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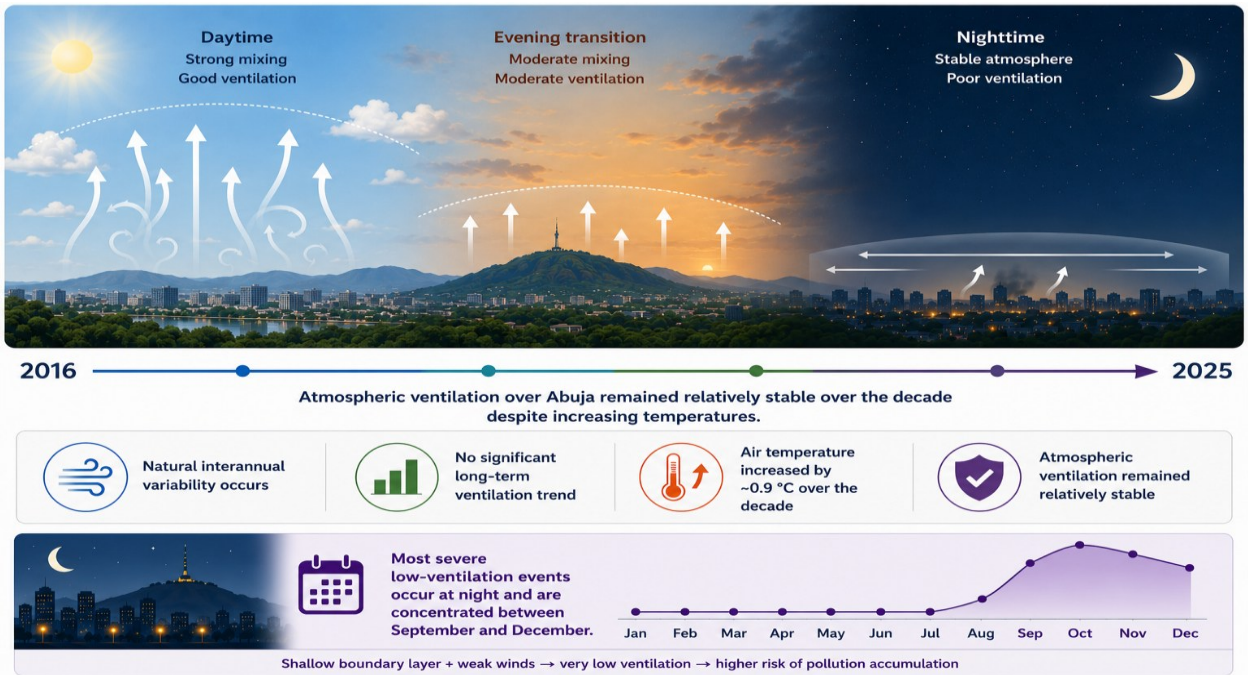
Graphical Abstract



Long-Term Characteristics of Atmospheric Ventilation over Abuja, Nigeria: Variability, Trends, and Extreme Events

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Abstract: *Atmospheric ventilation plays a critical role in determining the capacity of the atmosphere to disperse pollutants and maintain air quality in urban environments. However, long-term information on atmospheric ventilation characteristics over rapidly growing tropical cities remains limited. This study investigated the climatology, interannual variability, long-term trends, and extreme low-ventilation events associated with atmospheric ventilation over Abuja, Nigeria, using ERA5 reanalysis data from 2016 to 2025. Boundary-layer height (BLH), wind speed (WS), ventilation coefficient (VC), and 2-m air temperature (T2M) were analyzed using climatological, trend, variability, and extreme-event approaches. The results revealed pronounced seasonal variability in BLH and VC, indicating the strong influence of atmospheric mixing processes on ventilation conditions. Annual mean BLH ranged from 569.39 to 631.47 m, while VC varied between 835.63 and 959.86 m² s⁻¹ during the study period. Trend analysis showed a statistically significant increase in T2M of 0.091 °C yr⁻¹ (p = 0.028), corresponding to approximately 0.9 °C of warming over the decade. In contrast, no significant long-term trends were observed in BLH, WS, or VC (p > 0.05), suggesting that atmospheric ventilation remained relatively stable despite increasing temperatures. Stability analysis indicated that BLH and VC exhibited coefficients of variation (CV) of 112.30% and 115.12%, respectively, compared with 48.88% for WS and 14.66% for T2M. The twenty lowest ventilation events were* *characterized by exceptionally shallow boundary layers and weak winds, with most occurring during nighttime and early-morning hours and concentrated between September and December. The findings demonstrate that atmospheric ventilation over Abuja is closely associated with boundary-layer dynamics and exhibits substantial temporal variability but limited long-term change. This study provides the first decadal assessment of atmospheric ventilation over Abuja and offers valuable information for air-quality management, environmental planning, and future climate-impact assessments in tropical urban environments.*

