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RESEARCH ARTICLE

# Air travel as a catalyst for Urban Development: Examining Thunderstorm Occurrence on Flight Operations at Nnamdi Azikiwe International Airport, Nigeria

**Friday Noah Idoko[1], & Senator Endurance Okosun[2*]**

[1]Department of Geography, Federal University Lokoja, Lokoja, Nigeria
[*2]Department of Urban & Regional Planning, University of Benin, Benin, Nigeria
*Corresponding Author's Email: okosunsenator@gmail.com

## ABSTRACT

This study evaluates the influence and trend of thunderstorms on flight operations at Nnamdi Azikiwe International Airport, Abuja, Nigeria, from 1991 to 2020. This research employed secondary data on thunderstorm occurrences from the Nigerian Meteorological Agency (NIMET) and flight operations data from the Nigerian Airspace Management Agency (NAMA), both at Nnamdi Azikiwe International Airport, Abuja. The statistical analyses employed were line graphs, tables, simple correlation, and descriptive statistics. Simple linear regression was used to establish the influence and trend of thunderstorm occurrence values for the study area. The changes in the (number of years) (x) are associated with changes in the (thunderstorm occurrences) (y). The negative slope of -0.0643 indicates that as the independent variable (x) increases by one unit, the number of thunderstorm occurrences (y) decreases by approximately 0.0643 units. In other words, there is a negative relationship between the number of years (x) and the number of annual thunderstorm occurrences (y), suggesting that as the value of x increases, thunderstorm occurrences (y) tend to decrease. The y-intercept is the value of y when x is equal to 0. In this case, when x is zero, the number of thunderstorm occurrences (y) is expected to be approximately 240. This intercept represents the estimated baseline number of thunderstorm occurrences when the R-squared value is 0.0023. The results showed that there is a relationship between thunderstorm occurrences and flight operations at a 95% confidence level, although the relationship is not statistically significant ($p>0.05$). Recommendations were based on the fact that insufficient data on other parameters, such as flight delays, flight cancellations, and flight diversions, are due to inadequate record-keeping. Therefore, there is a need for all aviation organizations concerned to develop a grassroots information database and keep proper records of every flight operation activity.

**Keywords:** *Aviation; Flight operations; Abuja airport; Thunderstorm occurrences; Weather parameters*

## 1. INTRODUCTION

Thunderstorms in most airports are meteorological events that bring heavy rains, strong winds, hail, lightning, and tornadoes. Thunderstorms are generated by atmospheric imbalance and turbulence caused by a combination of several conditions, including unstable, warm air rising rapidly into the atmosphere, sufficient moisture to form clouds and rain, and upward lift of air currents caused by colliding weather fronts (cold and warm), sea breezes, or mountains. The aviation industry faces significant safety-related challenges, with a high rate of weather events such as thunderstorms. Okosun et al. (2021) the reasons adduced are that thunderstorms are a very significant climatic element that affects air travel and its operational activity.

Mohammed & Wasiu (2007) reported that air transport is recognized worldwide as the quickest, safest, and most reliable means of movement from one continent to another. Aircraft travel through the atmosphere, which varies vertically and horizontally in pressure, temperature, density, and atmospheric humidity. It contains a variable quantity of water vapor, which, when condensed, produces a gaseous fog and continues like that to cloud, sleet, hail, and precipitation, all of which affect visibility, as stated by Ehigiator & Orakpo (2010). The visibility of the pilot is dependent on various meteorological conditions such as thunderstorms, fog, rain, and hail, which are the principal causes of flight cancellations, diversions, or delays (Kulesa et al., 2013; International Airport, Nigeria, 2015).

In line with the Intergovernmental Panel on Climate Change (IPCC, 2007) report on extreme weather, particularly thunderstorms, heavy downpours, and hurricanes, which are extreme weather disasters affecting flight operations, there is a need to ensure the safety of flight operations through the provision of accurate weather reports from meteorological stations. Hence, accurate weather forecast and its impacts, provide vital information as regards to implication of thunderstorms on flight operations to various agencies of government related to the prevention of thunderstorms hazards to aircraft operations such as ministry of aviation and aerospace development, ministry of transportation, Nigerian Meteorological Agency (NIMET), Nigerian Airspace Management Agency (NAMA), Nigerian Civil Aviation Authority (NCAA), Federal Airport Authority of Nigeria (FAAN). It is also geared toward making a forecast for the impact of thunderstorms on flight operations for the period of thirty (30) years. This study will complement Nigeria Government`s efforts by providing deeper weather knowledge of its airspace for smooth flight operations. This study intends to contribute this needed knowledge in order to solve the problem of flight delays, cancellations, and diversions as well as plane crashes due to thunderstorm hazards.

Outside Nigeria, scholars have also worked on thunderstorm activity in North America by Spyrou (2010), in Scotland, Europe; Enete et al. (2015); and other notable contributions from Nigeria in Port Harcourt, southern Nigeria; Igbokwe (2005) in Lagos, South Western Nigeria; all aimed at addressing the impact of weather on flight operations. This study therefore is an attempt to fill the gap in knowledge by examining the effects of thunderstorms on flight operations in Nnamdi Azikiwe International Airport, Abuja, between 1991 and 2020. Several related studies have been carried out, addressing the impact of thunderstorms on flight operations. Some of these studies are included in the work of Weli & Emenike (2014), Qualley (2013), Kulesa et al. (2013), Sani (2010), and Spyrou (2010). These studies, however, tend to ascertain the influence of turbulent weather conditions (thunderstorms) on aircraft operations and their implications for aviation safety in the study area. Also, air terminal for smooth flight operations, particularly during landing and take-off; that is why Hauf & Sasse (2022) stressed that most of the air crashes were caused by severe thunderstorms.

