A PUBLICATION OF WORD ASTRA
wordastrajournals@gmail.com
www.*wordastrajournals.com*

Global Journal of Modern
Research and Emerging Trends (GJMRET)
Vol. 1, Issue 2, May 2025 // ISSN: 1595-076X

A Spatial Analysis of Thunderstorms and Flight Disruptions in Some Nigerian Airports from 1989–2023

Etukudo, Ukeme Francis[1]; Nwagbara, Moses Okemini[2]; Kpang, MeeluBari Barinua Tsaro[3]

[1,2]Department of Geography and Environmental Management
Faculty of Social Sciences
University of Port Harcourt, Nigeria.

[3]Department of Meteorology and Water Resources
Faculty of Environmental Sciences
Michael Okpara University of Agriculture, Umudike, Nigeria.
Corresponding Author: ukemefrancisetukudo@gmail.com; +2348036766782

DOI: https://doi.org/10.5281/zenodo.15596901

Citation: Etukudo, U. F., Nwagbara, M. O., & Kpang, M. B. T. (2025). A Spatial Analysis of Thunderstorms and Flight Disruptions in Some Nigerian Airports from 1989–2023. *Global Journal of Modern Research and Emerging Trends,* 1(2).

Abstract

This study examines the spatial patterns of thunderstorms and their relationship with flight disruptions in selected Nigerian international airports over a 35-year period (1989–2023). Focusing on two core objectives—identifying spatial variations in thunderstorms across Nigeria's major airports and ascertaining the number of flights cancelled, delayed, diverted, or crashed due to thunderstorms—an ex post facto research design was employed. Data sources included primary data from structured questionnaires administered to aviation personnel and directors of the Federal Airports Authority of Nigeria (FAAN), as well as secondary data comprising thunderstorm records and flight logs sourced from the Nigerian Meteorological Agency (NiMet) and the Nigerian Airspace Management Agency (NAMA). Six international airports with at least 35 years of continuous operation were purposively selected for analysis. Spatial interpolation using kriging in ArcGIS was utilized to map thunderstorm distributions, while time series analysis assessed trends over the study period. Descriptive statistics summarized the impact on flight operations. Hypothesis testing using one-way ANOVA revealed no statistically significant spatial variation in thunderstorm *occurrences across the airports ($F = 1.604$, $p > 0.05$). Multiple linear regression analysis indicated that thunderstorms contributed to flight disruptions but accounted for a modest portion of the variance ($R^2 = 0.157$). The study highlights the operational challenges thunderstorms pose to Nigeria's aviation sector, with increased delays, cancellations, and diversions, although not consistently across all airports. The findings underscore the need for enhanced weather monitoring, staff training, and investment in meteorological infrastructure to mitigate thunderstorm-related disruptions in Nigerian airports.*

Keywords: Thunderstorms, Flight disruptions, Nigerian airports, Spatial analysis, Aviation safety, Meteorological hazards

1.1 Introduction

Thunderstorms, characterized by intense convective activity including lightning, thunder, heavy rainfall, and strong winds, represent a significant meteorological hazard with substantial implications for aviation. Globally, thunderstorms are recognized as a leading cause of flight disruptions, contributing to delays, diversions, cancellations, and, in rare cases, accidents (Vittorio, 2021; Kinza et al., 2023). Their localized, short-lived yet severe nature poses operational challenges for air traffic management and passenger safety (Lia et al., 2024).

Nigeria, situated near the Inter-Tropical Convergence Zone (ITCZ), is particularly susceptible to thunderstorm formation, especially during the rainy season from April to October (Onwuadiochi et al., 2023; Yunisa et al., 2022). This high frequency of thunderstorms directly impacts flight operations at key international airports, including Lagos, Abuja, Port Harcourt, and others. The concentration of air traffic at these hubs means that even moderate weather disturbances can cascade into significant operational challenges, affecting airlines, passengers, and airport authorities alike (Dixit & Jakhar, 2021).

While global studies have extensively explored the impact of adverse weather on aviation operations (Lui et al., 2020; Taszarek et al., 2020), there remains a paucity of empirical research focused specifically on Nigeria's unique thunderstorm patterns and their direct operational implications. Most existing studies emphasize general aviation safety and air traffic management without a detailed examination of the spatial characteristics of thunderstorms or their quantifiable impact on flight operations (Olabode, 2021; Onwuadiochi et al., 2023).

This study seeks to address this research gap by investigating the spatial variations of thunderstorms across selected Nigerian international airports and determining the extent of flight disruptions—delays, cancellations, diversions, and crashes—attributable to thunderstorms over a 35-year period (1989–2023). Using a combination of spatial analysis, time series evaluation, and descriptive statistics, the research aims to provide insights into the localized impacts of thunderstorms and the operational vulnerabilities of Nigerian airports.

The findings from this study will enhance the understanding of thunderstorm-related aviation disruptions in Nigeria's unique meteorological landscape. Additionally, the results will inform policymakers, aviation authorities, and other stakeholders on the need for effective mitigation strategies, including improved weather monitoring, staff training, and infrastructural resilience. Ultimately, this research aims to contribute to a safer, more efficient aviation sector in Nigeria amid the challenges posed by frequent and severe thunderstorms.

1.2 Statement of the Problem

Thunderstorms significantly impact aviation safety and efficiency worldwide, accounting for nearly 20% of weather-related flight disruptions (Akay & Tarhan, 2023). Nigeria's position near the Inter-Tropical Convergence Zone (ITCZ) makes its airspace particularly vulnerable to frequent and severe thunderstorms, especially during the rainy season (Nigeria Meteorological Agency, 2020). This presents a critical challenge for flight operations at major international airports like Lagos, Abuja, and Port Harcourt, where reliable air travel is essential due to poor road infrastructure and security concerns.

Despite their operational impact, there is limited understanding of the spatial patterns of thunderstorms across Nigeria's airports and their specific effects on flight delays, cancellations, diversions, and accidents. Nigeria's aviation sector also struggles with outdated meteorological systems and inadequate radar coverage, leaving pilots and air traffic controllers with limited situational awareness during storms (Kwasiborska et al., 2023). According to the Nigerian Civil Aviation Authority (NCAA, 2023), thunderstorms contribute to up to 35% of annual weather-related flight delays and cancellations, yet only a fraction of airports have functioning wind shear detection systems (Ministry of Aviation, 2019).

These operational challenges lead to aborted landings, emergency diversions, and network-wide congestion, impacting both airlines and passengers (Olabode, 2021). The economic cost is significant, with annual losses estimated at over ₦10 billion due to thunderstorm-induced disruptions (NAHCO, 2022). Yet, few studies have systematically examined the spatial distribution of thunderstorms and their operational impacts in Nigeria over an extended period.