Keywords: *Atmospheric ventilation; Boundary-layer height; Ventilation coefficient; ERA5 reanalysis; Long-term trends; Air quality; Abuja.*

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1.0 Introduction

Atmospheric ventilation is a fundamental meteorological process that controls the transport, dilution, and removal of air pollutants within the lower atmosphere. The effectiveness of this process depends on the interaction between atmospheric turbulence, boundary-layer development, and wind-driven transport, which collectively determine the atmosphere's ability to disperse contaminants emitted from natural and anthropogenic sources. Efficient atmospheric ventilation promotes pollutant dilution and reduces human exposure to harmful pollutants, whereas poor ventilation associated with shallow boundary layers and weak winds results in pollutant accumulation near the surface, increasing the likelihood of air pollution episodes and their associated environmental and health impacts. As urban populations continue to expand and anthropogenic emissions intensify, understanding the long-term behaviour of atmospheric ventilation has become increasingly important for urban environmental management, sustainable city planning, and climate adaptation (IPCC, 2021; Oke *et al.,* 2017; Borge *et al.,* 2023; Mahmud *et al.,* 2023). The atmospheric boundary layer (ABL) plays a significant role in regulating atmospheric ventilation because it is the lowest portion of the atmosphere directly influenced by exchanges of heat, momentum, and moisture between the Earth's surface and the air above it. Changes in boundary-layer height (BLH) determine the depth available for vertical pollutant mixing, while the ventilation coefficient (VC), defined as the product of BLH and wind speed (WS), provides an integrated measure of atmospheric ventilation by combining vertical mixing depth and horizontal transport. Consequently, BLH and VC are widely used indicators for evaluating atmospheric dispersion potential and urban air-quality conditions. Previous studies have demonstrated substantial spatial and temporal variability in BLH across different climatic regions, although the magnitude and direction of these variations differ among locations because of differences in climate, surface characteristics, and atmospheric forcing (Liu and Liang, 2010; Moreira *et al.,* 2022; Seidel *et al.,* 2012; Deng *et al.*, 2023). While these studies have improved understanding of boundary-layer dynamics, relatively fewer investigations have integrated BLH and wind speed into a long-term assessment of atmospheric ventilation conditions, particularly in tropical African urban environments.

Beyond describing short-term meteorological variability, long-term assessments of atmospheric ventilation provide important insights into the persistence, evolution, and stability of atmospheric mixing conditions. Such investigations facilitate the identification of climatological trends, interannual variability, and periods of low ventilation that may substantially reduce pollutant dispersion and increase the risk of poor air quality. They also provide fundamental information for evaluating the effects of climate variability and rapid urbanization on atmospheric dispersion processes. Recent studies have continued to employ long-term meteorological datasets and reanalysis products to investigate temporal changes in boundary-layer dynamics and atmospheric dispersion potential, demonstrating the value of climatological approaches for understanding urban atmospheric environments and supporting environmental decision-making (Seidel *et al.,* 2012; Zhang *et al.,* 2022; Soleimanpour *et al.,* 2023; Xi *et al.,* 2024).