Over the years, flight operations have been significantly affected, in terms of takeoff, landing, and even in-flight, by extreme weather events (significantly thunderstorms). Thunderstorm have long been known to be threatening to all aspects of air transportation, each year more than one quarter to one-half of all accidents is weather related, (National Weather Service

(NWS) (2022) The safety of modern air transportation is closely tied to accurate weather reports from meteorological stations (Nigeria Safety and Investigation Bureau (NSIB) (2013); University Corporation for Atmospheric Research (UCAR) (2022) Studies by Ayoade (2004) have revealed that adverse weather conditions (thunderstorm) may cause delays, diversions, accidents and even out right cancellations of journeys, causing loss of time, revenue and even lives. It is against this background that this study seeks to examine the impact of thunderstorms on flight operations over a climatic period of thirty years (1991-2020) to ascertain the characteristics and trend of thunderstorm occurrences at the Nnamdi Azikiwe International Airport, Abuja, Nigeria.

## 2. LITERATURE REVIEW

The growth of the aviation industry in Nigeria and the increased adoption of air transportation as one of the best means of transport have been obstructed by various weather hazards. There is a greater need for aviation weather forecasters to deliver quality forecasts. It is therefore necessary to identify the most dangerous and most common weather hazards that are detrimental to the aviation industry so as to enhance expertise in addressing them. Weli & Ifediba (2022) examined various weather hazards, which include thunderstorms, fog, dust haze, and line squall that affect flight operations such as flight delays, diversion, and cancellation. The study revealed that fog accounted for 13.2% of flight cancellations at the airport, and line squall similarly accounted for 10.1% of delays, 8.4% of diversions, and 20% of cancellations from 2000-2009 at the airport in Nigeria.

Enete et al. (2015) carried out research work on the impacts of thunderstorms on flight operations at Port Harcourt International Airport. This study focused on the monthly and annual occurrences of thunderstorms, the trend/pattern of thunderstorms, and their influence on the number of flight diversions, delays, and cancellations. In order to evaluate this impact, six years of data on thunderstorm frequency and the number of flight diversions, delays, and cancellations were obtained. The statistical analyses employed were simple and Multiple bar charts and Pearson's product-moment correlation. From the analysis, it was observed that thunderstorms occur mostly in the rainy season months (monsoon periods), with an increasing trend over the years due to the meridional movement of the weather/ITD zones. The study revealed that thunderstorms accounted for 32% of flight cancellations with 218 occurrences, 0.2% of diversions with 291 occurrences, and 24% of delays with 526 occurrences at the airport from 2008-2013. From the Analysis, thunderstorms have a greater influence on the number of flight cancellations and delays than on diversions, with correlation values of $r=0.57$, 0.49, and -0.04, respectively. The study concluded that thunderstorms occur in the study area during monsoon periods, and it has more impact on delays and cancellations than on diversions.

Weli & Emenike (2014) examined turbulent weather conditions and their relationship to aircraft operations as well as the influence of dry and wet seasons on weather parameters of rainfall, thunderstorm, and fog at the Port Harcourt International Airport. Data on turbulent weather conditions (fog, thunderstorm, and rainfall) were obtained from the Nigeria Meteorological Agency, and data on flight operations were similarly obtained from the operators of different airlines (Arik Air, Dana, and Aero Contractors). The study revealed that for all aspects of aircraft operations thunderstorm associate's rainfall had significant relationship with aircraft operations, as it accounted for 90.4% variations in flight delays, ($r = 0.951$) at $p>0.05$, it also accounted for 89.68% variations in the case of flight cancellation with an r value of 0.947, thunderstorm in the case of flight divert accounted for 88.36% variation with an r value of 0.940 at $p>0.05$. Findings indicate that thunderstorms were the only turbulent weather parameter that significantly affected aircraft operations, especially flight cancellations. The study also revealed that seasons influence weather parameters.

Okoro et al. (2018) assessed the significance of weather conditions on aviation transport at Nnamdi Azikiwe International Airport, Abuja. Records on visibility, rainfall, cloud cover, wind speed and direction to cloud cover, and two aspects of flight operations (flight delays and cancellations) for 15 years (2000-2014) were collected from secondary sources. The Spearman rank correlation coefficient, the coefficient of determination, t-test, and multiple linear correlations were used to ascertain relationships between weather elements and flight operations (flight delays and cancellations). Findings of this study show that wind speed has no effect on flight delays since the test of significance value of 1.63 was less than the critical value of 1.77. The major weather element that influenced flight operations was cloud cover. Individual weather elements on their own do not affect flight operations; however, when they are combined, affects aviation transportation significantly.