This study aims to fill this gap by analyzing the spatial variation of thunderstorms across selected Nigerian international airports and evaluating their effect on flight disruptions over a 35-year period (1989–2023). The findings will guide recommendations to enhance weather monitoring, operational procedures, and aviation safety in Nigeria.

1.3 Objectives of the Study

The study aims at meeting the objectives of**:**

i. identifying the spatial variations of thunderstorms across Nigeria, with particular emphasis on selected international airports;

ii. and ascertaining the flights cancelled, delayed, diverted, or crashed due to thunderstorms during the period under review.

1.4 Research Questions

i. What are the spatial variations of thunderstorms across Nigeria over the past 35 years?

ii. How many flights were cancelled, delayed, diverted or crashed owing to thunderstorms over airports in Nigeria during the past 35 years?

1.5 Hypotheses

i. There is no statistically significant spatial variation in the thunderstorm characteristics across the study area.

ii. Flights cancelled, delayed, diverted or crashed do not significantly depend on thunderstorms in Nigeria during the past 35 years

1.6 Significance of the Study

This study is significant for several reasons. First, it provides a comprehensive spatial analysis of thunderstorm distribution across Nigerian airports over the past 35 years, filling a critical knowledge gap in weather-related aviation challenges. By pinpointing high-risk areas and seasons, the research offers insights that can aid aviation authorities and airlines in developing more effective weather monitoring and risk management strategies.

Second, the study empirically assesses how thunderstorms disrupt flight operations through delays, cancellations, diversions, and flight safety incidents, offering practical evidence for operational decision-making. This is particularly important for pilots, air traffic controllers, and airport managers who must balance safety with efficiency in a busy aviation environment.

Finally, the findings have important implications for aviation policy and infrastructure planning in Nigeria. By highlighting the operational and economic consequences of thunderstorms, the study underscores the need for investment in modern weather forecasting systems, wind shear detection, and resilient infrastructure. This can improve flight safety, reduce disruptions, and strengthen public confidence in air travel, supporting Nigeria's broader economic growth.

2.1 Conceptual Framework

Vulnerability refers to the degree to which aviation systems are exposed to adverse weather, particularly thunderstorms, which are common in Nigeria due to its proximity to the Inter-Tropical Convergence Zone (Nigeria Meteorological Agency, 2020). These thunderstorms vary in frequency, intensity, and spatial distribution, affecting airports differently (Rehfeld et al., 2020; Burbidge et al., 2023). This underscores Objective i, which focuses on identifying the spatial distribution of thunderstorms across selected airports.

Sensitivity captures the extent to which flight operations, such as takeoff, landing, and en-route flight, are disrupted by thunderstorms through turbulence, wind shear, and reduced visibility (Hassan et al., 2021; Grootel et al., 2020). High sensitivity increases the likelihood of delays, diversions, and safety risks.

Adaptability refers to how well aviation systems respond operationally through dynamic scheduling, rerouting, and emergency protocols (Wang & Bo, 2023; Impram et al., 2020). This aligns with the second objective, which examines flight disruptions (delays, cancellations, diversions, and crashes) caused by thunderstorms. Adaptability enhances resilience, reducing the impact of severe weather on flight operations.

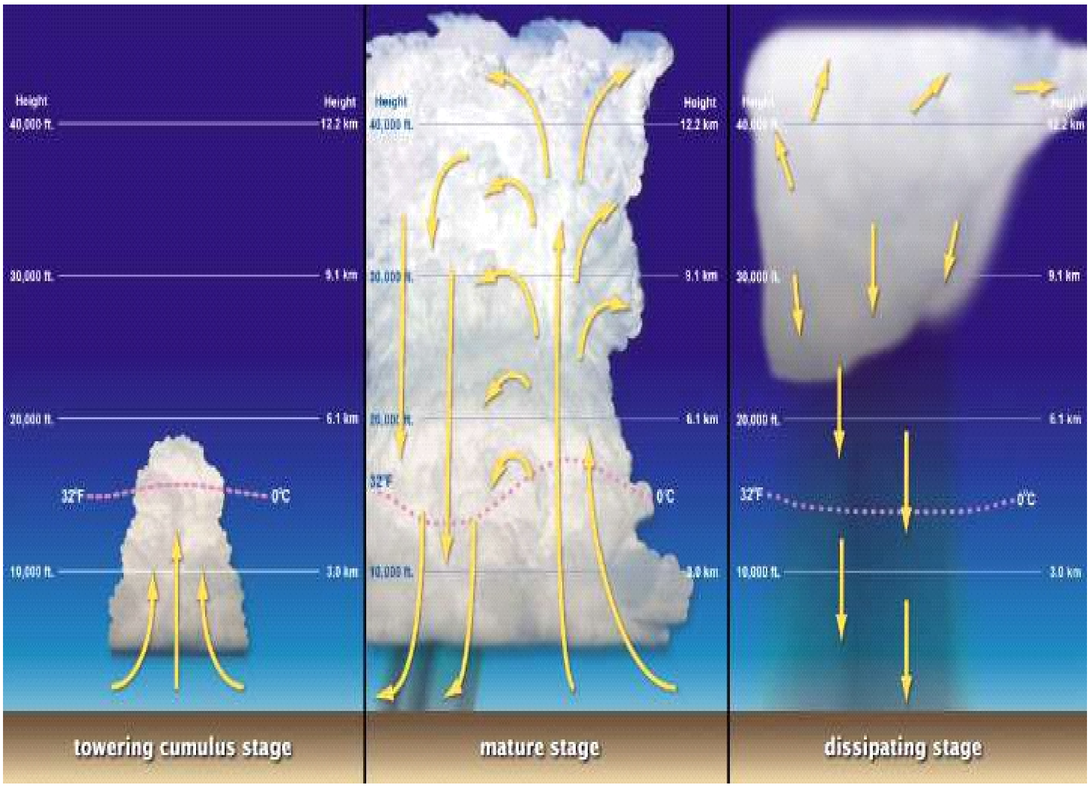


Figure 2.2: Thunderstorm explained
Source: Lashkari and Hojati, (2012)

2.1.1 Spatial Variation in Thunderstorms and Aviation Impact

Thunderstorms are a major meteorological hazard that significantly affects aviation safety and operational efficiency, especially in tropical regions like Nigeria. Due to frequent convective activity, thunderstorms can cause flight delays, diversions, cancellations, and, in rare cases, accidents resulting from severe turbulence, lightning, wind shear, hail, and intense rainfall (Olive et al., 2023). These disruptions are particularly critical in terminal areas where aircraft are most vulnerable during takeoff and landing. While extensive research has explored thunderstorm impacts in developed countries such as the United States (Kohler et al., 2017), there remains a critical gap in understanding the spatial variation and characteristics of thunderstorms affecting Nigeria's major international airports—an issue this study seeks to address.

