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Research Article

Altitudinal Estimation and Modeling of Wind Shear Association with Flight Operations at two selected International Airports in Nigeria

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Abstract

The aviation industry experiences a significant setback due to its heavy dependence on weather amid escalating global uncertainty. The study estimated wind shear to 100m above ground level and modeled its association with flight operations at Murtala Mohammed and Port Harcourt International Airports, Nigeria. The data were obtained from the Nigerian Airspace Management Agency and the Nigerian Meteorological Agency. The study employed Pearson's product-moment correlation and regression methods. The number of flight diversions, delays, and cancellations is positively and insignificantly related to wind shear extrapolated at 100 meters above ground level at Murtala Mohammed International Airport. At Port Harcourt Airport, results demonstrate a positive but negligible association between wind shear extrapolated at 100 meters above ground level and the number of flight diversions and delays. In contrast, wind shear and flight cancellations are negative but insignificantly related. The best regression relationship between wind shear at 100m above ground level and the number of flight diversions and delays is exponential at Murtala Mohammed Airport. The relationship between wind shear at 100m above ground level and the number of flight cancellations is quadratic. The best regression relationship between wind shear extrapolated at 100m above ground level and the number of flight diversions, delays, and cancellations at Port Harcourt Airport is cubic. The study proposes consistent wind shear observation at the airports, and steady forecasts utilizing the models. It also calls for additional research on wind shear, particularly in Nigeria and other tropical areas.

Keywords: Altitude; Modeling; Wind Shear; Weather Uncertainty; Flights; Climate Change.

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1. Introduction

When analyzing airplanes flying in the atmospheric boundary layer, the wind is critical due to short-scale gusts or turbulence and large-scale changes in the mean wind (Frost and Camp, 1977; Suomi and Vihma, 2018). Because of topographical flaws, the mean wind in the planetary boundary layer degrades closer to the surface more quickly and exhibits large horizontal oscillations (Frost and Camp, 1977; Krishnamurthy *et al.*, 2021). Consequently, the mean surface winds encountered during rising and descending aircraft trajectories show spatial and temporal variability (Frost and Camp, 1977).

Low-level wind shear severely threatens civil aircraft's flying safety (Chen *et al.*, 2020). The need for wind shear monitoring and forecasting, among other disruptive weather occurrences, has increased in the aviation industry in this era of climate change and its effects (Onwuadiochi *et al.*, 2021a). In Nigeria and the surrounding tropical region, wind shear is more frequent than everywhere else on the planet, necessitating the need for accurate wind shear forecasts in the area (Onwuadiochi *et al.*, 2021a; Onwuadiochi *et al.*, 2021b).

Many studies have assessed aircraft motion (Etkin, 1982; McRuer *et al.*, 2014). However, most of them only consider steady winds, ignoring the impact of wind shear (Frost and Camp, 1977). Recent investigations have emphasized wind shear in the planetary boundary layer as a key contributor to the caus-

es of commercial flight accidents, delays, diversions, and cancellations (Laynor, 1974; Laynor, 1986; O'Connor and Kearney, 2018; Onwuadiochi *et al.*, 2020b; Onwuadiochi *et al.*, 2021b).

According to Onwuadiochi *et al.* (2021b), the functional relationships between the number of flight delays, cancellations, diversions, and wind shear at 20 metres above the ground were exponential, exponential, and quadratic, respectively. The models demonstrate that the number of flight delays, cancellations, and diversions can be predicted if the wind shear at 20 metres above the ground level is known. However, the results show that variations in wind shear contribute to increased flight diversions, cancellations, and delays in the region. Chen *et al*. (2020) indicate that wind shear occurrences at Hong Kong International Airport (HKIA) are more prevalent in March, April, July, and August compared to November. The likelihood of wind shear at HKIA increases with winds coming from the east, southeast, south, and southwest (Chen *et al.*, 2020). The study concludes that accurately estimating wind shear occurrences using only hourly meteorological observations is challenging due to the transient and irregular wind shear nature. Based on operational flight data, the stochastic wind was modelled using the Karhunen-Loève extension, enabling the creation of new realisations of wind series that adhered to the original statistical properties (Wang *et al.*, 2020).

Low-level wind shear is mostly caused by two factors: the geographical environment around an airport, which includes complicated topography and structures, and unfavourable weather, such as sea breezes and microbursts (Chen *et al.*, 2019; Li, and Chan, 2012). Numerous studies have been conducted to ascertain how these factors affect the frequency of low-level wind shear. Numerical simulation was employed to simulate terrain-induced wind shear (Lei *et al.*, 2013; Chan, 2019) and the low-level effects caused by buildings (Leung *et al.*, 2012; Li *et al.*, 2012). Numerous wind shear situations were also examined using observational and aircraft data (Chan, 2014; Onwuadiochi *et al.*, 2020a; Onwuadiochi *et al.*, 2021a).

