Assessing the Relationships between Weather Variables and Heavy Rainfall in the Guinea Savanna Ecological Zone of Nigeria

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Abstract

Heavy rainfall is a feature of rainfall in Nigeria. Hence this research aimed at assessing the relationships between weather variables such as thunderstorms (TSs), relative humidity (RH), wind direction as well as wind speed (predictors) and heavy rainfall (predictant) in the Guinea Savanna Ecological Zone of Nigeria (GSEZN). Daily data on the predictors and the predictant from 1981 to 2015 (35 years) were sourced from the Nigerian Meteorological Agency (NiMet), Oshodi, Lagos and used for the research. The objectives of the study were to determine the compatibility of weather variables in running multiple linear regression and to assess the relationships between weather variables and heavy rainfall. The correlation matrix and Multiple Linear Regression (MLR) were used to analyse the data. Results showed that temperature and relative humidity have strong negative relationship, hence not compatible in running MLR, while relative humidity as well as other predictants are compatible in running MLR and that TSs have the strongest relationship with heavy rainfall over the study area. Recommendations focused on the monitoring and forecasting of TSs and heavy rainfall.
Key words: Rainfall, heavy rainfall, thunderstorms, relative humidity, wind

Introduction

Rain is the major type of precipitation in Nigeria and it varies over time as well as space in the nature of occurrence, time, amount, duration, intensity and general distribution. Chup (2005) opined that rain is one type of precipitation and it connotes water droplets with a radius of 0.5–7 mm which are associated mostly with convective clouds. Gitau and Ogallo (2008) opined that, rainfall is the most important climate variable over Nigeria, yet it shows the highest disparity in both space and time. This disparity is observed in either the intensity of rainfall or distribution of these amounts or both. Audu *et al*. (2020) observed that rainfall peaks occur in cycles across Nigeria. Syed *et al.* (2004) cited in Harris *et al.* (2007) observed that 70%-80% of the disparity noted in the terrestrial water cycle is attributed to rainfall. This was corroborated by Abubakar (2015) who opined that rainfall displays an important role in the water cycle. So, for water cycle to be functional and sustainable, rainfall is essential.

In Nigeria, rain onset, cessation, amount, duration, frequency, intensity and other general attributes are usually propelled by the interaction of almost all the meteorological variables and convective features such as inter tropical discontinuity (ITD), maximum gust, cloud top temperature and waves especially the African Easterly Jet (AEJ), thunderstorms (TSs) and squall lines. A TS also known as an electrical storm, a lightning storm or a thundershower is a type of storm characterised by the presence of lightning and its acoustic effect on the earth's atmosphere known as thunder (Salahu, 2017). Thunderstorms occur in association with cumulonimbus and are usually accompanied by strong winds, heavy rain and sometimes snow, sleet, hail or in contrast, no rain. Several definitions have been given about TS ranging from being a convective storm that is accompanied by lightening, thunder and other variety of weather such as local heavy shower, hails, gusty wind, sudden temperature change and occasionally tornadoes (Ochei *et al.*, 2015). TSs are common feature of rainfall in Nigeria.

Heavy rainfall seems to have more spontaneous effects on the environment directly and on man indirectly hence the need to study the weather variables that have relationships with it. Heavy rainfall is expected in Nigeria because of global warming, climate variability and climate change (Audu *et al.*, 2014). Climate change is a major environmental problem which has gained a universal discourse in recent times. In the view of Yahaya *et al.* (2011), climate change is a change in the statistical distribution of weather over periods that range from decades to millions of years. Umar (2012) confirmed climate change in Nigeria with its attendant heavy rainfall in northern Nigeria mostly in the midland and Sahel. This midland corresponds with the Guinea Savanna Ecological Zone of Nigeria (GSEZN).

In the tropics with particular reference to Nigeria, extreme weather events such as heavy rainfall, lighting, thunderstorms (TSs), heat waves, dry spells, droughts, windstorm, rainstorm, gusts, hailstorm and alteration of the general weather system are becoming regular features of weather (Audu *et al.*, 2013a; Nnoli and Ogundeji, 2013; Mngutyo, 2014). Studies have shown that the greatest proportion (about 70 %) of the annual rainfall of West Africa countries come from deep convective systems (Ochei *et al.*, 2015). This has been discovered to be largely due to the occurrence of TSs systems that contribute mostly to the summer rainfall (Ochei *et al.*, 2015). So, the annual nature of wet TSs and deep wet convective systems are probably parts of the reasons why rainfall is seasonal in Nigeria.