Hosea (2019), in his studies, examined the effect of climate change on airline flight operations with specific reference to aviation delays, diversion, and cancellation at Nnamdi Azikiwe International Airport. Abuja, Nigeria. Monthly records of the occurrence of fog, thunderstorms, harmattan haze, and flight diversion, delay, and cancellation for Abuja International Airport were collected from secondary sources for a period of eighteen (18) years (2000-2017). The statistical analyses employed were trend, correlation, and multiple regression analyses using econometric software (EViews9). Results indicated that harmattan haze occurred most, followed by thunderstorms, while Fog had the fewest occurrences at the Airport. Annual trends revealed a steady increase in thunderstorm and fog occurrences, while a very slight decrease in harmattan haze occurrence was recorded within 2000-2017 at Abuja Airport. The study reveals a positive statistical relationship between weather elements and flight operations (flight cancellation, delay, and diversion) at the 95% confidence level. The impacts of weather elements (harmattan haze, fog, and thunderstorm) were statistically significant on flight cancellation only.

Iornongo et al. (2022) evaluated the effects of low horizontal visibility on flight operations in Nnamdi Azikiwe International Airport, Abuja, Nigeria. The data for low horizontal visibility frequency (2009-2018) were collected from the Nigerian Meteorological Agency (NIMET), while the data for flight operations and air accidents were obtained from the Nigerian Airspace Management Agency (NAMA) and the Accident Investigation Bureau, respectively. The linear regression analysis was used to examine the relationship between the selected weather parameter and flight operations in the study area; it was achieved with the use of the data analysis pack of the Microsoft Excel program. To compare the relationship between the weather element (visibility) and air accidents at the Nnamdi Azikiwe International Airport, Abuja, the linear regression analysis was also used to determine the degree of relationship that exists between these two variables of interest. The time series plot of the monthly total visibility and monthly average visibility shows that the poor visibility at Nnamdi Azikiwe International Airport occurred during dry seasons, mostly the January and December periods under the years of study. The lowest occurred in the month of January. The trend in visibility in the study area on an annual and monthly basis both have a negative trend, which means that visibility on an annual and monthly basis is decreasing. The coefficient of visibility (-5.531E-5) is negative, meaning the lower the visibility, the higher the number of flight diversions. The F-statistic value of 15.804 at 5% ($p<0.05$) implies that there is a significant relationship between flight diversion and visibility during the year of study. The coefficient of visibility (1.078E-6) is negative, meaning the lower the visibility, the lower the air accidents. The F-statistic value of 2.727 at 5% ($p>0.05$) implies that there is no significant relationship between air accidents and visibility during the year of study.

Pepple et al. (2020) assessed trends of meteorological parameters and aviation operations in Port Harcourt International Airport. Records of rainfall, thunderstorms, wind speed, fog, pressure, and temperature, and three aspects of flight operations (flight diversions, delays, and cancellations) from 2010-2018 were collected from secondary sources. Multiple regression analysis was used to determine the trend of the meteorological parameters as predictors of aviation operations. The findings of the study showed that flight operations experienced more disruptions during the dry season; weather elements such as rainfall, thunderstorms, fog, and pressure have significant effects on flight operations between 2010 and 2018. The study also showed that when combined, the meteorological factors can be used to predict flight cancellations at a 95% confidence level.

Onwuadiochi et al. (2020) examined wind shear and its relationship with aircraft operations using Sam Mbakwe Airport, Imo State. Data on wind shear and aircraft operations were collected from the Nigerian Meteorological Agency (NIMET) and Nigerian Civil Aviation Authority (NCAA) for the period of one and a half years. Correlation and Regression analyses were carried out for the measured wind shear and flight delays and cancellations. The study revealed that the wind measured at 20m above ground level had a weak positive relationship with flight delays and cancellations. This implies that as wind shear increases, both flight delays and cancellations also increase. The correlation between wind shear measured 20m above ground level and flight delays and cancellations was 0.195 and 0.392, respectively, showing that the measured wind shear was responsible for 51.4% and 67.1% of the flight delays and cancellations, respectively. The regression relationship formulated was significant for the entire hypothesis because the P-values of the ANOVA were less than 0.05. Since the relationship was significant, the expressions can be used to predict the extent of flight delays and cancellations if the wind shear is known.

Abiodun (2021), in his study carried out at Murtala Muhammed International Airport, Ikeja, Lagos, Nigeria, adopted the Statistical Package for the Social Sciences (SPSS) software for the descriptive and inferential analysis. Time series analysis, Pearson Moment Correlation for interrelationships among the weather parameters and flight disruption data, and multiple linear regression analysis were applied to determine the influence of weather parameters on flight disruption data. He observed that thunderstorm, cloud cover, and high visibility are negatively correlated. Wind speed has a positive relationship with wind direction, and an inverse relationship with visibility, thunderstorm, and fog. A direct relationship exists between highest visibility and thick dust; wind speed and cloud cover indicate increased visibility levels in the study area. Flight delay is more prominent than flight diversion and cancellation, which indicates their relevance in air traffic in the study area. The prediction model indicates a high degree of cloud cover at the beginning of every year and later declines sharply in 2035; the visibility flattens out by the year 2025, and a low pattern of thick dust was calculated in the same pattern year in 2011, 2016, and 2027.