Enhanced comprehension of low-level wind shear events from these studies has facilitated the detection and forecasting of wind shear at Murtala Mohammed and Port Harcourt International Airports. To the authors' knowledge, there is a paucity of published research investigating the connection between wind shear and aircraft operations at 100 metres above ground level. As a result, the results of this study can offer some references and useful data for researchers who are similarly interested in learning more about low-level wind shear.

2. Materials and Methods

2.1. Study Area

The two study locations are Port Harcourt International Airport in Rivers State and Murtala Mohammed International Airport in Lagos State. Lagos State is positioned approximately between latitude 60 221N and 60 421 N of the equator and between longitude 20 421E and 30 221E of the Greenwich Meridian (Onwuadiochi *et al.*, 2021a). Its borders are as follows: the Republic of Benin to the west, Ogun State, Nigeria, to the north and east, and the Atlantic Ocean to the south.

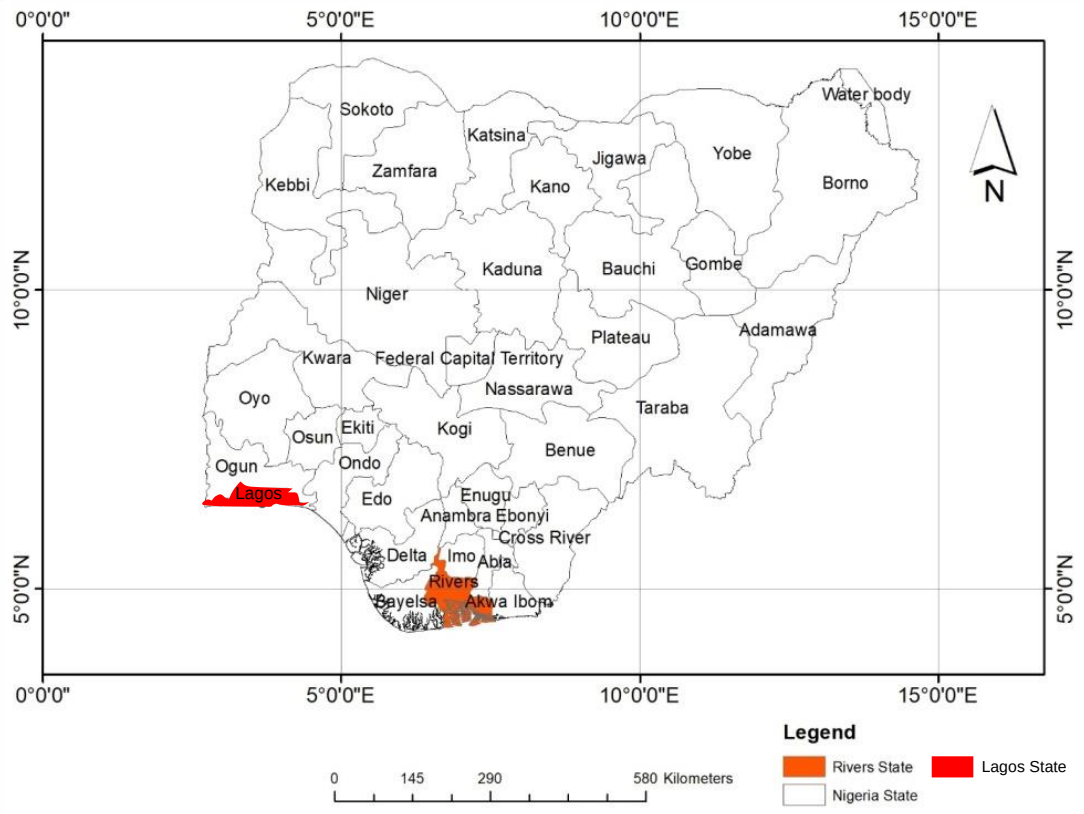


Figure 1. Map of Nigeria showing Lagos and Rivers States