Technological advancements like Doppler radar, satellite imagery, and range-height indicators (RHIs) have enhanced the monitoring and analysis of thunderstorm structures, improving forecasting accuracy and operational decision-making (Kurdzo et al., 2015; González-Arribas et al., 2019). However, thunderstorms exhibit considerable spatial variability driven by local factors such as humidity, temperature gradients, and wind patterns (Taszarek et al., 2019). In Nigeria, these factors contribute to the formation of intense convective systems that vary significantly across regions and airport locations. Recognizing these spatial differences is crucial in understanding their direct impact on aviation operations, including delays, diversions, and safety risks, and for developing tailored risk management strategies. Moreover, the potential influence of climate change on thunderstorm frequency and severity highlights the need for ongoing research and policy interventions to improve aviation resilience in the country's dynamic weather environment (Rädler et al., 2019; Onwuadiochi et al., 2023).

2.1.2 Flight Disruption Incidents

Thunderstorms are a major source of flight disruptions in Nigeria's aviation sector, particularly during the rainy season when convective activity intensifies. Due to regional climate differences, these storms vary spatially across Nigeria's international airports, impacting the frequency and severity of disruptions. Thunderstorms often bring intense rainfall, lightning, wind shear, and reduced visibility that can halt terminal operations and create hazardous conditions during takeoff and landing. Wind shear, in particular, poses serious hazards, as illustrated by incidents such as the 2006 ADC Airline crash near Abuja and the 2006 Sosoliso crash near Port Harcourt, both highlighting the critical need to understand the relationship between thunderstorms and aviation safety.

Operational impacts of thunderstorms on aviation processes include flight delays, cancellations, and diversions. When severe weather makes it unsafe to land or take off, aircraft may be delayed until conditions improve or diverted to alternate airports, disrupting schedules and straining logistics for airlines. These delays can cascade through the air traffic system, compounding congestion and affecting overall efficiency. Although other weather phenomena such as fog, harmattan dust, and strong winds also affect aviation, thunderstorms remain the most impactful due to their rapid development and severe conditions. The increasing intensity and frequency of thunderstorms, potentially driven by climate change, underscore the importance of improved weather forecasting, radar coverage, and risk assessment to enhance aviation safety and operational efficiency in Nigeria's airports. Documenting and analyzing flight disruptions caused by thunderstorms at selected airports is crucial for quantifying their impact and developing targeted mitigation strategies.

2.2 Theoretical Framework

This research is anchored on two theories: aviation safety theory and risk management theory. Aviation safety theory provides a foundational lens for analyzing how thunderstorms disrupt flight operations in Nigeria's major airports. This theory encompasses historical models such as Heinrich's Domino Theory of accident causation and James Reason's Swiss Cheese Model, which emphasize the systemic nature of safety risks. The Swiss Cheese Model, in particular, highlights how multiple layers of defense—technical systems, human factors, and organizational practices—can align in such a way that hazards, like thunderstorms, penetrate all defenses, leading to incidents. By applying these insights, the study can evaluate how thunderstorms interact with the complex aviation ecosystem in Nigeria, where multiple factors (e.g., weather monitoring, pilot decision-making, and ground operations) determine overall flight safety and efficiency.

Risk management theory, rooted in decision theory and refined through contributions from Knight, Arrow, and ISO frameworks, complements aviation safety theory by offering a systematic approach to identifying, assessing, and mitigating risks posed by thunderstorms, directly addressing Objective (ii). This theory advocates for a structured process—risk identification, risk assessment, risk mitigation, and continuous monitoring—to manage hazards that can impede organizational objectives. In the context of Nigerian airports, this involves identifying the frequency and severity of thunderstorms at major hubs like Lagos, Abuja, and Port Harcourt; assessing their impact on flight delays, cancellations, and diversions; and developing mitigation strategies such as advanced radar systems, real-time weather monitoring, and staff training to ensure operational safety and efficiency during storm events.

Together, aviation safety theory and risk management theory enable a multidimensional examination of how thunderstorms affect flight operations. The theories recognize that aviation is a high-risk industry where safety outcomes depend on the interplay of technical systems, human decision-making, and organizational protocols. This study applies these frameworks to explore both immediate operational disruptions—like flight delays, diversions, and cancellations—and underlying systemic factors, including equipment vulnerabilities, weather forecasting limitations, and communication lapses that may exacerbate the impact of thunderstorms.

By grounding the study in these theories, researchers can not only assess the direct effects of thunderstorms but also recommend evidence-based strategies for enhancing aviation safety. This includes improving meteorological services, reinforcing safety cultures, investing in staff training, and developing adaptive risk management plans tailored to the unique weather patterns of Nigeria. Ultimately, this theoretical framework supports a comprehensive understanding of thunderstorm-induced disruptions and enables the development of robust recommendations to enhance aviation safety and operational continuity at major Nigerian airports.

2.3 Empirical Review

2.3.1 Spatial Variations in Thunderstorms and Aviation Impact

Understanding the spatial variability of thunderstorms is essential for aviation safety, especially during critical flight phases like take-off and landing. Research by Lopukh and Berazhkova (2019) and Cintineo et al. (2020) underscores the value of analysing spatial and temporal storm patterns using meteorological data, satellite imagery, and machine learning to enhance forecasting accuracy. Tan et al. (2022) showed that incorporating Doppler lidar data into weather models significantly improved short-term predictions near airports. Additionally, geographic and socioeconomic factors shape the spatial distribution of thunderstorm warnings, as highlighted by White and Stallins (2017) in the U.S. and by Singh and Bhardwaj (2019), Tyagi (2021), and León-Cruz et al. (2023) in India and Mexico, respectively, emphasising the need for regionalised risk assessments in aviation planning.

Technological advancements have further strengthened aviation weather forecasting and hazard mitigation. Javier et al. (2021) and Eduardo et al. (2021) introduced innovative tools such as convective risk mapping and scenario-based trajectory planning to reduce rerouting. The use of convolutional neural networks by Aniel et al. (2023) and Roman et al. (2024) has enhanced thunderstorm prediction and air traffic management across Europe. Meanwhile, Ismail et al. (2019) highlighted the role of integrating high-resolution sensing technologies, such as lidars and UAVs, into next-generation forecasting systems. Collectively, these studies reflect the growing precision and effectiveness of data-driven models and spatial climatology in safeguarding aviation operations from thunderstorm-related hazards.

2.3.2 Flight Disruption Incidents

Flight disruption management is a critical area of research, given its significant operational and financial impacts on airlines. Hassan Santos and Vink (2021) reviewed literature from 2009 to 2018, highlighting the importance of integrating multiple resources—aircraft, crew, and passengers—into disruption recovery analyses to bridge the gap between theoretical models and real-world operations. Lee, Marla, and Jacquillat (2020) proposed a Stochastic Reactive and Proactive Disruption Management (SRPDM) model, combining stochastic queuing with integer programming to minimize recovery costs through proactive decisions like departure holds. Similarly, Rhodes-Leader et al. (2021) introduced a multi-fidelity modeling framework for the Aircraft Recovery Problem, integrating deterministic solutions with simulation optimization to handle uncertainty effectively.