Onwuadiochi et al. (2023) analyzed the distribution of measured and extrapolated wind shear at Murtala Muhammed and Port Harcourt International Airports, Nigeria. The annual time series secondary data used for this study were sourced from the Nigerian Airspace Management Agency (NAMA) at Murtala Muhammed Airport, Lagos, and Port Harcourt International Airport, and the Nigerian Meteorological Agency (NIMET). Power Law Model was used to extrapolate wind shear at 20m above ground level to 50m and 100m above ground level for both airports. The data were compiled and presented in tables and charts for easy understanding and further analysis. The statistical techniques employed in achieving the research target were descriptive statistics (such as mean, standard deviation, coefficient of variation, and charts). The study shows that wind shear increases with altitude at the study areas due to a decrease in frictional resistance, which is more pronounced close to the ground. A similarity in the distribution pattern of wind shear at 20m, 50m, and 100m above ground level at Murtala Muhammed International Airport was revealed by the study. The same similarity in the distribution pattern was also revealed at Port Harcourt International Airport. Evidently, the study reveals some temporal variations in the mean and standard deviation of wind shear in the study areas. The study also reveals, based on the effects of wind shear and its resultant flight delays, diversions, and cancellations, that Port Harcourt International Airport, with an overall higher coefficient of variation (CV), is considered safer for flight landings.

**Empirical Gaps in Literature**

From the literature, there is a dearth of empirical analysis of the effects of thunderstorms on flight operations at the Nnamdi Azikiwe International Airport, Abuja. Also, there is a gap in flight operations data (1991-1996) because of insufficient data on other parameters such as flight delays, flight cancellations, and flight diversions due to inadequate record-keeping. However, available data for this study were from 1997-2020. To examine the nature of occurrences and variability of the frequency of thunderstorms in relation to their effects on flight operations, Aremu (2014) discussed the influence of Jos Plateau on the occurrence of thunderstorm activity in Jos, Zaria, and Kaduna in his work on temporal and comparative analysis of thunderstorms and related phenomena (hail, squall, and Lightening). Adefolalu (2010); Akinsala & Ogunjobi (2014); Weli & Emenike (2014); Adelekan (2008); Hosea (2015); Onwuadiochi (2021) were other notable contributions from Nigeria. Outside Nigeria, scholars have also worked on thunderstorm activity (Rafferty (2011); Seneviratne et al. (2012); Doswell (2021); Stull (2017); Wurman et al. (2021); Krider (2022); Hauf & Sasse (2022). Despite these contributions, no real attempt has been made to study thunderstorms in their entire diurnal, seasonal, annual, and decadal trends in a single study. This study seeks to carry out a detailed analysis of thunderstorms over Abuja Airport because of its importance in Nigeria. This study, therefore, is an attempt to investigate temporal trends and to fill the gap in knowledge by examining the effect of thunderstorms on flight operations between 1991 and 2020 at Nnamdi Azikiwe International Airport, Abuja. During the rainy season, there are delays and diversions of flights as a result of thunderstorm occurrences, and in the dry season, there is the dust haze that reduces visibility Hosea (2015). During periods of poor visibility, flights can be diverted to alternate airports when it is difficult to land at their original destination due to poor weather conditions (thunderstorms) (Hauf & Sasse, 2022). All of these conditions pose a great risk to passengers and increase the cost of flight operations; this has been experienced at the Nnamdi Azikiwe International Airport, Abuja.

## 3. MATERIALS AND METHODS

**Study Area**

The study area covers the confines of Nnamdi Azikiwe International Airport, in the Federal Capital Territory (FCT), Abuja, Nigeria. Established and commissioned on September 29, 1982, and named after Nigeria's first president, Dr. Nnamdi Azikiwe. The airport was built in 2000 and opened in 2002 (Federal Airport Authority of Nigeria, 2011). It consists of an international and a domestic terminal; both terminals share the same runway. It is about 49 kilometers south of the city. The airport covers an area of about 1,476km2 and lies between latitude 80 59' 0" and 90 1' 30"N and longitude 70°14'30" E and 70°17'0" E, with an altitude of 314.98m. The airport type is public; the elevation (AMSL) is 1, 123ft/342m above mean sea level (AMSL); the runway direction is 04/22; and the length is 3,610m/11,844ft (Nigerian Aeronautical Information Publication, 2013). The climate of the study area is generally tropical (Okosun et al., 2021). This includes a warm, humid rainy season and a dry season. The month of April marks the onset of the wet season; this runs through to October yearly. The dry season runs from November to March of the following year. Abuja experiences a tropical climate.