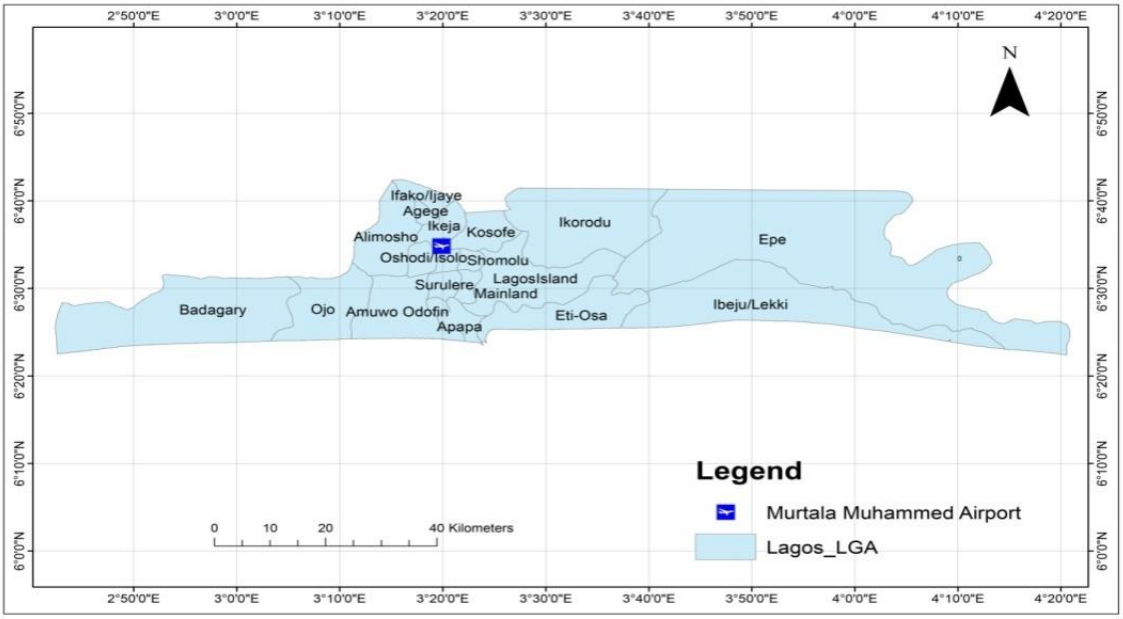


Figure 2. Map of Lagos State showing Murtala Mohammed International Airport

Tropical wet and dry climate prevails in Lagos (Fasona *et al.*, 2019). The West African monsoon system, propelled by the intertropical discontinuity migration, and mesoscale processes is responsible for the rainy season, which runs from March to November (with peaks in July and September) (Omotosho

and Abiodun, 2007). A small dry period occurs in August, and then a lengthy dry season lasts from December to March (Oteri and Ayeni, 2016). Murtala Mohammed International Airport (MMIA) is an international airport located in Ikeja, Lagos State.

Port Harcourt is located between latitudes 40301 and 40471 north of the Equator and longitudes 70001 and 70151 east of the Greenwich Meridian in Nigeria's southernmost region (Ajie and Dienye, 2014; Onwuadiochi *et al.*, 2021). Port Harcourt is bordered on the east and west by meandering creeks, and to the south by the first dockyard creek (Bonny River) and mangrove swamps (Ajie and Dienye, 2014). Its northern boundary is formed by the Ikwerre Local Government Area, which has available land.