The availability of modern atmospheric reanalysis datasets has considerably improved the investigation of atmospheric ventilation and boundary-layer processes. Among these datasets, the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5) provides globally consistent hourly meteorological fields with enhanced temporal and spatial resolution, making it particularly suitable for long-term assessments of atmospheric mixing, pollutant dispersion, and urban climatology. ERA5 has been extensively applied in studies of boundary-layer climatology, atmospheric stability, air-quality modelling, and environmental monitoring because of its continuous temporal coverage and physically consistent representation of atmospheric processes (Hersbach *et al.,* 2020; Muñoz-Sabater *et al.,* 2021; Yang and Pan, 2025; Xi *et al.,* 2024).

Abuja provides an important setting for investigating atmospheric ventilation because of its rapid urban development, increasing population, expanding transportation networks, and growing anthropogenic activities (Mashi *et al.,* 2025; Fahad, 2025). As a tropical inland city, its atmospheric dispersion conditions are influenced by seasonal changes in boundary-layer development, wind regimes, temperature, and atmospheric stability. These characteristics can produce substantial temporal differences in the atmosphere's ability to disperse pollutants (Omokungbe *et al.,* 2026). Understanding the climatology and variability of atmospheric ventilation over Abuja is therefore important for evaluating the city's potential vulnerability to pollution accumulation and for supporting sustainable urban and environmental management.

Although previous studies have examined boundary-layer dynamics and air-quality conditions in different regions, important gaps remain in the understanding of atmospheric ventilation over tropical African cities. Recent assessments have highlighted limitations in air-quality monitoring, atmospheric observations, and meteorological characterization across African urban centres, constraining a comprehensive understanding of atmospheric processes relevant to air-quality management (Borge *et al.,* 2023). In particular, limited evidence is available on how atmospheric ventilation varies from year to year, whether it exhibits detectable long-term trends, how its statistical characteristics vary over time, and when periods of low ventilation are most likely to occur.

In Nigeria, available studies have largely emphasized pollutant concentrations and their spatial or temporal distributions, with comparatively limited attention to the meteorological conditions governing pollutant dispersion (Mahmud *et al.,* 2023). For Abuja, these aspects have not been comprehensively characterized using a consistent long-term reanalysis dataset. This limits the availability of a quantitative climatological baseline for assessing atmospheric dispersion potential and identifying periods of elevated vulnerability to pollution accumulation

The aim of this study was to characterize the long-term atmospheric ventilation conditions over Abuja, Nigeria, using ERA5 reanalysis data for the period 2016–2025. Specifically, the study evaluated the climatological and seasonal characteristics of BLH, WS, VC, and T2M; quantified their interannual variability and temporal trends; assessed their statistical characteristics; and identified the timing and characteristics of periods of low ventilation. By providing a decadal climatological characterization of atmospheric ventilation over Abuja, this study establishes a quantitative baseline for understanding the variability, persistence, and evolution of boundary-layer mixing and pollutant-dispersion conditions in a rapidly urbanizing tropical city. The identification of long-term trends and periods of low ventilation also provides a basis for assessing conditions under which atmospheric pollutant dispersion may be substantially reduced. Scientifically, the findings contribute to the limited body of knowledge on atmospheric ventilation and boundary-layer dynamics in tropical African cities and provide a reference dataset for future investigations of urban meteorology and climate variability. From an applied perspective, the results can support air-quality assessment and forecasting, emission-management strategies, urban and environmental planning, and the development of evidence-based policies for mitigating pollution risks in Abuja and comparable tropical African cities.

2.0 Methodology

2.1 Study Area

Abuja, the capital city of Nigeria, is located within the Federal Capital Territory (FCT) in the central region of the country. The city lies near latitude 9.07°N and longitude 7.49°E and experiences a tropical savanna climate characterized by distinct wet and dry seasons. The wet season typically extends from April to October and is associated with enhanced cloud cover, increased precipitation, and relatively lower temperatures, while the dry season spans November to March and is characterized by reduced rainfall, higher solar radiation, and greater diurnal temperature variability. Rapid urbanization, increasing transportation activities, and expanding energy consumption have intensified concerns regarding atmospheric pollution and air-quality management within Abuja. The city therefore provides a suitable tropical urban environment for investigating long-term variability in atmospheric ventilation and boundary-layer dynamics. For the present study, ERA5 meteorological fields were extracted over a 1° × 1° geographical domain bounded by 8.25°–9.25°N and 6.50°–7.50°E. The domain was selected to encompass Abuja and its immediate surrounding atmospheric environment. To obtain representative atmospheric conditions for Abuja, the ERA5 fields were spatially averaged across all grid cells within the domain. All subsequent analyses were performed using the resulting hourly time series.