***Table 1. Climatic elements for Nnamdi Azikiwe International Airport, Abuja. For the year 2020***

| Month | Avg. Tem. (°C)/(°F) | Precipitation/ Rainfall(mm) | Humidity (%) | Rainy/days (d) | Avg. sunshine In (Hours). | Wind Speed (Km/h) |
|---|---|---|---|---|---|---|
| January | 27 (80.5) | 2 (0.1) | 26% | 1 | 10. | 7.6 |
| February | 28.6 (83.5) | 6 (0.2) | 29% | 1 | 10. | 7.1 |
| March | 29.6 (85.2) | 20 (0.8) | 38% | 3 | 10.0 | 6.6 |
| April | 28.6 (83.4) | 57 (2.2) | 57% | 7 | 8.0 | 7.3 |
| May | 26.5 (79.7) | 138 (5.4) | 73% | 14 | 6.0 | 6.8 |
| June | 24.5 (74.2) | 205 (8.1) | 82% | 17 | 4.0 | 6.3 |
| July | 23.4 (74.1) | 269 (10.6) | 85%l | 21 | 4.0 | 5.9 |
| August | 22.9 (73.3) | 326 (12.8) | 87% | 21 | 4.0 | 5.6 |
| September | 23.6 (74.5) | 290 (11.4) | 85% | 20 | 5.0 | 5 |
| October | 24.7 (76.5) | 144 (5.7) | 80% | 15 | 6.0 | 4.8 |
| November | 26.4 (79.5) | 11 (0.4) | 51% | 2 | 10.0 | 5.2 |
| December | 26.7 (80) | 1 (0) | 29% | 0 | 10.0 | 7.5 |

*Source: Nigerian Meteorological Agency (NIMET) (2022)*

**Sources and Types of Data**

The study utilized secondary sources of data on thunderstorms, which were sourced from the Nigerian Meteorological Agency (NIMET), and data on flight operations were sourced from the Nigerian Airspace Management Agency (NAMA). The data on thunderstorm frequency from 1991-2020 were collected from the Nigerian Meteorological Agency (NIMET) Headquarters in Abuja, while the data on flight cancellations, delays, and diversions from 1997-2020 were collected from the Nigerian Airspace Management Agency (NAMA) at Nnamdi Azikiwe International Airport, Abuja, Nigeria. At Nnamdi Azikiwe International Airport, Abuja, flight operations data were collected for the period of 23 years (1997-2020) because there were no data on flight operations at Nnamdi Azikiwe International Airport, Abuja. From 1991 to 1996. There is a gap in flight operations data (1991-1996). However, available data for this study were from 1997-2020.

**Data Analysis**

The statistical analyses employed were inferential statistics, which were used to determine the relationship between thunderstorm occurrences and flight operations as well as to establish the relationship between thunderstorm trends and flight operations for the study area. Data presentation included skewness and kurtosis, thunderstorm frequency and trend analysis, and correlation analysis, which were presented and analyzed from 1991- 2020. Also, in analyzing the required data, simple statistical techniques such as line graphs and tables were employed. In addressing the normality of the collected thunderstorm frequency data, the Skewness and Kurtosis analysis was used. The Skewness of the thunderstorm frequency data was analyzed and used.

## 4. RESULTS AND DISCUSSION

**Monthly Thunderstorm occurrences at Nnamdi Azikiwe International Airport, Abuja from 1991-2020**

The monthly occurrences of thunderstorms show that thunderstorm occurrences were lowest in the months of January and December, averaging less than 1 per month. February and November also have relatively low averages, fewer than 2 occurrences per month. The months with the highest number of thunderstorms were July, August, and September; particularly, August had the highest total occurrences over the 30 years with 576, averaging about 19 per year. July and September followed closely with averages of 18 and 18 occurrences, respectively. The surge of thunderstorm activity occurred from March, with a notable increase in the average monthly occurrences, peaking in August with a gradual decline in activity through to December. Specifically, the thunderstorm activity shows a substantial surge from April to October, with each of these months averaging more than 10 occurrences. Moreover, March and November act as transition months, where the activity begins to increase (March) and then decrease (November) considerably. This result is in agreement with the findings of Anne-Duncan (2010) at Port-Harcourt International Airport, Omagwa, Rivers State, Nigeria. In the study, it was noted that the months of August and September are mostly characterized by thunderstorms and line squalls with the attendant turbulence, microbursts, and lightning.

The mean monthly variability and trend of the occurrence of thunderstorms show a slightly increasing trend over the months at Nnamdi Azikiwe International Airport throughout the study period. This implies that the occurrence of thunderstorms is more prevalent during the middle and end of the year than the beginning of the year. The result of this study is in agreement with the result of Akanni et al (2016), which showed an increasing trend in the occurrence of thunderstorms from 2004 to 2013 in Lagos State. Meanwhile, the result is at variance with the findings of Enete et al. (2015), which showed that thunderstorm occurrence was fluctuating without either a decreasing or increasing trend. The difference between the findings of Enete et al (2015) and this study could be due to the difference in the location and the period of the study.

Overall, the results suggest a clear seasonal pattern for thunderstorm occurrence; the months from April to October, particularly July to September, can be considered as the 'thunderstorm season' given the high averages of occurrence (Table 2). This could be due to climatic factors typical of the monsoon or summer season in many parts of Nigeria, including the study area. Conversely, the winter months (January and December) witness the least thunderstorm activity. The months right before and after the peak season (March and November) also experience relatively low occurrences, indicating the transition between low and high activity periods. This result is in agreement with the finding of Akanni et al (2016), in which it was found that thunderstorms were most frequent in August and September and least frequent in December and January. This result is also in agreement with the finding of Maxwell (2008) at Port-Harcourt International Airport, Omagwa, Rivers State, which observed that the monsoon period of the year is the worst for bad weather and flight delays due to the resultant convective weather activities.

