, and Nguru.

Dew Point Temperature: Significant positive impact in Sokoto and Yola.

The same predictor (e.g., North Atlantic SST) can have opposite effects (negative vs. positive) at different stations, highlighting regional variability. Many stations (especially Kano, Potiskum, Yelwa) showed very weak models with no significant predictors and/or poor explanatory power (low Adjusted R^2). This indicates the selected climate indices alone are insufficient to reliably predict annual rainfall at these locations. However, the threshold for ITD Proximity is determined when dew point temperature (DP Temp) is ≤15°C and suggests that the ITD is near or slightly north of a location, as lower dew points indicate drier air (typical of the Harmattan from the Sahara) rather than moist maritime air from the south. The Intertropical Discontinuity (ITD) marks the boundary between moist maritime air (high dew point) and dry continental air (low dew point). Years with higher DP TEMP (e.g., 2020: 13.28°C, 847.1 mm) often align with higher rainfall, supporting the link between northerly ITD positions and wetter conditions.

Exceptions (e.g., 2007: 13.9°C, 589.1 mm) highlight other factors (e.g., convective activity, monsoon duration) that modulate rainfall beyond ITD position alone. The rainfall trends when ITD is over Bauchi station indicates two categories of years; the higher rainfall years: 1996 (991.6 mm), 1999 (1121.3 mm), 2000 (950.9 mm), 2013 (1772.9 mm) and the lower rainfall years: 2005 (429.8 mm), 1997 (809 mm). This suggests that while the ITD's presence (DP Temp ≥ 15°C) generally increases rainfall, other factors (e.g., SSTs, and ENSO) also influence totals. The ITD is most likely positioned over Bauchi when dew point temperatures reach ≥15°C, which corresponds to peak monsoon months (June–September). Years with DP Temp ≥ 15°C generally had above-average rainfall, except in cases like 2005 (drought influence). 2013 had the highest rainfall (1772.9 mm) with DP Temp at 15.58°C, indicating strong ITD influence. 2005 had very low rainfall (429.8 mm) despite DP Temp ≥15°C, possibly due to suppressed convection or dry spells.

4.5: CONCLUSION

This study has critically analyzed the dynamics of rainfall trends and variability in the Sudano-Sahelian region of Nigeria for thirty-year period (1994-2023) by obtaining monthly data on three climate variables-rainfall, raindays and dew point temperature from the archives of the Nigerian Meteorological Agency (NiMET) and subjecting it to different statistical techniques ranging from means, percentages, standard deviation, coefficient of variation, Mann-Kendall test, and Multiple Linear Regression. Monthly Nino Indices, North Atlantic, South Atlantic and Global Sea Surface Temperature (SST) values were also obtained from Climate Prediction Centre (CPC) for the same period and subjected to multiple linear regression analysis for determining the relationship between the three rainfall variables (as dependent variables) and the Nino SST values (as independent variables). The results indicate that the SD values are relatively similar across stations, ranging from 3.9 days to 6.2 days Stations with higher *average* rain days generally have slightly higher SDs. The CV values are remarkably high across *all* stations, ranging from 9.45% to 13.55%. Values consistently above 100% signal exceptionally high year-to-year variability in the number of rainy days. The dominant Predictors for Multiple Linear Regression Model revealed that the Global SST emerged as a significant positive driver in Bauchi, Maiduguri, and Nguru.

The analysis of the Intertropical Discontinuity (ITD) across ten meteorological stations in Sudan and Sahelian regions underscores the complex interplay between dew point temperature (DP Temp ≥15°C), ITD positioning, and rainfall variability. Key findings include ITD Threshold Utility: The 15°C DP Temp threshold reliably indicates ITD presence at northern stations (e.g., Kano, Sokoto, Yola), correlating with higher rainfall. However, moisture alone is insufficient for rain (e.g., Gusau), as atmospheric dynamics like monsoon surges, squall lines, or aerosol effects modulate outcomes. Regional disparities for Northern stations (Kano, Sokoto) show recent northward ITD shifts linked to monsoon expansion, while southern Sahelian stations (Nguru, Potiskum) remain outside the ITD's typical reach, relying on localized convection. Climate trends shows Post-2018 northward ITD shifts in Sokoto contrast with aridification trends in Kano, highlighting dynamic regional responses to climate change.

4.6: RECOMMENDATIONS

Based on the outcome of the computed results discussed in the previous discussion, the following recommendations are put forward:

1. There should be an improved drainage systems, flood control infrastructure, and urban planning to mitigate flood risks in flood-prone areas like Yola and Yelwa.
2. There should be an enhanced water conservation practices, promote rainwater harvesting, and develop efficient irrigation systems to counter water scarcity in drought-prone areas like Kano and Katsina.
3. Governments at all levels should encourage the adoption of drought-resistant crops in drying regions and flood-tolerant varieties in wetter areas.
4. Further researches should be conducted into localized impacts of ENSO events to refine predictive models and better anticipate future changes.
5. Promote agro-climatic advisories tailored to ITD-influenced zones, emphasizing planting cycles aligned with monsoon surges.

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