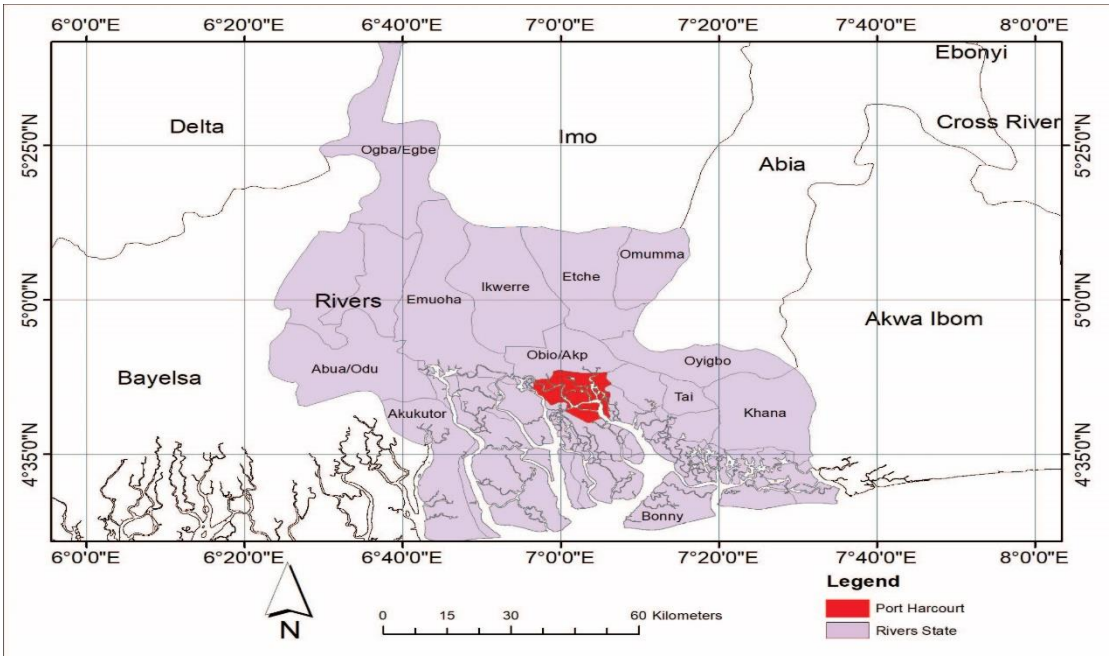


Figure 3. Map of Rivers State showing Port Harcourt

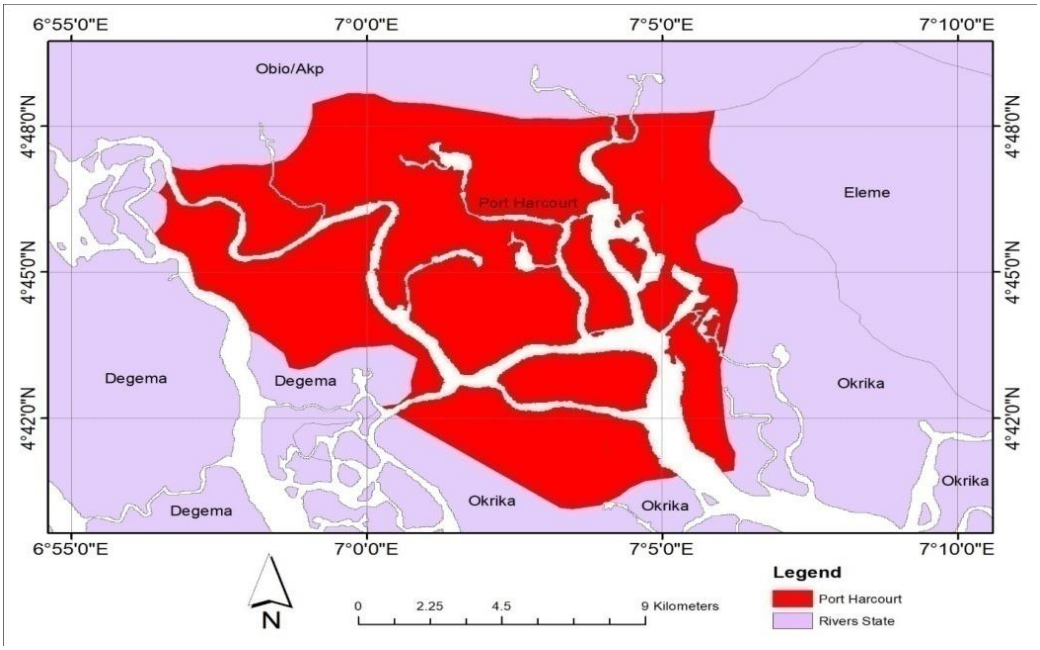


Figure 4. Map of Port Harcourt

The Port Harcourt Airport is characterized by a tropical monsoon climate with long, heavy rainy seasons and brief dry seasons (World Meteorological Organization, 2018; National Oceanic and Atmospheric Administration, 2018). Only December and January fall within the category of dry season months in Port Harcourt (World Meteorological Organization, 2018; National Oceanic and Atmospheric Administration, 2018). Rainfall is seasonal, variable, and energetic (Enete *et al.*, 2015). Generally, in the south of latitude 050N, rain occurs on average every month of the year but with various degrees of duration and circulation over the region (Enete *et al.*, 2015). The Port Harcourt International Airport lies between latitude 4º 72¹N and 4º 91¹N of the equator and longitude 6º 88¹E and 7º 12¹E of the Greenwich Meridian (Weli and Emenike, 2016). Omagwa, a neighbourhood of Port Harcourt in Rivers State, Nigeria, is home to the Port Harcourt International Airport (Enete *et al.*, 2015).

2.2. Data Collection

The annual time series data for flight operations and wind shear utilized in this study were given by the Nigerian Airspace Management Agency (NAMA) and Nigerian Meteorological Agency (NIMET) respectively. The data was obtained from January 2008 to December 2018 across an eleven-year period. The data was compiled and displayed in tabular form.

2.3. Data analysis

2.3.1 Calculation of wind shear at 50m above ground level (AGL)

Power Law.

Calculating wind shear at various heights is simple mathematically using the power law (Wagner *et al.*, 2011). It is a useful representation of the vertical wind profile that Hellman developed in 1916 using empirically generated data that reflects atmospheric wind profiles under non-neutral atmospheric conditions. The power law states that the wind profile depends on surface roughness and thermal stability (Abdulla, 2014). It determines how height affects wind shear growth. Equation 1 shows the power law.