***Table 2. Monthly Occurrence of Thunderstorms in Nnamdi Azikiwe International Airport, Abuja from 1991-2020***

| **Months** | **Total Occurrences** | **Mean Occurrences** | **% of Total Occurrences** |
|---|---|---|---|
| January | 12 | 0.4 | 0.360902256 |
| February | 20 | 0.667 | 0.601503759 |
| March | 86 | 2.867 | 2.586466165 |
| April | 207 | 6.9 | 6.22556391 |
| May | 406 | 13.533 | 12.21052632 |
| June | 440 | 14.667 | 13.23308271 |
| July | 527 | 17.567 | 15.84962406 |
| August | 576 | 19.2 | 17.32330827 |
| September | 545 | 18.167 | 16.39097744 |
| October | 435 | 14.5 | 13.08270677 |
| November | 56 | 1.867 | 1.684210526 |
| December | 15 | 0.5 | 0.45112782 |

*Source: Adapted and modified from* NIMET (2023)

**Annual and Decadal Thunderstorm Occurrences at Nnamdi Azikiwe International Airport, Abuja, Nigeria**

*Annual*

The total annual thunderstorm occurrences for 30 years ranged from 88 (2017 and 2018) to 137 (2012). The 1990s showed a relatively stable frequency of thunderstorms, with a slight dip in 1995 but generally hovering around 110 occurrences (Figure 2). There's a noticeable dip in the year 2000, where occurrences dropped to 94, the lowest in the first decade of this study. The mid-2000s, especially from 2005 onwards, showed an increasing trend, peaking in 2007 at 130 occurrences. The highest thunderstorm occurrence of 137 was recorded in 2012. After 2012, there was a decline, with the lowest thunderstorm occurrences of 88 in 2017 and 2018. These were the most significant dips during the study period. Towards the end of the period, the number of occurrences hovered between 105 and 111 (2019-2020). The annual occurrences reveal that 2012 had the highest number of thunderstorm occurrences at the Nnamdi Azikiwe International Airport, Abuja. The result is at variance with that of Akanni et al (2008) at Murtala Muhammed International Airport, Lagos, which showed that 2008 had the highest number of thunderstorm occurrences (Figure 2)

*Decadal*

In terms of the decadal insights, the 1990s showed thunderstorm occurrences were relatively stable in the 1990s, with slight fluctuations, and remained predominantly lower than 110. Also, the early 2000s saw some decline in the number of thunderstorms, but the latter half of the decade marked an upward trend, reaching a peak in 2007. (Figure 2) In the 2010s, thunderstorm occurrences were slightly decreasing, reaching a high in 2012, then followed by a downward trend until 2018, and a slight recovery towards the end of the decade. The occurrences of thunderstorms have shown variability over the three decades, with certain years or periods having increased or decreased frequencies. The second decade (2001-2010) showed a clear increasing trend in thunderstorm occurrences, as indicated by the positive slope and a relatively high $R^2$ value. On the other hand, the first and third Decades (1991-2000 and 2011-2020) indicated weak decreasing trends, especially in the first Decade (Figure 2). This variability might have been influenced by changes in local weather dynamics or other environmental factors such as temperature, rainfall, relative humidity, visibility, wind speed, atmospheric instability, cloud cover, sea level, and pressure. The result of this study agrees with that conducted by Akinsanola and Ogunjobi (2014), in which long-term trends and decadal trends further suggest a sequence of alternately decreasing and increasing decadal thunderstorm frequency in the study area.

*Sub-period*

The average occurrence showed that the sum of the occurrences in the first sub-period (1991-2005) is 1631, so the average is 108.6 thunderstorms per year. The highest occurrence was revealed in 2005 with 128 thunderstorms, while the lowest occurred in 2000 with 94 thunderstorms. In terms of the characteristics, this sub-period (1991-2005) starts and ends with numbers around the low 110s (Figure 2). The occurrences fluctuate without any distinct rising or declining trend throughout the sub-period. This sub-period generally experienced a slight increase in thunderstorm occurrences, especially in 1991, 1997, and 2005, which particularly stand out as sub-periods with notably high occurrences.

In these sub-periods, the total thunderstorm occurrences were 1694, resulting in an average of 113 thunderstorms per year. The maximum peak occurred in the year 2012 with 137 thunderstorms. In 2017 and 2018, both the lowest occurrences in this sub-period showed 88 thunderstorms each (Figure 2). These sub-periods are characterized by the highest (2012) and lowest (2017 and 2018) occurrences in the entire 30 years' life span. While the sub-periods started with high occurrences, there was a noticeable dip in the latter half of this sub-period, particularly in 2017 and 2018.

The sub-periods (2006-2020) experienced a slightly higher average of thunderstorm occurrences compared to the sub-periods (1991-2005). However, the sub-period (2006-2020) saw an average closer to that of the sub-period (1991-2005). It is worth noting the variability within each sub-period, with particularly high peaks and lows in the sub-period (2006-2020). The 2007 period with (130) occurrences and 2012 with (137) occurrences stand out with notably high thunderstorm occurrences. In contrast, 2017 (88) and 2018 (88) experienced the lowest thunderstorm occurrences over the 30 years (Figure 2). This sub-period (2006-2020) analysis offers a broad view of the characteristics of thunderstorm occurrences, showing that while there are annual fluctuations, no distinct long-term trend can be deduced from the results. Over the 30 years, while there have been years of increased thunderstorm activity, there have also been significant lows. The frequencies of thunderstorms showed a consistent upward or downward trend over the entire period but do display periods of increase and decrease, which can be deduced from the results. The result showed clear inter-annual variability without any consistent upward or downward trend throughout the entire 30-year period. Also, this result is at variance with the findings of Enete et al (2015) in Port-Harcourt International Airport, Omagwa, Rivers State, which showed that thunderstorm occurrence was fluctuating without either a decreasing or increasing trend. This difference in results between Enete et al (2015) and this study could be due to the difference in the location and the period of the study. The finding is in agreement with the result of Maxwell (2008), which observed that the monsoon period of the year is the worst for bad weather delays due to resultant convective weather activities.