Several studies have focused on modeling the complex dynamics of aircraft recovery and the propagation of delays. Guimarans et al. (2015) emphasized the stochastic nature of disruption propagation using a Large Neighborhood Search metaheuristic, outperforming deterministic approaches. Pang (2020) examined how disruptions at full-service carriers (FSCs) affect competitor airlines, highlighting that interconnected resources can amplify delays across the industry. Sun and Wandelt (2018) analyzed the vulnerability of global airline networks to disruptions, revealing that many airlines are less robust than previously thought, suggesting a need to enhance resilience. Jong and Lieshout (2021) quantified the environmental impact of airspace disruptions, noting that strikes increased aircraft kilometres flown by millions, leading to higher fuel consumption and CO2 emissions, underscoring the need for better strategic planning.

Operational responses to disruptions also play a vital role. Scozzaro et al. (2023) proposed flight rescheduling strategies to manage airport access disruptions, significantly reducing stranded passengers. Su et al. (2021) reviewed integrated recovery approaches, covering aircraft, crew, and passenger recovery. Sousa et al. (2015) introduced an automated approach using Ant Colony Optimization to dynamically recover disrupted schedules, while Wu et al. (2017) applied an iterative fixed-point method for aircraft reassignment. Collectively, these studies illustrate the growing sophistication of modeling and algorithmic solutions in managing flight disruptions, emphasizing the importance of data-driven decision-making and integrated approaches for efficient airline operations.

3 Methodology

This study employed an ex post facto research design to analyse historical data on the impact of thunderstorms on flight operations at major Nigerian airports. The population included operational staff at 12 key airports, from which six international airports with at least 35 years of activity—such as Lagos, Abuja, and Kano—were purposively selected to align with the climate data timeframe. Data were drawn from structured questionnaires and secondary sources, including the Nigerian Aerospace Management Agency (NAMA) and the Nigerian Meteorological Agency (NiMet). Climate variables such as thunderstorms, rainfall, temperature, wind conditions, visibility, and cloud types were analysed over a 35-year period, alongside flight operation records detailing lifted, cancelled, diverted, delayed, or crashed flights. Additionally, four FAAN directors of operations from the selected airports were interviewed to provide qualitative insights into flight disruptions.

The data analysis was aligned with two key objectives. To examine the characteristics and spatial variations of thunderstorms, spatial analysis tools such as kriging in ArcGIS and time series trend analysis were used. To evaluate flight disruptions, including cancellations, delays, diversions, and crashes, frequency and percentage analyses were combined with time series techniques and visualisations like grouped bar charts. This methodological approach ensured a comprehensive understanding of how thunderstorms affect aviation operations in Nigeria, linking spatial and operational data to produce evidence-based conclusions.

The two formulated hypotheses will be analysed using ANOVA and MLR. Hypothesis one (there is no spatial variation in the thunderstorm characteristics across the study area) will be tested using ANOVA. The mathematical formula for ANOVA is given by the formula below:

ANOVA Equation

$$\text{TES} = \sum x^2 - \frac{(\sum x)^2}{N} \quad \text{----} \quad \text{----} \quad \text{----} \quad 3.1$$

$$\text{ESS} = \frac{(\sum x_1)^2}{n_1} + \frac{(\sum x_2)^2}{n_2} + \frac{(\sum x_3)^2}{n_3} + \frac{(\sum x_4)^2}{n_4} - \frac{(\sum x)^2}{N} \ldots\ldots 8\,x$$

$$\text{WSS} = \text{TSS} - \text{BSS} \quad \text{----} \quad \text{----} \quad 3.2$$

Where: TSS = Total Sum of Squares
BSS = Between Sample Sum of Squares
WSS = Within Sample Sum of Squares
$n_1 \ldots n_4$ = Number of Samples means being compared
N = Total items of all groups.

Hypothesis two (Flights cancelled, delayed, diverted or crashed do not significantly depend on thunderstorms in Nigeria during the past 35 years) will be tested using multiple linear regressions. This analysis will be conducted using IBM/SPSS V/22.

4.1 Results and Discussion of findings

Research Question One: What are the spatial variations of thunderstorms across Nigeria over the past 35 years?

Table 4.1: Annual thunderstorms and their impact on flight operations in selected Nigerian international airports.

Years	Abuja	Enugu	Kaduna	Kano	Ikeja-Lagos	Port Harcourt
1989	99	109	93	42	93	149
1990	109	122	91	46	104	161
1991	96	136	100	62	81	144
1992	89	109	81	55	83	148
1993	90	107	94	51	76	150
1994	101	111	108	35	98	155
1995	95	120	92	48	92	153
1996	99	107	97	58	106	136
1997	95	118	98	51	75	166
1998	87	106	104	62	88	151
1999	95	118	94	59	76	172
2000	82	104	89	46	96	146
2001	88	105	92	62	66	151
2002	101	120	95	54	84	152
2003	94	107	91	60	90	157
2004	83	116	96	39	97	140
2005	98	113	91	57	94	138
2006	87	120	91	55	107	132
2007	92	109	79	47	89	142
2008	83	116	86	57	103	144
2009	90	115	87	50	83	142
2010	103	105	96	61	103	152
2011	83	107	106	52	97	147
2012	99	135	97	54	109	140
2013	77	117	83	50	102	127
2014	93	113	100	42	109	132
2015	96	113	74	41	102	139
2016	101	105	85	57	94	148
2017	87	116	79	44	128	141
2018	89	126	92	60	137	141
2019	111	121	92	53	126	168
2020	108	109	96	56	100	136
2021	95	99	85	56	126	151
2022	116	103	102	57	117	126
2023	104	108	83	47	128	147
2024	101	97	81	53	100	140
Mean	**94.89**	**112.83**	**91.67**	**52.19**	**98.86**	**146.22**

Table 4.1 presents the characteristics of thunderstorms over the past thirty-five years across selected international airports in Nigeria. The data reveal notable spatial and temporal variations in thunderstorm occurrences, which significantly impact flight operations. The mean annual thunderstorm days for the period under review varied across locations, with Port Harcourt recording the highest mean thunderstorm days at 146.22, followed by Enugu (112.83) and Ikeja-Lagos (98.86). Conversely, Kano had the lowest mean thunderstorm days (52.19), while Kaduna and Abuja recorded 91.67 and 94.89 thunderstorm days, respectively.

Table 4.2: Spatial variation in thunderstorms in selected Nigerian international airports.