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\propto} \qquad (1)$$

Where V1 is the wind shear measured at a certain height Z1, V2 is the wind shear measured at a certain height Z2, and α is the wind shear exponent obtained empirically.

$$\propto = \frac{In(V_2/V_1)}{In(Z_2/Z_1)} \qquad (2)$$

The annual time series data for flight operations and wind shear utilized in this study were provided by the Nigerian Airspace Management Agency (NAMA) and the Nigerian Meteorological Agency (NIMET), respectively. The data was obtained over eleven years, from January 2008 to December 2018. It was compiled and displayed in tabular form.

This study employed inferential statistics, including regression analysis and Pearson's Product Moment Correlation (PPMC). Pearson's correlation method was used to determine whether the relationship between the dependent (flight delays, cancellations, and diversions) and independent (wind shear) variables is positive, negative, significant, or insignificant. While regression analysis method was used to

model, predict, and show the nature of the mathematical relationship between wind shear and the independent variables at 100 metres above ground level.

Pearson's Correlation. The extent and relationship between the study variables were validated using Pearson's correlation technique without one suppressing the other. This statistical estimating method was deemed appropriate because all the variables under examination had undergone log transformation to become continuous data. Pearson's correlation coefficient is generally calculated as:

$$r = \frac{Cov\,(M,N)}{\sqrt{(Var\,(M))(Var\,(N))}} = \frac{\sum_{i=1}^{T}[(M-\bar{M})(N-\bar{N})]}{\sqrt{\left[\sum_{i=1}^{T}(M-\bar{M})^2\right]\left[\sum_{i=1}^{T}(N-\bar{N})^2\right]}} \quad (3)$$

Where, r is the correlation coefficient, $Cov\,(M,N) = \sum_{i=1}^{T}[(M-\bar{M})(N-\bar{N})]$ is the covariance of M and N series, $Var\,(M) = \sum_{i=1}^{T}(M-\bar{M})^2$ is the variance of the M series, $Var\,(N) = \sum_{i=1}^{T}(N-\bar{N})^2$ is the variance of the N series, T = Total number of observations, $\bar{M}$ and $\bar{N}$ and mean values of series of M and N values, M and N are variables of interest.

Regression Analysis. The functional relationship among the selected variables was determined using the classical linear regression technique. The relationship is shown geometrically as follows:

$$Number\ of\ Flight\ diversions, delays\ and\ cancellations = f(wind\ shear)$$

Such that:

$$LFDS, LFDL, LFCL = f(WS) \quad (4)$$

Where, FDS = Number of flight diversions, FDL = Number of flight delays, FCL = Number of flight cancellations, L = Log-transformational operator, and WS = Wind shear

However, Microsoft Excel, Eviews, and the Statistical Package for Social Sciences (SPSS) version 25.0 for Windows were also utilized as statistical software.

3. Results and Discussion

The Pearson's correlation estimate in Table 1 with ($r_{LWS.LFDS}$ = 0.504, p=0.0944>0.05; $r_{LWS.LFDL}$ = 0.372, p=0.2337>0.05; $r_{LWS.LFCL}$ = 0.388, p=0.2129>0.05) shows that wind shear (LWS) extrapolated at 100 meters above ground level (using the power law model) relate positively and insignificantly with the number of flight diversions (LFDS), delays (LFDL), and cancellations (LFCL). The result also demonstrates a positive correlation between the number of flight delays, cancellations, and diversions, with only the correlation between the number of delays and cancellations being statistically significant ($r_{LFDS.LFDL}$ = 0.197, p=0.5385>0.05; $r_{LFDS.LFCL}$ = 0.109, p=0.7356>0.05; $r_{LFDL.LFCL}$ = 0.946, p=0.0000<0.05). The results suggest that while an increase in flight diversions is a weakly positive predictor of flight delays and cancellations, an increase in flight delays is a significant predictor of flight cancellations. Increased wind shear, however, encourages aircraft cancellations, delays, and diversions in the chosen airports.

Table 1. Pearson's correlation matrix illustrates the association between wind shear extrapolated at 100 meters above ground level (using a power law model) and flight diversions, delays, and cancellations at Murtala Mohammed International Airport in Lagos.