**Relationship between thunderstorms and years of study**

The changes in the (number of years) (x) are associated with changes in the (thunderstorm occurrences) (y). The negative slope of -0.0643 indicates that as the independent variable (x) increases by one unit, the number of thunderstorm occurrences (y) decreases by approximately 0.0643 units. In other words, there is a negative relationship between the number of years (x) and the number of annual thunderstorm occurrences (y), suggesting that as the value of x increases, thunderstorm occurrences (y) tend to decrease. The y-intercept is the value of y when x is equal to 0. In this case, when x is zero, the number of thunderstorm occurrences (y) is expected to be approximately 240. This intercept represents the estimated baseline number of thunderstorm occurrences when the R-squared value is 0.0023; it indicates that the number of years (x) included in the regression equation explains only a very small proportion of the variance in the thunderstorm occurrences, and that the model explains very little of the variation in thunderstorm occurrences. The negative slope of -0.0643 suggests that, for each unit increase in the number of years (x), the number of annual thunderstorm occurrences (y) is expected to decrease by approximately 0.0643 units. (Figure 2)

However, in this case, the model has a very weak explanatory power, so the relationship may not be practically significant despite being statistically significant. The y-intercept represents the estimated baseline number of annual thunderstorm occurrences when the number of years (x) is zero, which is approximately 240. However, with an R-squared of 0.0023, it's important to understand that the model does not capture much of the variability in annual thunderstorm occurrences. Airport, Abuja.

The R-squared suggests that there are other factors or variables, such as temperature, rainfall, relative humidity, visibility, wind speed, atmospheric instability, cloud cover, sea level, and pressure, not included in the model that influence annual thunderstorm occurrences to a much greater extent.

In such cases, the predictive power of the model is quite limited. This finding is in agreement with the work of Enete et al (2015), which reported that there is a negative relationship between the number of years and the number of annual thunderstorm occurrences, but that the relationship was insignificant due to weather modification. It can be concluded that annual thunderstorm occurrences are not statistically significant, which agrees with the findings of Wellis and Emenike (2016) and Idoko et al (2024), which show that there is no statistically significant relationship between the number of years and the number of thunderstorm occurrences at Nnamdi Azikiwe International Airport, Abuja.

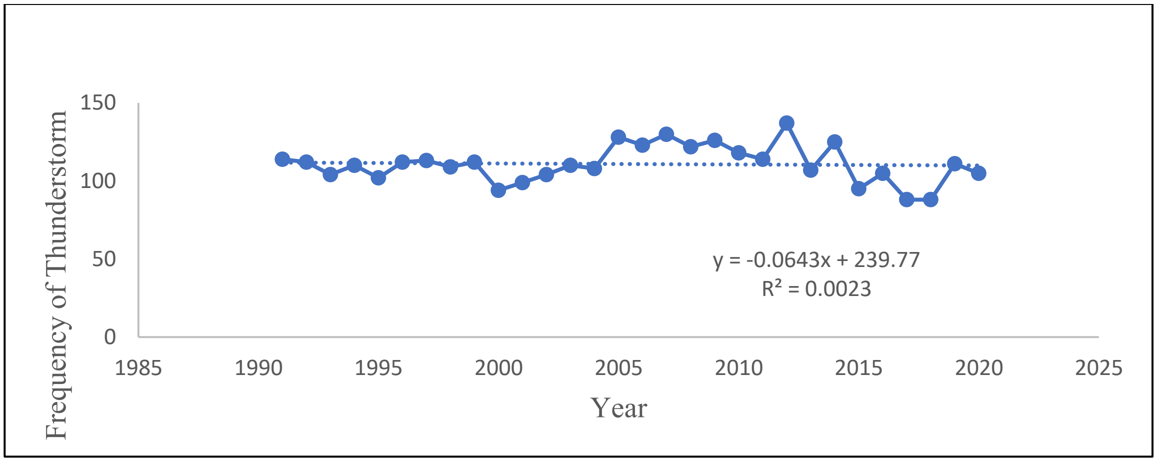


***Figure 2. Thunderstorm Frequency***

**Causal Relationship Amongst Annual Frequency of Thunderstorms and Flight Diversions, Delays and Cancellations for the entire Study period (1997-2020)**

The results of flight cancellations, delays, and diversions from 1997 to 2020, a total of 24 years period, show a total of 5104 flight cancellations. The annual cancellations fluctuated, with the highest number in 2020 (241 cancellations) and the lowest in 1997 (187 cancellations). Reasons were due to convective weather factors, such as thunderstorms, visibility, wind shear, squall lines, operations, and mechanical issues. In terms of flight delays, there were a total of 3588 flight delays between 1997 and 2020. The annual delays ranged from a maximum of 177 in 2007 to a minimum of 121 in 1997. Reasons were due to convective weather factors, thunderstorms, and operations, while a total of 3648 flights were diverted in this period.