In a research conducted by Ayoola *et al.* (2016) on the temporal variation of thunderstorms (TSs) rainfall in Ilorin metropolis, 1984–2013; results showed that TSs rain occurred more between 1801–0000 hours (24 hours), followed by 1201–1800 hours (6 hours), while 0001–0600 and 0601-1200 hours have the lowest TSs rainfall. 1801–2100 hours recorded the highest number of months (10 months) with highest amount of rainfall, with September recording the highest TSs rain value (1600 mm). The TSs rainfall was higher than rainfall without TSs. Ochei *et al.* (2015) conducted a research on spatial, seasonal and inter–seasonal variations of TSs frequency over Nigeria. The data used were daily TSs and associated rainfall amount from1991–2000 (10 years) using the coefficient of variation. Results showed that there exists a latitudinal belt of reduced TSs activity between 8^{o} and 10^{o}N. Due to the non-existing little dry season (LDS) in South-Eastern part of the country, they do not experience double maxima TSs activity.

In describing heavy rainfall, Karl *et al.* (1996); Groisman and Coauthors (1999) opined that heavy rainfall climatologically is assessed on the basis of the mean annual number of days in which 24 hours accumulation exceeds 50.8 mm. Odekunle *et al.* (2008), Dami (2008); Ifabiyi and Ojoye (2013) referred to heavy rainfall as an accumulation of rain >50 mm per day (24 hours). In this study, heavy rainfall is taken to be a period of accumulated rainfall of $\geq$50 mm within 24 hours (Audu *et al*., 2018; Audu *et al*., 2019).

Many researches seem to have been conducted on the relationships of weather variables with rainfall, Arkin and Karimkhani (2014); Oyewole *et al*. (2014); Arkin (2016). Specifically, the study of Akinsanola and Aroninnuola (2016) used the data on spatial pattern of precipitation, horizontal divergence of moisture flux and vertical structure of the zonal wind speed to evaluate the 29th September, 2012 heavy rainfall event over Nigeria. None of these researches attempted assessing the relationships between weather variables and heavy rainfall in the Guinea Savanna Ecological Zone of Nigeria; hence this research.

Research Questions

1. What are the compatible weather variables for running multiple linear regression model?
2. What are the relationships between weather variables and heavy rainfall?

Aim and Objectives of the Study

This study aimed at assessing the relationships between weather variables and heavy rainfall in the Guinea Savanna Ecological Zone of Nigeria (GSEZN), while the objectives were to:

1. determine the compatibility of weather variables in running multiple linear regression
2. assess the relationships between weather variables and heavy rainfall

The Study Area

The study area is the Guinea Savanna Ecological Zone of Nigeria (GSEZN) which lies between longitudes 4^{o}–10^{o}E and latitudes 6^{o}–11^{o}30^{1}N (Figure 1). The data points within the study area are evenly distributed across the study area and include Makurdi, Lokoja, Ibi, Ilorin, Lafia, Abuja, Minna, Jos and Kaduna. GSEZN is bordered to the north by the Sudano-Sahelian Ecological Zone of Nigeria (SSEZN) and to the south by the Rain Forest Ecological Zone of Nigeria (RFEZN). The zone enjoys two seasons namely wet (April-October) and dry (October-April), while harmattan is experienced between November and February. The annual rainfall ranges between 1300mm–2200mm (Binbol, 1995; Abdulkadir, 2007; Odekunle *et al.*, 2007; Yusuf and Yusuf, 2008; Audu, 2012a; Yusuf, 2012). Mean annual temperature is about 28.03^{o}C. Dry season relative humidity is about 30%, while the wet season relative humidity is about 70% (Audu, 2001; Audu, 2012b; Audu *et al.*, 2013b). The two (2) predominant air masses that influence the weather and climate of the zone are Tropical Maritime Air mass (mT) which is moisture laden and stimulates rainfall across the area and the Tropical Continental (cT) air blows in the dry season. It is described as a dry and dusty wind which has a desiccating effect (Iwena, 2000). The average daily wind speed is about 89.9km/hr.

The area consists of gently undulating plain with some hills, ridges and plateaux whose heights are between 300m-900m (Balogun, 2001). There are also rock outcrops like the Zuma Rock at Suleja, Niger State and Wase Rock in Plateau State, Nigeria (Chup, 2005).