Covariance Analysis: Ordinary **Sample: Jan. 2008 – Dec. 2018** **Included observations: 12**				
Correlation t-Statistic Probability	LWS	LFDS	LFDL	LFCL
LWS	1.000000			

LFDS	0.504425	1.000000		
	1.847383	-----		
	0.0944	-----		
LFDL	0.372006	0.197451	1.000000	
	1.267343	0.636935	-----	
	0.2337	0.5385	-----	
LFCL	0.387798	0.109155	0.946445**	1.000000
	1.330440	0.347254	9.269925	-----
	0.2129	0.7356	0.0000	-----

Source: Researchers' work, 2022

**Correlation is significant at the 0.01 level (2-tailed); r_p= Pearson's Correlation; WS = Wind Shear extrapolated at 50m above ground level; FDS = Flight diversions; FDL = Flight delays; FCL = Flight cancellations.

Table 2 shows the quantitative correlations between wind shear projected at 100 meters above ground level (using a power law model) and the number of flight delays, cancellations, and diversions at Murtala Mohammed International Airport in Lagos.

Table 2. Regression models demonstrate the association between the WS at 100 meters above ground and the FDS, FDL, and FCL at Murtala Mohammed International Airport in Lagos.

Independent variable (Regressor)	**Dependent variable (Regressand)**	**Regression line/Equation**	**Regression identity**
Wind shear (WS)	Flight diversions (FDS)	LFDS = $e^{0.210WS+2.329}$	Exponential
Wind shear (WS)	Flight delays (FDL)	LFDL = $e^{0.275WS+2.304}$	Exponential
Wind shear (WS)	Flight cancellations (FCL)	LFCL = 5.534– 3.211WS + 1.089WS^2	Quadratic

Source: Researchers' work, 2022

**L stands for log-transformational operator.

As shown in Table 2, the relationship between wind shear at 100m above ground level at Murtala Mohammed International Airport in Lagos and the number of flight delays and diversions is best described as exponential. The relationship between wind shear at 100m above ground level and the number of flight cancellations at the location is best described as quadratic.

Table 3 shows a positive but negligible correlation between the frequency of flight delays and diversions and the estimated wind shear at 100 metres above ground ($r_{LWS.LFDS}$ = 0.101, p=0.7545>0.05; $r_{LWS.LFDL}$= 0.019, p=0.9538>0.05). In contrast, the frequency of flight cancellations is weakly negatively correlated with extrapolated wind shear at 100 metres above ground level. ($r_{LWS.LFCL}$ = − 0.189, p=0.5561>0.05). The number of flight diversions, delays, and cancellations strongly correlate ($r_{LFDS.LFDL}$ = 0.421, p=0.1732>0.05; $r_{LFDS.LFCL}$ = 0.316, p=0.3166>0.05; $r_{LFDL.LFCL}$ = 0.890, p=0.0001<0.05). A statistically significant correlation exists between the number of flight delays and cancellations.

Table 3. Pearson's correlation matrix shows the association between wind shear extrapolated at 100m above ground level (using the power law model) and flight diversions, delays, and cancellations at Port Harcourt International Airport.

Covariance Analysis: Ordinary **Sample: Jan. 2008 – Dec. 2018** **Included observations: 12**				
Correlation t-Statistic Probability	LWS	LFDS	LFDL	LFCL
LWS	1.000000			

LFDS	0.101137	1.000000		
	0.321472	-----		
	0.7545	-----		
LFDL	0.018791	0.420754	1.000000	
	0.059433	1.466686	-----	
	0.9538	0.1732	-----	
LFCL	-0.189123	0.316225	0.889905	1.000000
	-0.609050	1.054082	6.169355	-----
	0.5561	0.3166	0.0001	-----

Source: Researchers' work, 2022

**Correlation is significant at the 0.01 level (2-tailed); r_p = Pearson's Correlation; WS = Wind Shear extrapolated at 50m above ground level; FDS = Flight diversions; FDL = Flight delays; FCL = Flight cancellations.

Table 4. Regression models show the relationship between WS at 100m above ground level and FDS, FDL, and FCL at Port Harcourt International Airport.

Independent variable (Regressor)	**Dependent variable (Regressand)**	**Regression line/Equation**	**Regression identity**
Wind shear (WS)	Flight diversions (FDS)	LFDS = −7.490+ 14.357WS −3.663WS^3	Cubic
Wind shear (WS)	Flight delays (FDL)	LFDL = −6.342+ 24.161WS^2 −14.146WS^3	Cubic
Wind shear (WS)	Flight cancellations (FCL)	LFCL = −4.367+ 18.643WS^2 −11.081WS^3	Cubic

Source: Researchers' work, 2022

**L stands for log-transformational operator.

Table 4 illustrates the regressional associations between wind shear, extrapolated at 100 metres above ground level (using a power law model) and the frequency of flight delays, cancellations, and diversions at Port Harcourt International Airport.