The highest annual diversions were 174 in 2010, while the lowest was 109 in 1999. Reasons were due to convective weather factors, thunderstorms, operations, and mechanical issues. Moreover, thunderstorms occurred 2671 times between 1997 and 2020. The frequency ranged from 137 in 2012 to 88 in both 2017 and 2018. Hence, flight cancellations happened at a rate of 41.4% of the thunderstorm frequency, which implies that within 1997-2020, flight cancellations occurred almost twice as frequently as thunderstorms. Flight delays happened at a rate of 29%, meaning they were 34.3% more frequent than thunderstorms over the period; and flight diversions happened at a rate of 29.6%, meaning they were 36.6% more frequent than thunderstorms over the same period. It is noted that flight cancellations over the period (5104) were notably higher than both flight delays (3588) and flight diversions (3648). Even though the data provides the annual frequency of thunderstorms, there is no direct evidence to assert that thunderstorms are the sole reason for the flight disruptions (Table 3). It is possible, however, that there are other factors such as climate patterns (weather), land use changes, or atmospheric conditions. It is noteworthy that 2020 had the highest number of flight cancellations. While this result does not specify the reasons, one could hypothesize that global events, like the coronavirus pandemic, might have influenced this number.

***Table 3. Annual and Decadal Frequency of Thunderstorm and Flight Diversions, Delays and Cancellations (1997-2020)***

| Year | Flight Cancellations | Flight Delays | Flight Diversions | Thunderstorms frequency |
|---|---|---|---|---|
| 1997 | 187 | 121 | 154 | 113 |
| 1998 | 200 | 149 | 160 | 109 |
| 1999 | 205 | 128 | 109 | 112 |
| 2000 | 208 | 140 | 124 | 94 |
| 2001 | 198 | 156 | 140 | 99 |
| 2002 | 198 | 137 | 168 | 104 |
| 2003 | 217 | 173 | 135 | 110 |
| 2004 | 213 | 152 | 147 | 108 |
| 2005 | 231 | 139 | 149 | 128 |
| 2006 | 218 | 158 | 158 | 123 |
| 2007 | 200 | 177 | 149 | 130 |
| 2008 | 219 | 147 | 140 | 122 |
| 2009 | 221 | 142 | 149 | 126 |
| 2010 | 194 | 150 | 174 | 118 |
| 2011 | 208 | 133 | 147 | 114 |
| 2012 | 202 | 157 | 155 | 137 |
| 2013 | 206 | 150 | 168 | 107 |
| 2014 | 235 | 152 | 172 | 125 |
| 2015 | 226 | 140 | 141 | 95 |
| 2016 | 211 | 151 | 164 | 105 |
| 2017 | 214 | 161 | 157 | 88 |
| 2018 | 222 | 159 | 155 | 88 |
| 2019 | 230 | 153 | 172 | 111 |
| 2020 | 241 | 163 | 161 | 105 |
| Total | 5104 | 3588 | 3648 | 2671 |
| Total (%) | 41.4 | 29 | 29.6 | 100 |

*Source: NAMA and NIMET, 2024*

## 5. CONCLUSION

The results of the study showed that thunderstorm occurrences from 1991 to 2020 were lowest in the years 2000 and 2001, with 94 and 99 total occurrences, respectively, while the monthly occurrences were highest in August (576) and lowest in January (Krider, 2022; Idoko et al 2025). Thunderstorm characteristics showed consistent frequencies in the 1990s, a growth trend in the 2000s, and a period of highs and lows in the 2010s, culminating in a moderate stabilization by the decade's end. The influence and trend of thunderstorm occurrences on flight operations was not significant (p-value >0.05). The occurrences of thunderstorms in the next 30 years showed a high range of stability across the years (2021-2050). Based on the observations and conclusions drawn from the study, the following recommendations for further studies are proposed: To better understand the direct and indirect impacts of thunderstorms on flight operations, future studies should integrate additional data variables such as wind speed, rainfall, and other climatic parameters. This would provide a more holistic understanding of weather's impact on aviation.

i. A study focusing on the economic implications of flight delays, cancellations, and diversions due to thunderstorms would be beneficial. This would shed light on the financial strain or savings these weather occurrences might be causing the aviation industry.

ii. Flight takeoff time should be planned based on the prevailing weather conditions to prevent delays, cancellations, and to minimize accidents associated with air transport.

iii. It would be beneficial to study and evaluate the current operational strategies of the airport, specifically during thunderstorm occurrences. Understanding the immediate responses, safety protocols, and backup plans in place can provide insights into real-world practices against theoretical predictions.

iv. Considering the possibility of climate change effects on weather patterns, a longer-term study extending beyond 50 years may provide insights into longer-term patterns and their impacts on aviation.

v. This study is limited to one climatic parameter (predicted thunderstorm occurrences) because of insufficient data on other parameters such as flight delays, flight cancellations, and flight diversions due to inadequate record-keeping. Therefore, there is a need for all aviation organizations concerned to develop a grassroots information database and keep proper records of every flight operation activity.

## 6. COMPETING INTERESTS

None to declare

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