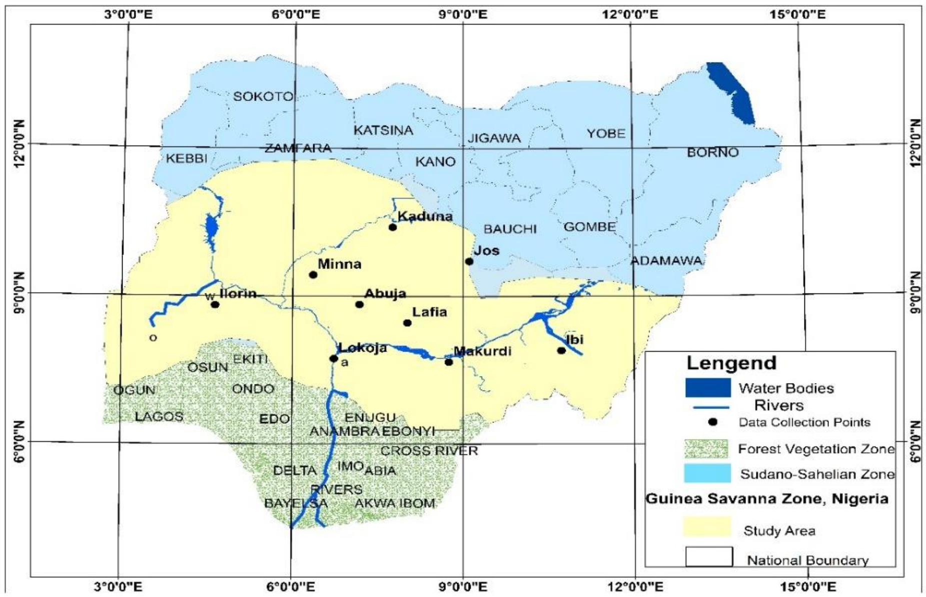

Figure 1: The Study Area showing the study locations
Source: Adapted from Audu (2019)

Types of Data Utilised

Secondary data on daily basis were used for this research and they include wind (both direction and speed), relative humidity (%), rainfall (mm) and thunderstorms (TSs). Wind speed was in minute per second (m/s). Temperature and maximum gust were excluded from the predictors because they have strong relationships with relative humidity and wind speed. It should be noted that when two (2) or more variables are strongly related in a linear model, they tend to dilute the model's reliability (Audu, 2019).

The data were in numerical form except for wind direction which was in alphabets or letters. Wind direction was converted to numerical values using the angular bearings. Data on thunderstorms (TSs) were converted into factor of yes or no. Yes, means occurrence of TSs, while no means absence of it during heavy rainfall. Heavy rainfall data were extracted from the daily rainfall using micro soft excels in a manner that, all cells containing the considered data were selected. The conditional formatting was then chosen, while cells rules were highlighted and greater than was clicked. The available text box with the threshold value of ≥50 mm was then clicked and all the dates with rainfall ≥50 mm appeared. Other predictors such as wind (both direction and speed), relative humidity (%), and TSs on the heavy rainfall dates; were also extracted from the daily data and used for this research.

Source of Data

The data used for this research, namely; wind, thunderstorms, rainfall and relative humidity on daily basis 1981-2015; were obtained from the archives of the Nigerian Meteorology Agency (NiMet), Oshodi, Lagos.

Data Analysis

To analyse the data, they were first re–arranged and re–represented by converting them into absolvable values for the programme. Correlation matrix was created first for the model output using relative humidity. It was used to determine the variables that are compatible or not. The model was run when it was observed that the variables were compatible.

Multiple Linear Regression (MLR) was used to examine the relationships between the predictors and predictant (heavy rainfall). MLR fits a model to predict a predictant (y) variable (heavy rainfall) from two or more predictors (relative humidity, wind speed, wind direction and TSs). The statistical tool R was downloaded online and used to process the MLR. The RStudio environment was used to run the model. The steps involved in creating the correlation model include: i. set working directory ii. read data iii. create correlation matrix iv. create model, and v. view model summary. MLR is expressed as:

$$Y_i = \beta_o + \beta_1 x_{i,1} + \beta_2 x_{i,2} + \cdots + \beta_{p-1} x_{i,p-1} + e_i \; for \; i = 1,2, \ldots \ldots, n \qquad 1a$$