2.2 Data Source

Hourly meteorological data were obtained from the ERA5 atmospheric reanalysis for January 2016 through December 2025. The variables extracted were boundary-layer height (BLH; m), 10-m eastward/zonal wind component (u10; m s^{-1}), 10-m northward/meridional wind component (v10; m s^{-1}), and 2-m air temperature (T2M; K). T2M was converted from Kelvin to degrees Celsius (°C) before analysis. Wind speed was subsequently derived from u10 and v10, while the ventilation coefficient was calculated from BLH and wind speed. The data were obtained at the ERA5 grid resolution of 0.25° × 0.25° and spatially averaged across the 25 grid cells within the study domain. The complete hourly record from January 2016 to December 2025 was used, and no missing values were identified.

2.3 Atmospheric Ventilation Assessment

Wind speed (WS) was calculated from the zonal and meridional wind components according to:

$$WS = \sqrt{(u_{10}^2 + v_{10}^2)} \quad (1)$$

where WS is wind speed (m s^{-1}), u_{10} is the zonal wind component (m s^{-1}), and v_{10} is the meridional wind component (m s^{-1}).

Atmospheric ventilation was represented using the ventilation coefficient (VC), calculated as:

$$VC = BLH \times WS \quad (2)$$

where VC is the ventilation coefficient (m^2 s^{-1}) and BLH is the boundary-layer height (m)

Wind speed was first calculated for each hourly observation from the corresponding u10 and v10 components, after which the hourly ventilation coefficient was calculated as the product of the simultaneous hourly BLH and wind-speed values. Monthly and annual ventilation coefficients were subsequently obtained by averaging the calculated hourly VC values rather than by multiplying separately averaged BLH and wind-speed values.

The ventilation coefficient is widely used as an indicator of atmospheric dilution potential because it incorporates both vertical mixing through boundary-layer development and horizontal transport through wind motion. Higher VC values indicate enhanced atmospheric dispersion capacity, whereas lower values reflect reduced ventilation and greater potential for pollutant accumulation.

2.4 Monthly Climatology and Interannual Variability Analysis

Monthly climatological averages of BLH, WS, VC, and T2M were calculated from the complete hourly dataset for 2016–2025. For each calendar month, all corresponding hourly observations across the ten-year period were averaged to obtain the monthly climatological mean. This procedure was used to identify recurring annual patterns in atmospheric ventilation and boundary-layer development, while heatmap visualizations were generated to illustrate the evolution of atmospheric conditions across individual years.

To assess interannual variability, annual mean values of BLH, WS, VC, and T2M were calculated by averaging all available hourly observations within each calendar year from 2016 to 2025. This produced ten annual observations for each variable. The resulting annual series were used to characterize year-to-year variability and subsequently for the long-term trend analysis.

2.5 Long-Term Trend Analysis

Long-term trends in BLH, WS, VC, and T2M were assessed using linear regression analysis applied to the ten annual mean observations generated for the period 2016–2025. The regression model was expressed as:

$$Y = a + bt \quad (3)$$

where Y represents the atmospheric variable, a is the intercept, b is the trend slope, and t is time (year). The trend slope was used to quantify the magnitude and direction of long-term change, while the coefficient of determination (R^2) was used to evaluate the proportion of variance explained by the regression model. Positive slopes indicate increasing atmospheric conditions through time, whereas negative slopes indicate declining conditions. Statistical significance of the trends was evaluated at the 95% confidence level ($p < 0.05$).