ANOVA

Thunderstorm

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	505609.833	5	101121.967	1.604	.171
Within Groups	4160082.167	66	63031.548		
Total	4665692.000	71			

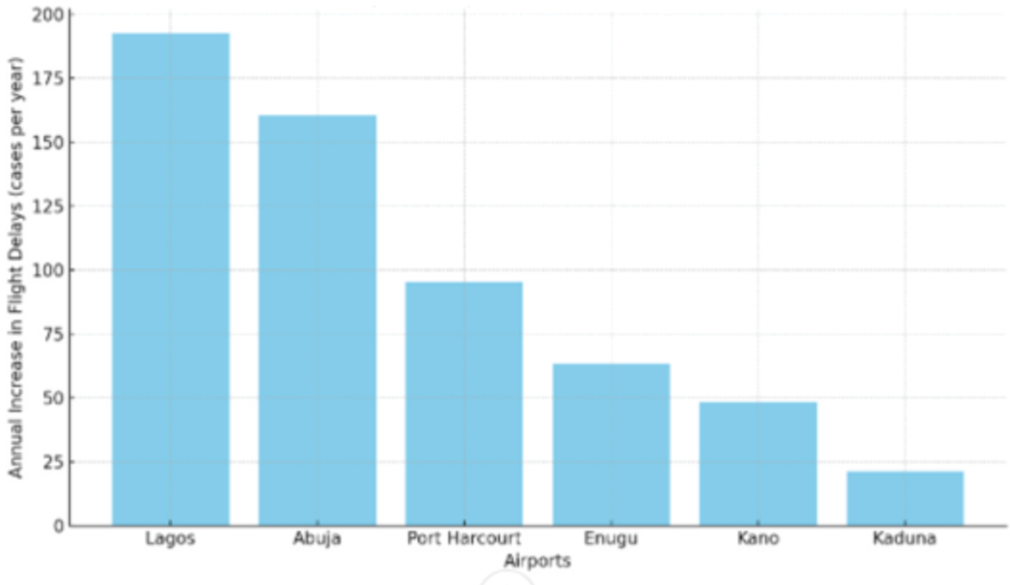
***Source:** Author's computation (2025)*

Table 4.2 examines the spatial differences in thunderstorm characteristics across selected Nigerian international airports, with ANOVA results revealing that the model is not statistically significant at $p < 0.05$ ($F = 1.604$, Sig. = 0.171). This outcome suggests that the null hypothesis cannot be rejected, indicating no significant spatial variation in thunderstorm occurrences among the selected airports. Although thunderstorms vary in frequency across locations, these differences are not statistically strong enough to establish meaningful spatial disparities. Nonetheless, local meteorological factors, such as topography, proximity to water bodies, and prevailing wind patterns, may still influence the intensity and frequency of thunderstorms at individual airports.

Research Question Two: How many flights were cancelled, delayed, diverted or crashed owing to thunderstorms over airports in Nigeria in the past 35 years?

The analysis of thunderstorm-related flight disruptions at selected Nigerian international airports over the past 35 years reveals a marked increase in delays, diversions, and cancellations, with Lagos Airport recording the highest disruptions annually. Abuja Airport saw flight delays rising at a rate of 160.48 cases per year, with a peak between 2009 and 2019, and cancellations increasing by 51.04 cases annually; no crashes linked to thunderstorms were recorded. Lagos Airport experienced the highest annual increase in delays at 192.40 cases and cancellations at 87.09 cases, alongside a steady rise in diversions at 14.28 cases per year, though major incidents like the Dana Air Flight 992 crash in 2012 were not directly attributed to thunderstorms. Port Harcourt Airport recorded significant disruptions, with delays increasing by 95.33 cases and cancellations by 45.67 cases annually, raising safety concerns following the 2005 Sosoliso Airlines crash, though not all incidents were storm-related. Enugu Airport saw delays rise by 63.29 cases per year and cancellations by 39.81 cases, while Kano Airport recorded lower levels of disruptions (delays at 48.22 cases and cancellations at 28.19 cases annually). Kaduna Airport had the lowest disruption levels, with delays increasing by 21.10 cases and cancellations by 11.89 cases per year; the 2021 Nigerian Air Force crash was not confirmed as storm-related. Overall, Lagos Airport recorded the highest increase in annual flight disruptions, while Kaduna Airport experienced the lowest during the period under review.

Fig. 1: Annual Increase in Flight Delays Due to Thunderstorms (35-Year Review)



4.2 Test of Hypothesis

Null Hypothesis One: There is no statistically significant spatial variation in thunderstorm across the study area.

To analyse the hypothesis, we reference the ANOVA results presented in Table 4.2. The analysis yielded an F-value of 1.604 and a p-value (Sig.) of 0.171, which exceeds the conventional significance threshold of 0.05. This indicates that the differences in thunderstorm characteristics among the selected Nigerian international airports are not statistically significant.

- **Decision Rule:** Reject H_0 if $p < 0.05$
- **Conclusion:** Since $p = 0.171 > 0.05$. The null hypothesis was therefore accepted.

This result suggests that while there may be observable differences in the frequency or pattern of thunderstorms across individual airports, these differences are not statistically robust enough to confirm significant spatial variation. However, this does not rule out the influence of local meteorological factors (e.g., topography, proximity to water bodies, prevailing wind patterns), which may still play a role in site-specific thunderstorm characteristics. Further analysis incorporating these localised variables could provide additional insights beyond the general spatial comparison.

Null Hypothesis Two: Flights cancelled, delayed, diverted or crashed do not significantly depend on thunderstorms in Nigeria during the past 35 years

Table 4.3: Model Summary of the Flights cancelled, delayed, diverted or crashed due to thunderstorms in Nigeria during the past 35 years

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.396	.157	-.021	1.763

a. Predictors: (Constant), Crashed, Cancelled, Diverted, Delays

The hypothesis test ($H0_2$) examined whether flights cancelled, delayed, diverted, or crashed significantly depended on thunderstorms in Nigeria over 35 years. The results presented in Table 4.3 show a coefficient of determination (R^2) of 0.157, indicating that only 15.7% of the variance in flight disruptions is explained by thunderstorm occurrences. However, the adjusted R^2 is negative (-0.021), suggesting limited explanatory power when accounting for the number of predictors. The standard error of the estimate is 1.763, highlighting notable deviation between observed and predicted values. These findings suggest that while thunderstorms contribute to flight cancellations, delays, diversions, and crashes, other factors likely play a more significant role in explaining these disruptions, highlighting the complexity of aviation operations and the multifaceted nature of flight disruptions in Nigeria.