where:
$Y_i$is the value of the response variable for *ith* case
$e_i \sim^{iid} N(0, \sigma^2)$ exactly as before
β_o is the intercept (think multidimensionally)
$\beta_1, \beta_{2,} \ldots \ldots \ldots, \beta_{p-1}$ are the regression coefficients for the explanatory variable for the *ith* case
$x_{i,k}$ is the value of the *kth* explanatory variable for the *ith* case
Parametres include all the $\beta's$ as well as σ^2. These were estimated from the data
The simple linear regression model in scalar form is:

$$Y_i = \beta_o + \beta_i x_i x e_i \qquad 1b$$

Where:
$e_i \sim^{iid} N(o. \sigma^2)$
Considering writing an equation for each observation:

$$Y_1 = \beta_o + \beta_1 x_1 + e_1$$

$$Y_2 = \beta_o + \beta_1 x_2 + e_2$$

$$\vdots$$

$$Y_n = \beta_o + \beta_1 x_n + e_n$$

The simple linear regression model in matrix form is:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} = \begin{bmatrix} \beta_o + \beta_1 x_1 \\ \beta_o + \beta_1 x_2 \\ \vdots \\ \beta_o + \beta_1 x_n \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix}$$

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} = \begin{bmatrix} 1\ x_1 \\ 1\ x_2 \\ \vdots\ \vdots \\ 1 x_n \end{bmatrix} \begin{bmatrix} \beta_o \\ \beta_1 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix}$$

Results

Figures 2-10 show the correlation matrices for the data collection centres.