The optimal operational association between wind shear projected at 100m above ground level (using a power law model) at Port Harcourt International Airport and the frequency of flight delays, cancellations, and diversions is, respectively, cubic, as indicated by the regression estimate in Table 4.

Table 5. Panel correlation matrix showing the association between wind shear extrapolated at 100m above ground level (using power law model) and flight diversions, delays and cancellations at Murtala Mohammed and Port Harcourt International Airport, Nigeria.

Covariance Analysis: Ordinary **Sample: Jan. 2008 – Dec. 2018** **Included observations: 24**				
Correlation t-Statistic Probability	LWS	LFDS	LFDL	LFCL
LWS	1.000000			

LFDS	0.319700	1.000000		
	1.582580	-----		
	0.1278	-----		
LFDL	0.136093	0.309002	1.000000	
	0.644329	1.523925	-----	
	0.5260	0.1418	-----	
LFCL	0.257967	0.259414	0.892972	1.000000
	1.252362	1.259889	9.305242	-----
	0.2236	0.2209	0.0000	-----

Source: Researchers' work, 2022

**Correlation is significant at the 0.01 level (2-tailed); r_p = Pearson's Correlation; WS = Wind Shear extrapolated at 50m above ground level; FDS = Flight diversions; FDL = Flight delays; FCL = Flight cancellations.

The panel correlation estimate in Table 5 indicates that the number of flight delays, cancellations, and diversions exhibits positive yet insignificant associated with wind shear projected at 100m above ground level $r_{LWS.LFDS}$ = 0.320, p=0.1278>0.05; $r_{LWS.LFDL}$ = 0.136, p=0.5260>0.05; $r_{LWS.LFCL}$ = 0.258, p=0.2236>0.05). Additionally, the interactions among flight diversions, delays, and cancellations are positively correlated ($r_{LFDS.LFDL}$ = 0.309, p=0.1418>0.05; $r_{LFDS.LFCL}$ = = 0.259, p=0.2209>0.05; $r_{LFDL.LFCL}$ = 0.893, p=0.0000<0.05). A statistically significant correlation exists between the number of flight delays and cancellations.

4. Conclusion and Recommendation

The study demonstrates that wind shear is a factor in flight diversions, cancellations, and delays at Nigeria's Murtala Mohammed and Port Harcourt International Airports. Additionally, it created models that could be applied to forecast flight cancellations, delays, and diversions at the two airports.

The study suggests regular wind shear observation at the airports and steady forecasting using the proposed models, as wind shear can have a detrimental effect on the aviation industry. The study indicates that additional research on wind shear is required, particularly in Nigeria and other tropical countries.

References

Abdulla, A.O. (2014). Wind Analysis and Estimate of the Wind Shear Exponent of the Sulaymanyiah International Airport Area. *M.Sc. Thesis*, University of Sulaimani, Sulaimani, Iraq.

Ajie, U.E. and Dienye, A. (2014). Spatial Data Analysis of Solid Waste Management System in Port Harcourt Metropolis after 100 years of its existence. *FIG Congress*, Kuala Lumpur, Malaysia.

Chan, P.W. (2014). Observation and Numerical Simulation of Vortex/Wave Shedding for Terrain-disrupted Airflow at Hong Kong International Airport during Typhoon Nesat in 2011. *Meteorological Applications*, 21(3), pp.512–520.

Chan, P.W., Hon, K.K., and Li, Q.S. (2019). A Comprehensive Study of Terrain-disrupted Airflow at Hong Kong International Airport Observations and Numerical Simulations. *Weather*, 75(7), pp.199–206.

Chen, F., Peng, H., Chan, P., and Zeng, X. (2019). Low-level Wind Effects on the Glide Paths of the North Runway of HKIA: A Wind Tunnel Study. *Building and Environment*, 164, p.106337.

Chen, F., Peng, H., Chan, P., Ma, X., & Zeng, X. (2020). Assessing the Risk of Windshear Occurrence at HKIA using Rare-Event Logistic Regression. *Meteorological Applications*, 27.

Enete, I.C., Ajator, U., and Nwoko, K.C. (2015). Impacts of Thunderstorm on Flight Operations in Port-Harcourt International Airport, Omagwa, Rivers State, Nigeria. *International Journal of Weather, Climate Change and Conservation Research*, 1(1), pp.1 – 10.

Etkin, B. (1982). *Dynamics of Flight*. John Wiley & Sons.

Fasona, M., Muyiolu, K., Soneye, A., Ogundipe, O.T., Otusanya, O., Adekanmbi, O.H., Adeonipekun, P.A., and Onuminya, T.O. (2019). Temporal Analysis of the Present and Future Climate of the Lagos Coastal Environment. *Unilag Journal of Medicine, Science and Technology* (UJMST), 7(1), pp.113-128.