Table 4.4: Analysis of variance of regression of the Flights cancelled, delayed, diverted or crashed due to thunderstorms in Nigeria during the past 35 years

Model		Sum of Squares	df	Mean Square	F	Sig.
	Regression	10.961	4	2.740	.882	.493
	Residual	59.039	19	3.107		
	Total	70.000	23			

a. *Dependent Variable: Airports*
b. *Predictors: (Constant), Crashed, Cancelled, Diverted, Delays*

Table 4.4 shows that the regression model has an F-value of 0.882, which is not significant at the 0.493 level. This result indicates that the regression model does not significantly explain the variations in flights cancelled, delayed, diverted, or crashed due to thunderstorms in Nigeria over the past 35 years. Consequently, the null hypothesis—that there is no significant linear relationship between flight disruptions and thunderstorms—cannot be rejected. This finding suggests that while thunderstorms may contribute to some disruptions, they are not strong standalone predictors of such events, underscoring the need to explore additional factors influencing flight operations for a more comprehensive understanding of the issue.

5.1 Conclusion

This study comprehensively analyzed thunderstorm characteristics and their effects on aviation processes at selected Nigerian international airports over the past 35 years. The findings revealed that while thunderstorms do occur frequently, their spatial variations across airports were not statistically significant. However, thunderstorms were found to significantly disrupt aviation operations, including increased flight delays, cancellations, diversions, and safety risks. Importantly, the analysis showed that thunderstorms alone did not fully account for the variations in flight disruptions, suggesting the influence of additional factors such as operational practices and infrastructure. This highlights the urgent need for integrated strategies to improve aviation resilience and safety during severe weather events.

5.2 Recommendations

Based on the study's objectives and findings, the following recommendations are proposed to mitigate the impacts of thunderstorms on aviation operations and enhance operational efficiency:

i. Improve meteorological capabilities at Nigerian airports to enhance thunderstorm forecasting accuracy and provide timely warnings to aviation stakeholders.
iii. Conduct regular training for aviation personnel (including pilots and air traffic controllers) on thunderstorm management protocols to better handle weather-related disruptions.

iv. Develop adaptive scheduling strategies for airlines, particularly during peak thunderstorm seasons, to minimize delays and cancellations while ensuring passenger safety.
v. Strengthen collaboration between meteorological agencies and aviation stakeholders to ensure timely and accurate dissemination of severe weather information.
vi. Educate passengers about the potential impacts of thunderstorms on flight schedules to improve awareness and cooperation during weather-related disruptions.

5.3 Contributions to Knowledge

i. This research provides empirical evidence on the effects of thunderstorms on aviation processes in Nigeria, addressing a critical gap in aviation safety literature.
ii. The study identifies key meteorological factors influencing thunderstorm occurrences and their temporal patterns, offering insights that can guide future research and operational planning.
iii. The study establishes a foundation for further investigations into the relationship between climate variability and aviation safety in Nigeria, paving the way for future policy and operational improvements.

References

Arrow, K. J. (1965). Aspects of the theory of risk-bearing. Yrjö Jahnssonin Säätiö.

Burbidge, R., Paling, C., & Dunk, R. (2023). A systematic review of adaption to climate change impacts in the aviation sector. *Transport Reviews*, 44, 8 - 33. https://doi.org/10.1080/01441647.2023.2220917.

Burbidge, R., Paling, C., & Dunk, R. (2025). Adapting Latin American and Caribbean airports to a changing climate: Impacts, challenges and solutions. *Climate Risk Management*. https://doi.org/10.1016/j.crm.2024.100684.

Cintineo, J., Pavolonis, M., Sieglaff, J., Wimmers, A., Brunner, J., & Bellon, W. (2020). A Deep-Learning Model for Automated Detection of Intense Midlatitude Convection Using Geostationary Satellite Images. Weather and Forecasting. https://doi.org/10.1175/waf-d-20-0028.1.

Dixit, A., & Jakhar, S. (2021). Airport capacity management: A review and bibliometric analysis. *Journal of Air Transport Management*, 91, 102010. https://doi.org/10.1016/j.jairtraman.2020.102010.

Eduardo, Andrés., Daniel, González-Arribas., Manuel, Soler., Maryam, Kamgarpour., Manuel, Sanjurjo-Rivo. (2021). Informed scenario-based RRT for aircraft trajectory planning under ensemble forecasting of thunderstorms. Transportation Research Part C-emerging Technologies, doi: 10.1016/J.TRC.2021.103232

Federal Aviation Administration. (2021). Safety management system (SMS) manual. FAA.

Federal Ministry of Aviation. (2019). About the Ministry of Aviation. Retrieved from https://aviation.gov.ng/index.php/about-us/mandates

Grootel, A., Chang, J., Wardle, B., & Olivetti, E. (2020). Manufacturing variability drives significant environmental and economic impact: The case of carbon fibre reinforced polymer composites in the aerospace industry. *Journal of Cleaner Production*, 261, 121087. https://doi.org/10.1016/j.jclepro.2020.121087.

Guimarans, D., Arias, P., & Mota, M. (2015). Large neighbourhood search and simulation for disruption management in the airline industry. , 169-201. https://doi.org/10.1007/978-3-319-15033-8_6.

Hassan, L., Santos, B., & Vink, J. (2021). Airline disruption management: A literature review and practical challenges. Comput. Oper. Res., 127, 105137. https://doi.org/10.1016/j.cor.2020.105137. https://www.faa.gov/about/initiatives/sms

Impram, S., Neşe, S., & Oral, B. (2020). Challenges of renewable energy penetration on power system flexibility: A survey. *Energy Strategy Reviews*, 31, 100539. https://doi.org/10.1016/j.esr.2020.100539.

Ismail, Gultepe., Robert, Sharman., Paul, Williams., Binbin, Zhou., Gary, P., Ellrod., Patrick, Minnis., Stanley, B., Trier., Sarah, M., Griffin., Seong, Soo, Yum., Bahram, Gharabaghi., Wayne, F., Feltz., Marouane, Temimi., Zhaoxia, Pu., Luke, N., Storer., Philipp, Kneringer., Michael, Weston., Hui-ya, Chuang., Ludovic, Thobois., A., P., Dimri., Sebastian, J., Dietz., Gutemberg, Borges, França., Manoel, Valdonel, de, Almeida., F., L., Albquerque, Neto. (2019). A Review of High Impact Weather for Aviation Meteorology. Pure and Applied Geophysics, doi: 10.1007/S00024-019-02168-6

Javier, García-Heras., Manuel, Soler., Daniel, González-Arribas., Kurt, Eschbacher., Carl-Herbert, Rokitansky., Daniel, Sacher., Ulrike, Gelhardt., Jürgen, Lang., Thomas, Hauf., Juan, Pablo, Simarro., Alfonso, Valenzuela., Antonio, Franco., Damián, Rivas. (2021). Robust flight planning impact assessment considering convective phenomena. Transportation Research Part C-emerging Technologies, doi: 10.1016/J.TRC.2021.102968

Jong, G., & Lieshout, R. (2021). Disruption in the air: The impact of flight rerouting due to air traffic control strikes. Transportation Research Part D-transport and Environment, 90, 102665. https://doi.org/10.1016/j.trd.2020.102665.