2.6 Atmospheric Ventilation Stability Assessment

The temporal stability of atmospheric ventilation conditions was evaluated using descriptive statistical measures. For each atmospheric variable, the mean, standard deviation (SD), minimum, and maximum values were calculated over the study period. In addition, the coefficient of variation (CV) was determined as:

$$CV = (\sigma/\mu) \times 100 \quad (4)$$

where σ is the standard deviation and μ is the mean value of the variable.

The coefficient of variation provides a normalized measure of variability and enables comparison among variables with different magnitudes and units. Lower CV values indicate greater temporal stability, whereas higher CV values indicate stronger fluctuations and reduced stability. Frequency distributions of BLH and VC were further examined using histograms to characterize the spread and variability of atmospheric ventilation conditions over Abuja.

2.7 Extreme Low-Ventilation Event Analysis

Extreme low-ventilation events were identified by ranking all hourly ventilation coefficient (VC) values from lowest to highest throughout the study period. The twenty lowest ventilation coefficient events were selected for detailed investigation because they represent periods of severely reduced atmospheric dilution potential. For each extreme event, the corresponding date, time, BLH, WS, VC, and T2M were extracted. The temporal occurrence of these events was subsequently examined according to hour of occurrence, month, and year to identify periods most susceptible to severe ventilation suppression. This analysis was used to characterize the meteorological conditions associated with extreme low-ventilation episodes and their implications for atmospheric pollutant accumulation over Abuja.

2.8 Statistical Analysis

Descriptive and inferential statistical techniques were employed to analyze the temporal behavior of BLH, WS, VC, and T2M over Abuja during 2016–2025. Descriptive statistics, including the mean, standard deviation (SD), minimum, maximum, and coefficient of variation (CV), were computed to characterize the central tendency and variability of the atmospheric variables. Linear regression analysis was applied to annual mean values to quantify long-term trends and determine the magnitude and direction of change over the study period. The coefficient of determination (R^2) was used to assess the proportion of variance explained by the regression model, while statistical significance was evaluated at the 95% confidence level ($p < 0.05$).

For the analysis of extreme low-ventilation events, all hourly ventilation coefficient values were ranked from lowest to highest, and the twenty lowest events were selected for detailed examination. Their temporal occurrence was subsequently analyzed according to hour of occurrence and month of occurrence. Data processing, statistical analyses, and graphical visualization were performed using Python (version 3.13.9) within the Jupyter Lab environment (version 4.4.7). The Pandas, NumPy, SciPy, and Matplotlib libraries were used for data processing, statistical computations, trend analysis, and Fig. generation.

3.0 Results and Discussion

3.1 Results

3.1.1 Monthly Climatology and Interannual Variability of Atmospheric Variables

The monthly climatology and interannual variability of BLH, WS, VC, and T2M over Abuja during 2016–2025 are presented in Table 1 and Figs, 1–4. The annual statistics presented in Table 1 reveal notable interannual variations in boundary-layer dynamics and atmospheric ventilation over Abuja during the study period. Annual mean BLH ranged from 569.39 m in 2019 to 631.47 m in 2025, indicating a variability of approximately 62 m across the decade. Similarly, annual mean VC varied between 835.63 $m^2 s^{-1}$ in 2023 and 959.86 $m^2 s^{-1}$ in 2024, reflecting fluctuations in the atmospheric dilution potential from year to year. In contrast, annual mean wind speed exhibited comparatively small variability, ranging from 1.415 to 1.564 $m s^{-1}$. Air temperature showed a gradual increase during the study period, with the lowest annual mean value observed in 2018 (27.77 °C) and the highest values recorded in 2024 (28.84 °C) and 2025 (28.85 °C).