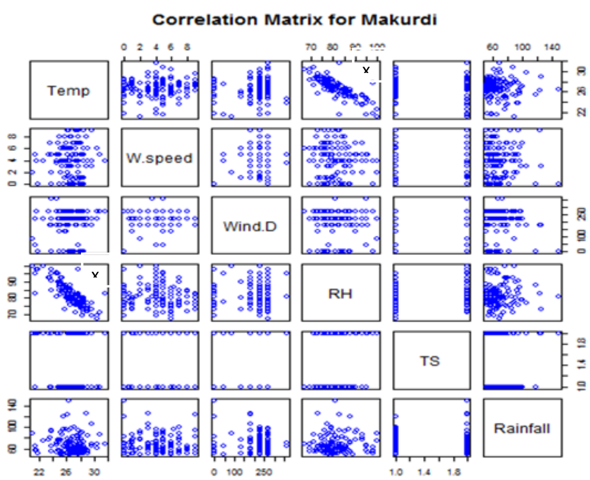

Figure 2: Correlation Matrix for Makurdi

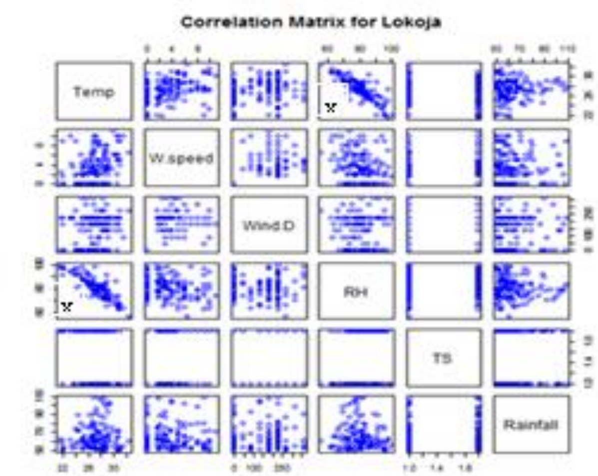

Figure **3:** Correlation Matrix for Lokoja

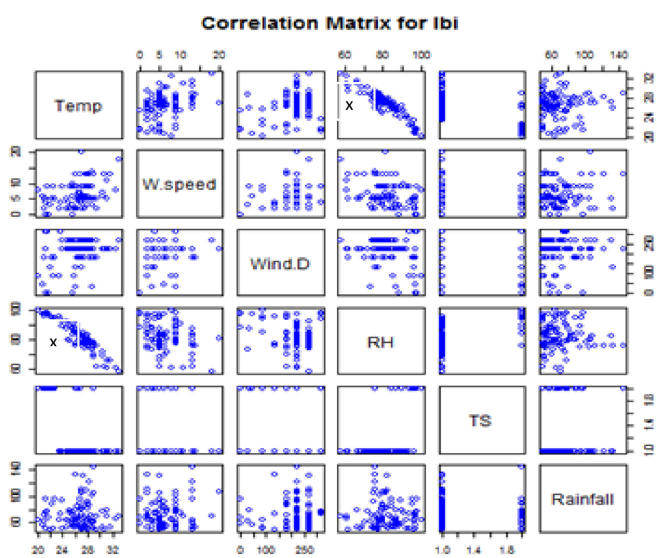

Figure 4: Correlation Matrix for Ibi

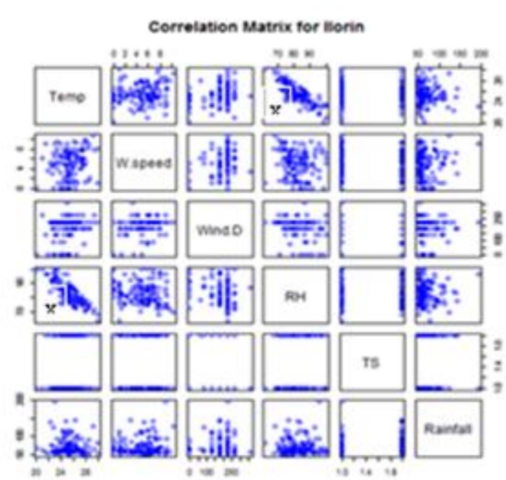

Figure 5: Correlation Matrix for Ilorin

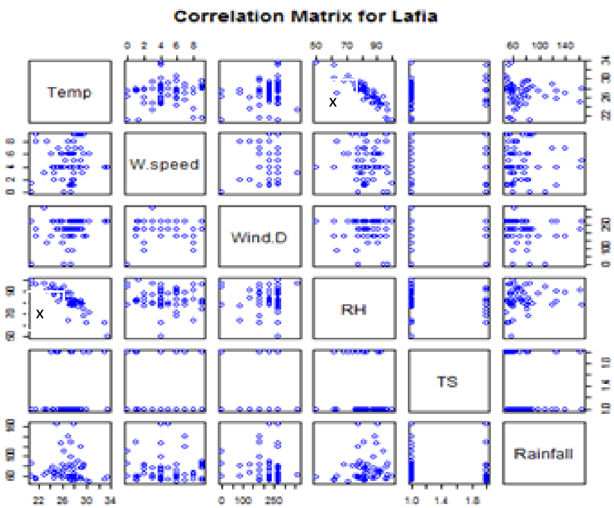

Figure 6: Correlation Matrix for Lafia

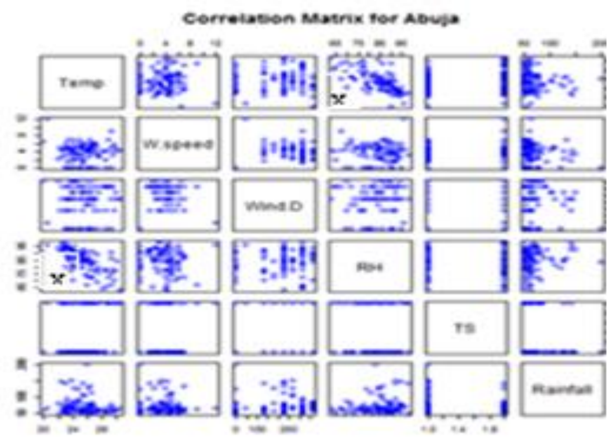

Figure 7: Correlation Matrix for Abuja

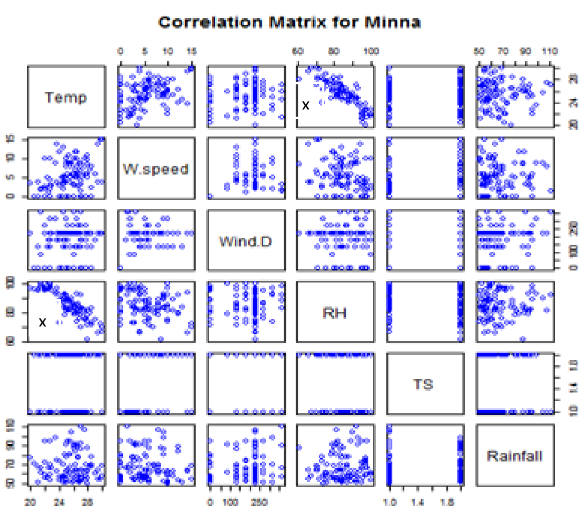

Figure 8: Correlation Matrix for Minna

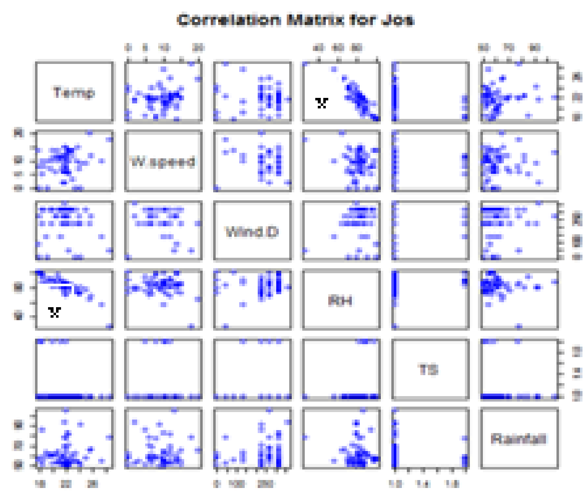

Figure 9: Correlation Matrix for Jos

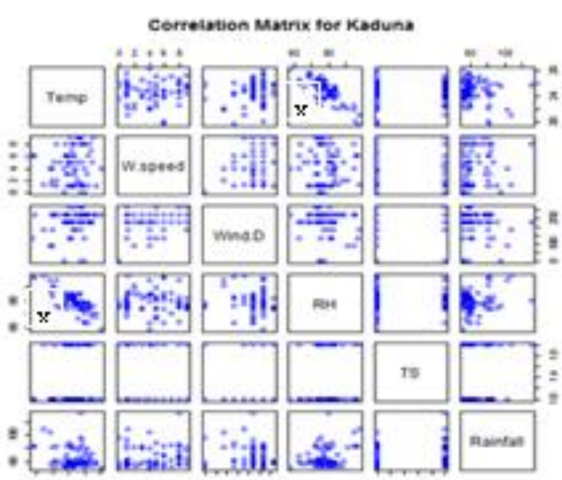

Figure 10: Correlation Matrix for Kaduna

Note: x in Figures 2-10 indicates the strong negative relationship between temperature and relative humidity.

The results on matrix indicate that, temperature and relative humidity showed strong negative relationship hence are not compatible for running the multiple linear models. On the other hand, relative humidity and other predictors show weak relationship hence are very perfect (compatible) in running the coefficients model (Figures 2-10 & Tables 1-9).

Tables 1-9 show the model output with relative humidity (RH) in percentage (%).

Table 1: Coefficients for Makurdi

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	64.67413	18.47599	3.500	0.000637