Kinza, Amjad., Muhammad, Sohail, Malik., Hamid, Ghous., Aftab, Hussain., Maryem, Ismail. (2023). Thunderstorms Prediction Using Satellite Images. doi: 10.58325/ijisct.002.01.0044

Knight, F. H. (1921). Risk, uncertainty, and profit. Houghton Mifflin.

Kohler, M., Tafferner, A., & Gerz, T. (2017). Cb-LIKE – Cumulonimbus Likelihood: Thunderstorm forecasting with fuzzy logic. *Meteorologische Zeitschrift*, 26, 127-145. https://doi.org/10.1127/METZ/2016/0805.

Kurdzo, J., Nai, F., Bodine, D., Bonin, T., Palmer, R., Cheong, B., Lujan, J., Mahre, A., & Byrd, A. (2015). Observations of Severe Local Storms and Tornadoes with the Atmospheric Imaging Radar. *Bulletin of the American Meteorological Society*, 98, 915-935. https://doi.org/10.1175/BAMS-D-15-00266.1.

Kwasiborska, A. (2021). Development of an Algorithm for Determining the Aircraft Pushback Sequence. *Acta Polytechnica Hungarica*, 18, 157-173. https://doi.org/10.12700/APH.18.6.2021.6.9.

Kwasiborska, A., & Kądzioła, K. (2023). Application of Causal Analysis of Disruptions and The Functional Resonance Analysis Method (Fram) In Analyzing the Risk of The Baggage Process. Scientific Journal of the Silesian University of Technology. Series Transport. https://doi.org/10.20858/sjsutst.2023.119.4.

Kwasiborska, A., Grabowski, M., Sedláčková, A., & Novák, A. (2023). The Influence of Visibility on the Opportunity to Perform Flight Operations with Various Categories of the Instrument Landing System. *Sensors (Basel, Switzerland)*, 23. https://doi.org/10.3390/s23187953.

Lee, J., & Collins, G. (2017). Risk analysis of lightning effects in aircraft systems. 2017 IEEE Aerospace Conference, 1-9. https://doi.org/10.1109/AERO.2017.7943671.

Lee, J., Marla, L., & Jacquillat, A. (2020). Dynamic Disruption Management in Airline Networks Under Airport Operating Uncertainty. Microeconomics: General Equilibrium & Disequilibrium Models eJournal. https://doi.org/10.2139/ssrn.3082518.

Lee, K., Kang, J., Paing, Z., & Baik, H. (2023). Prediction of aircraft delays at busy airports considering weather information with machine learning techniques. 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC), 1-6. https://doi.org/10.1109/DASC58513.2023.10311121.

León-Cruz, J., Caetano, E., Cortés-Ramos, J., Domínguez, C., & Méndez-Pérez, J. (2023). Thunderstorm and hailstorm environments in Mexico. International Journal of Climatology, 43, 4379 - 4395. https://doi.org/10.1002/joc.8093.

Lewis, B., Gawron, V., Esmaeilzadeh, E., Mayer, R., Moreno-Hines, F., Nerwich, N., & Alves, P. (2021). Data-Driven Estimation of the Impact of Diversions Due to In-Flight Medical Emergencies on Flight Delay and Aircraft Operating Costs. Aerospace medicine and human performance, 92 2, 99-105. https://doi.org/10.3357/AMHP.5720.2021.

Lopukh, P., & Berazhkova, K. (2019). Analysis and forecast spatiotemporal distribution of thunderstorms and hail in the territory of Belarus. Journal of the Belarusian State University. Geography and Geology. https://doi.org/10.33581/2521-6740-2019-1-35-45.

Lui, G., Liem, R., & Hon, K. (2020). Towards understanding the impact of convective weather on aircraft arrival traffic at the Hong Kong International Airport. IOP Conference Series: Earth and Environmental Science, 569. https://doi.org/10.1088/1755-1315/569/1/012067.

Marla, L., Vaaben, B., & Barnhart, C. (2016). Integrated Disruption Management and Flight Planning to Trade Off Delays and Fuel Burn. Transp. Sci., 51, 88-111. https://doi.org/10.1287/trsc.2015.0609.

Masrour, P., & Rezazadeh, M. (2023). Aerosol-cloud-precipitation interaction during some convective events over southwestern Iran using the WRF model. Atmospheric Pollution Research. https://doi.org/10.1016/j.apr.2023.101667.

Mazzarella, V., Milelli, M., Lagasio, M., Federico, S., Torcasio, R., Biondi, R., Realini, E., Llasat, M., Rigo, T., Esbrí, L., Kerschbaum, M., Temme, M., Gluchshenko, O., & Parodi, A. (2022). Is an NWP-Based Nowcasting System Suitable for Aviation Operations? Remote. Sens., 14, 4440. https://doi.org/10.3390/rs14184440.

Mburu, C., Gatebe, E., & Wambugu, F. (2016). Assessment Of Fire Safety Preparedness At Jomo Kenyatta International Airport. Journal of Agricultural Science and Technology, 17.

Mcfarlane, P. (2020). Linking aviation security failures to human-mediated error. A review of the related literature with directions for policy and research. Journal of Transportation Security, 1-19. https://doi.org/10.1007/s12198-020-00209-z.

Müller, R., Barleben, A., Haussler, S., & Jerg, M. (2022). A Novel Approach for the Global Detection and Nowcasting of Deep Convection and Thunderstorms. Remote. Sens., 14, 3372. https://doi.org/10.3390/rs14143372.

Mulu, A., & Enyew, B. (2018). Employing Data Mining Techniques to Predict Occurrence of Thunderstorms Using Hourly Weather Datasets: In the Case of Gondar Control Zone. International Journal of Engineering Research and, 7. https://doi.org/10.17577/IJERTV7IS050239.

Navarro-Labastida, R., & Farneti, R. (2023). The role of shallow and deep circulations in the Tropical Pacific Ocean heat budget. Frontiers in Marine Science. https://doi.org/10.3389/fmars.2023.1208052.

Nechaj, P., Gaál, L., Bartok, J., Vorobyeva, O., Gera, M., Kelemen, M., & Polishchuk, V. (2019). Monitoring of Low-Level Wind Shear by Ground-based 3D Lidar for Increased Flight Safety, Protection of Human Lives and Health. International Journal of Environmental Research and Public Health, 16. https://doi.org/10.3390/ijerph16224584.

Neto, R., Paris, L., Junior, F., & Fernandes, A. (2020). Environmental performance index for Brazilian public airports: The Infraero experience. Environmental Science & Policy, 112, 164-171. https://doi.org/10.1016/j.envsci.2020.05.023.