Frost, W. and Camp, D.W. (1977). *Wind Shear Modeling for Aircraft Hazard Definition*. US Department of Transportation, Federal Aviation Administration, Systems Research and Development Service, Washington, DC.

Krishnamurthy, R., Newsom, R.K., Chand, D., and Shaw, W.J. (2021). *Boundary Layer Climatology at ARM Southern Great Plains*. U.S. Department of Energy.

Laynor, W.G. (1974). *Performance Study DCA-74-A-14, NTS3*. Bureau of Aviation Safety, Washington, DC.

Laynor, W.G. (1986). Summary of Wind Shear Accidents and Views about Prevention. *SAE Transactions*, 95, pp.782–793.

Lei, L., Chan, P.W., Li-Jie, Z., and Hui, M. (2013). Numerical Simulation of Terrain-induced Vortex/Wave Shedding at the Hong Kong International Airport. *Meteorologische Zeitschrift*, 22(3), pp.317–327.

Leung, D.Y.C., Lo, W.Y., Chow, W.Y., and Chan, P.W. (2012). Effect of Terrain and Building Structures on the Airflow in an Airport. *Journal of Zhejiang University Science A*, 13(6), pp.461–468.

Li, L. and Chan, P.W. (2012). Numerical Simulation Study of the Effect of Buildings and Complex Terrain on the Low-level Winds at an Airport in Typhoon Situation. *Meteorologische Zeitschrift*, 21(2), pp.183–192.

McRuer, D.T., Graham, D., and Ashkenas, I. (2014) *Aircraft Dynamics and Automatic Control*. Princeton University Press.

National Oceanic and Atmospheric Administration (2018). Port Harcourt Climate Normals: 1961 – 1990.

O'Connor, A. and Kearney, D. (2018). Evaluating the Effect of Turbulence on Aircraft during Landing and Take-off Phases. *International Journal of Aviation, Aeronautics, and Aerospace*, 5(4).

Omotosho, J.B. and Abiodun, J. (2007). A Numerical Study of Moisture Uuild-up and Rainfall over West Africa. *Meteorological Applications*, 14, pp.209–225. DOI: 10.1002/met.11

Onwuadiochi, I.C., Ijioma, M.A., and Ozoemene, M.L. (2020a). Comparative Analysis of the Effects of Measured and Calculated Wind Shear on Aircraft Operations in Sam Mbakwe Airport, Imo State, Nigeria. *Environmental Review*, 7(1).

Onwuadiochi, I.C., Ijioma, M.A., Ezenwaji. E.E., and Obikwelu, M.C. (2020b). Effects of Wind Shear on Flight Operations in Sam Mbakwe Airport, Imo State, Nigeria. *Tropical Built Environment Journal*, 7(1).

Onwuadiochi, I.C., Ijioma, M.A., Mage, J.O., and Ozoemene, M.L. (2021a). Comparative Analysis of the Measured and Extrapolated Wind Shear Distributions at Murtala Mohammed and Port Harcourt International Airports, Nigeria. *Journal of Environment and Earth Science*, 11(5), pp.63-78.

Onwuadiochi, I.C., Ijioma, M.A., Ozoemene, M.L., and Obikwelu, M.C. (2021b). Mathematical Modeling of the Relationship between Wind Shear and Aircraft Operations at Murtala Mohammed and Port Harcourt International Airports, Nigeria. *IOSR Journal of Mathematics*, 17(3), pp.20-34.

Oteri, A.U. and Ayeni, R.A. (2016). *The Lagos Megacity*. Water, Megacities and Global Change.

Suomi, I. and Vihma, T. (2018). Wind Gust Measurement Techniques—From Traditional Anemometry to New Possibilities. *Sensors*, 18(4), p.1300. doi:https://doi.org/10.3390/s18041300.

Wagner, W., Courtney, M., Gottschall, J., and Marsden, P.L. (2011). *Accounting for the speed shear in wind turbine power performance measurement*. Roskilde, Denmark: Wiley Online Library.

Wang, X., Beller, L., Czado, C., and Holzapfel, F. (2020). Modeling of Stochastic Wind based on Operational Flight Data using Karhunen-Lovene Expansion Method. *Sensor*, 20, 4634.

Weli, V.E. and Emenike, G.C. (2016). Turbulent Weather Events and Aircraft Operations: Implications for Aviation Safety at the Port Harcourt International Airport, Nigeria. *International Journal of Weather, Climate Change and Conservation Research*, 2(3), pp.19 – 30.

World Meteorological Organization (2018). *World Weather Information Service* – Port Harcourt.