Relative Humidity	0.06542	0.21792	0.300	0.764520
Wind speed	0.07882	0.66909	0.118	0.906410
Wind Direction	-0.02168	0.02073	-1.046	0.297613
TSYES	5.07092*	3.16831	1.601	0.111912

Table 2: Coefficients for Lokoja

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	80.316278	11.519774	6.972	1.04e-10
Relative Humidity	-0.186260	0.139995	-1.330	0.185
Wind speed	-0.309162	0.482514	-0.641	0.523
Wind Direction	-0.004681	0.013472	-0.347	0.729
TSYES	2.943546*	2.396097	1.228	0.221

Table 3: Coefficients for Ibi

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	71.75000	25.68450	2.794	0.00628
Relative Humidity	-0.11072	0.29401	-0.377	0.70731
Wind speed	0.36475	0.57035	0.640	0.52399
Wind Direction	0.02099	0.03467	0.606	0.54624
TSYES	8.67041*	7.02199	1.235	0.21991

Table 4: Coefficients for Ilorin

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	58.075103	26.436565	2.197	0.0299
Relative Humidity	0.100916	0.286488	0.352	0.7252
Wind speed	0.685798	0.845570	0.811	0.4189
Wind Direction	-0.004218	0.034123	-0.124	0.9018
TSYES	3.931334*	4.188181	1.939	0.3497

Table 5: Coefficients for Lafia

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	41.37584	34.14451	1.212	0.231
Relative Humidity	0.51522	0.37081	1.389	0.170
Wind speed	0.31695	1.32226	0.240	0.811
Wind Direction	-0.05496	0.04896	-1.123	0.266
TSYES	5.54408*	8.53363	0.650	0.519