Ng, K., Keung, K., Lee, C., & Chow, Y. (2020). A Large Neighbourhood Search Approach to Airline Schedule Disruption Recovery Problem. 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 600-604. https://doi.org/10.1109/IEEM45057.2020.9309768.

Nigerian Aviation Handling Company. (2022). Impact of weather disruptions on airline operations: Annual report. Retrieved from https://www.nahcoaviance.com

Nigerian Civil Aviation Authority. (2022). Weather alert: Thunderstorms and their impact on aviation operations. Retrieved from https://ncaa.gov.ng/media/news/weather-alert/

Nigerian Civil Aviation Authority. (2023). Weather alert: Thunderstorms cause significant delays and cancellations. Retrieved from https://www.ncaa.gov.ng/media/news/weather-alert/

Nigerian Meteorological Agency. (2020). Seasonal rainfall prediction for Nigeria 2020. Abuja: Nigerian Meteorological Agency. Retrieved from https://www.nimet.gov.ng

Olabode, A. (2021). Statistical Analysis of Weather Parameters for Sustainable Flight Operation in Nigeria. Journal of Environmental Geography, 14, 47 - 53. https://doi.org/10.2478/jengeo-2021-0011.

Onwuadiochi, I., Egede, O., & Udeogu, A. (2023). Assessment of the Impacts of Thunderstorm on Flight Operations at Murtala Mohammed International Airport, Ikeja, Lagos State, Nigeria. Journal of Geographical Research. https://doi.org/10.30564/jgr.v6i1.5057.

Pang, M. (2020). When your problem becomes my problem: The impact of airline IT disruptions on on-time performance of competing airlines. Strategic Management Journal. https://doi.org/10.1002/SMJ.3090.

Rädler, A., Groenemeijer, P., Faust, E., Sausen, R., & Púčik, T. (2019). The frequency of severe thunderstorms across Europe is expected to increase in the 21st century due to rising instability. npj Climate and Atmospheric Science, 2, 1-5. https://doi.org/10.1038/s41612-019-0083-7.

Reason, J. (1990). Human error. Cambridge University Press.

Rehfeld, K., Hébert, R., Lora, J., Lofverstrom, M., & Brierley, C. (2020). Variability of surface climate in simulations of past and future. Earth System Dynamics. https://doi.org/10.5194/esd-2019-92.

Rhodes-Leader, L., Nelson, B., Onggo, B., & Worthington, D. (2021). A multi-fidelity modelling approach for airline disruption management using simulation. Journal of the Operational Research Society, 73, 2228 - 2241. https://doi.org/10.1080/01605682.2021.1971574.

Roman, Attinger., Gabriela, Aznar–Siguán., Hélène, Barras., Johannes, Landmann., Jivan, Waber., Kathrin, Wehrli., Szilvia, Exterde. (2024). Thunderstorm prediction using convolutional neural networks to support air traffic management in Switzerland. doi: 10.5194/ems2024-451

Scozzaro, G., Mancel, C., Delahaye, D., & Féron, E. (2023). An ILP approach for tactical flight rescheduling during airport access mode disruptions. International Transactions in Operational Research. https://doi.org/10.1111/itor.13396.

Singh, M., Kuang, Z., Maloney, E., Hannah, W., & Wolding, B. (2017). Increasing potential for intense tropical and subtropical thunderstorms under global warming. Proceedings of the National Academy of Sciences, 114, 11657 - 11662. https://doi.org/10.1073/pnas.1707603114.

Singh, O., & Bhardwaj, P. (2019). Spatial and temporal variations in the frequency of thunderstorm days over India. Weather, 74. https://doi.org/10.1002/wea.3080.

Sousa, H., Teixeira, R., Cardoso, H., & Oliveira, E. (2015). Airline Disruption Management - Dynamic Aircraft Scheduling with Ant Colony Optimization. , 398-405. https://doi.org/10.5220/0005205303980405.

Sun, X., & Wandelt, S. (2018). Complementary strengths of airlines under network disruptions. Safety Science, 103, 76-87. https://doi.org/10.1016/J.SSCI.2017.11.010.

Taszarek, M., Allen, J., Brooks, H., Pilguj, N., & Czernecki, B. (2020). Differing Trends in United States and European Severe Thunderstorm Environments in a Warming Climate. Bulletin of the American Meteorological Society. https://doi.org/10.1175/BAMS-D-20-0004.1.

Taszarek, M., Allen, J., Groenemeijer, P., edwards, R., Brooks, H., Chmielewski, V., & Enno, S. (2020). Severe Convective Storms across Europe and the United States. Part I: Climatology of Lightning, Large Hail, Severe Wind, and Tornadoes. Journal of Climate. https://doi.org/10.1175/JCLI-D-20-0345.1.

Taszarek, M., Allen, J., Marchio, M., & Brooks, H. (2021). Global climatology and trends in convective environments from ERA5 and radiosonde data. npj Climate and Atmospheric Science, 4, 1-11. https://doi.org/10.1038/s41612-021-00190-x.

Taszarek, M., Allen, J., Púčik, T., Groenemeijer, P., Czernecki, B., Kolendowicz, L., Lagouvardos, K., Kotroni, V., & Schulz, W. (2019). A Climatology of Thunderstorms across Europe from a Synthesis of Multiple Data Sources. Journal of Climate. https://doi.org/10.1175/JCLI-D-18-0372.1.

Taszarek, M., Kendzierski, S., & Pilguj, N. (2020). Hazardous weather affecting European airports: Climatological estimates of situations with limited visibility, thunderstorms, low-level wind shear and snowfall from ERA5. Weather and climate extremes, 28, 100243. https://doi.org/10.1016/j.wace.2020.100243.

Toma-Danila, D., Armaș, I., & Tiganescu, A. (2020). Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania. Natural Hazards and Earth System Sciences. https://doi.org/10.5194/nhess-2019-409.

Tyagi, A. (2021). Thunderstorm climatology over Indian region. MAUSAM. https://doi.org/10.54302/mausam.v58i2.1204.

Vittorio, A., Gensini. (2021). Severe convective storms in a changing climate. doi: 10.1016/B978-0-12-822700-8.00007-X

White, M., & Stallins, J. (2017). Nonmeteorological Influences on Severe Thunderstorm Warning Issuance: A Geographically Weighted Regression-Based Analysis of County Warning Area Boundaries, Land Cover, and Demographic Variables. Weather, Climate, and Society, 9, 421-439. https://doi.org/10.1175/WCAS-D-15-0070.1.

Yunisa, Y., Timothy, Z., Pius, O., Aminu, I., Samuel, S., F., & Mercy, L. (2022). Evaluation Of Signal Strength and Quality of a Ku-Band Satellite Downlink During Raining Season in Guinea Savanna Region of Nigeria. International Journal of Advanced Networking and Applications. https://doi.org/10.35444/ijana.2022.13502.