Table 6: Coefficients for Abuja

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	42.73629	28.59292	1.495	0.1383
Relative Humidity	0.48115*	0.32785	1.468	0.1455
Wind speed	-1.46136	1.27241	-1.148	0.2536
Wind Direction	-0.00877	0.02661	-0.330	0.7425
TSYES	-10.98234	5.42004	-2.026	0.0455

Table 7: Coefficients for Minna

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	66.817338	15.829865	4.221	5.48e-05
Relative Humidity	-0.006893	0.172688	-0.040	0.968
Wind speed	-0.550198	0.439872	-1.251	0.214
Wind Direction	0.030285*	0.018333	1.652	0.102
TSYES	-1.967201	3.086188	-0.637	0.525

Table 8: Coefficients for Jos

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	68.75248	13.50888	5.089	4.5e-06
Relative Humidity	-0.11196	0.15607	-0.717	0.476
Wind speed	-0.12072	0.38772	-0.311	0.757
Wind Direction	0.01407*	0.01792	0.785	0.436
TSYES	-2.47651	5.44083	-0.455	0.651

Table 9: Coefficients for Kaduna

Predictors	Estimate std	Margin of error	T-value	Pr(>/t/)
(intercept)	27.06241	17.80742	1.520	0.1326
Relative Humidity	0.54411	0.21047	2.585	0.0116
Wind speed	1.17639	0.55184	2.132	0.0361
Wind Direction	-0.05459	0.02447	-2.231	0.0285
TSYES	5.43170*	3.16292	1.717	0.0898

Note: * in Tables 1-9 shows the weather variable having the strongest relationship with heavy rainfall.

Results in Table 1 show that in Makurdi, thunderstorms (TSs) have the strongest relationship with heavy rainfall, followed by relative humidity and wind speed, while wind direction has the weakest relationship. Table 2 shows that over Lokoja, TSs have the strongest relationship with heavy rainfall followed by wind direction and relative humidity, while wind speed has the weakest relationship. Table 3 shows that in Ibi, TSs have the strongest relationship with heavy rainfall followed by wind speed and wind direction, while relative humidity has the weakest relationship. In Ilorin (Table 4), TSs have the strongest relationship with heavy rainfall followed by wind speed and relative humidity, while wind direction has the weakest relationship. In Lafia (Table 5), TSs have the strongest relationship with heavy rainfall followed by relative humidity and wind speed, while wind direction has the weakest relationship. The result in Table 6 shows that over Abuja, relative humidity has the strongest relationship with heavy rainfall followed by wind direction and wind speed, while TSs have the weakest relationship. The result in Table 7 shows that in Minna, wind direction has the strongest relationship with heavy rainfall followed by TSs and relative humidity, while wind speed has the weakest relationship. In Jos, wind direction has the strongest relationship with heavy rainfall followed by relative humidity and wind speed, while TSs have the weakest relationship (Table 8). Table 9 shows that in Kaduna, TSs have the strongest relationship with heavy rainfall followed by wind speed and relative humidity, while wind direction has the weakest relationship.

The relationships between TSs, relative humidity, wind speed and wind direction with heavy rainfall over the study area are summarized in Figure 11 and it revealed that; TSs have the strongest relationship with heavy rainfall, followed by relative humidity and wind speed; and lastly, wind direction.

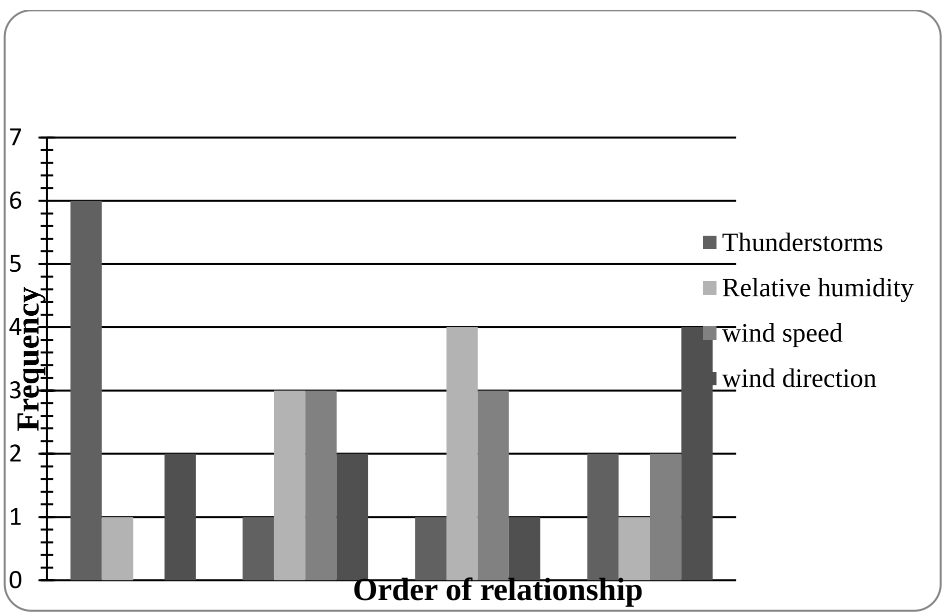

Figure 11: Relationships between thunderstorms, relative humidity, wind direction and wind speed (predictors) with heavy rainfall (predictant) over the study area

Discussion

The results of this research showed that TSs have the strongest relationship with heavy rainfall over the study area. This could be attributed to the tropical nature of the area. The tropical area enjoys high and long hours of sunshine which serve as catalyst to high temperature, high evaporation and rapid adiabatic cooling. Rainy season in the study area coincides with the period in which the position of the over-head sun is in the northern hemisphere (summer solstice) thereby leading to longer day and shorter night (Chup, 2005). The implication of this phenomenon is more sunshine hours. The research of Audu *et al.* (2016) confirmed the occurrence of seven (7) TSs over Abuja which triggered heavy rainfall on 3rd July, 2014. Rainfall over the study area is often characterized by the occurrence of TSs. As stated by Louisville (n.d.), thunderstorms often cause heavier rain since air usually rises at a much more rapid rate within developing TSs. In a related development, Orji (2016) observed that, North of latitude 10^{o}N; about 80% of the annual precipitation is provided by TSs. In the view of Ayoola *et al*. (2016), in Nigeria; the percentage contribution of TSs to total wet season rainfall increases significantly from the coastal areas inland with the coastal, middle belt and northern sections recording 17.8%, 30.4% and 35.8%.

Impact of relative humidity on rainfall is of importance as it contributes to the precipitation water in the atmosphere. The volume of relative humidity in the atmosphere contributes to the occurrence of rainfall over an area. Yahaya *et al*. (2016) observed an upward trend in relative humidity above 0.6 mm which indicates wetness. This is an indication that relative humidity and rainfall are strongly correlated positively.

Back and Bretherton (2005) stated that, faster winds are associated with substantially more precipitation, explaining a small; but highly statistically significant fraction of daily variability. Results also show that wind direction has the weakest relationship with heavy rainfall over the study area. The result of the study conducted by Audu (2019) showed that, all wind directions including calm wind has relationship with heavy rainfall, but south-west wind is predominant. In a study carried out by Audu *et al*. (2013b), on 8th May, 2011 that Lokoja LGA observed rainfall of about 11.0 mm, the wind direction was South-easterly, relative humidity was 70%, while wind speed was about 160/06. In a related development, Alison *et al*. (2014) opined that, the effects of surface entropy flux are amplified by low values of the gross moist stability and it has been shown that, the surface moist entropy flux exerts strong control over the amount of deep convective and mean rainfall rates.

Conclusion

This study used the daily data on thunderstorms, wind (both direction and speed), relative humidity termed as predictors and heavy rainfall (predictant) to assess the relationships between the predictors and the predictant. Correlation matrix and multiple linear regression were used for analysis. Part of the results revealed that temperature and relative humidity are strongly correlated negatively and are incompatible in running multiple linear regression model, while relative humidity shows weak relationship with thunderstorms, wind speed and wind direction hence are compatible in running multiple linear regression model. Results indicated that no single weather variable or convective feature has monopoly of relationship on heavy rainfall. However, TSs have the strongest relationship, while wind direction has the weakest relationship with heavy rainfall. It should be noted that the interaction among these meteorological variables and synoptic features are necessary for a deep wet convective system to occur which may later lead to heavy rainfall.

Recommendations

Based on the findings of this study, heavy rainfall forecasting is strongly advocated to serve as an early warning tool. Monitoring and forecasting of TSs are strongly advocated because of their strongest relationship with heavy rainfall over the study area. Other scientific methods should be adopted to carry out similar research to make the result more wholistic.

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