The monthly climatology of BLH (Fig. 1) demonstrates a recurring annual cycle characterized by enhanced boundary-layer development during the dry season and reduced boundary-layer growth during the wet season. The highest BLH values generally occurred during the late dry season when increased solar heating promoted stronger convective mixing, whereas the lowest values were observed during the wet season under conditions of increased cloud cover and reduced surface heating. A similar seasonal pattern is evident in the ventilation coefficient climatology (Fig. 2), although the magnitude of variability was moderated by the contribution of wind speed. Consequently, months characterized by relatively shallow boundary layers occasionally maintained moderate ventilation conditions when accompanied by stronger winds. This interaction highlights the combined influence of vertical mixing and horizontal transport on atmospheric ventilation.

The interannual variability plots (Figs. 3 and 4) indicate that interannual variations in VC were influenced by the combined behavior of BLH and wind speed. Years such as 2017, 2020, and 2024, which experienced relatively elevated BLH and/or stronger winds, generally recorded higher VC values. However, 2025 illustrates that a high BLH does not necessarily produce a high VC when accompanied by weak winds, as reflected by its relatively low wind speed of 1.415 m s^{-1} and intermediate VC of 886.82 m^2 s^{-1}.

3.1.2 Long-Term Ventilation Trends for Atmospheric Dispersion

Long-term trends in BLH, WS, VC, and T2M over Abuja during 2016–2025 are summarized in Table 2 and illustrated in Fig. 5.

Table 1: Annual mean boundary-layer height (BLH), wind speed (WS), ventilation coefficient (VC), and 2-m air temperature (T2M) over Abuja during 2016–2025

Year	BLH (m)	WS (m s^{-1})	VC (m^2 s^{-1})	T2M (°C)
2016	575.56	1.497	870.28	27.93
2017	629.04	1.481	941.05	28.42
2018	598.83	1.506	909.90	27.77
2019	569.39	1.461	836.56	27.90
2020	607.51	1.537	948.71	27.96
2021	597.16	1.480	879.72	28.35
2022	575.97	1.486	864.15	27.91
2023	572.99	1.463	835.63	28.43
2024	611.79	1.564	959.86	28.84
2025	631.47	1.415	886.82	28.85

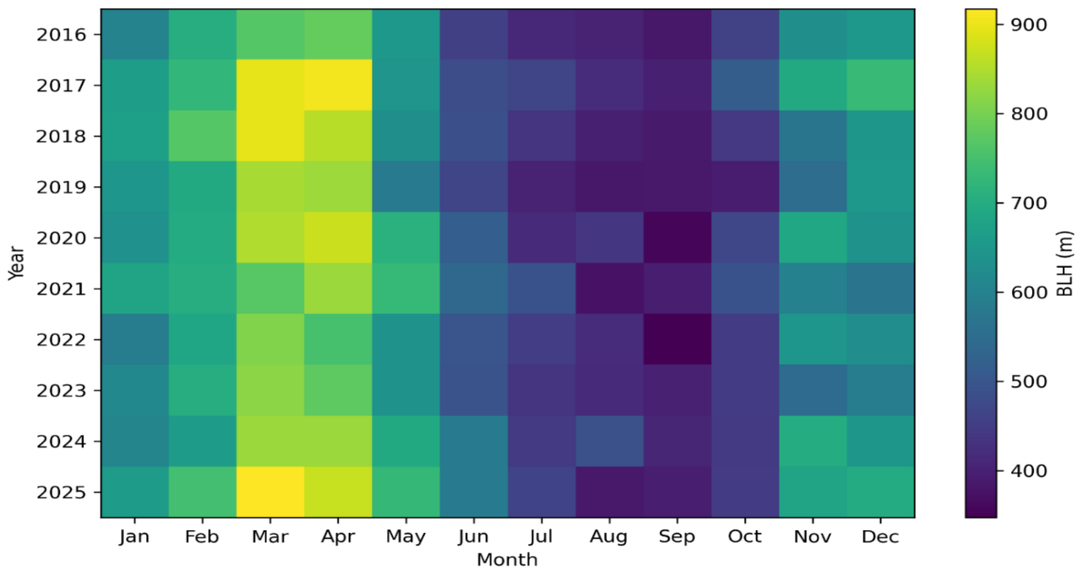

Fig. 1: **Monthly climatology heatmap of boundary-layer height (BLH) over Abuja during 2016–2025.**

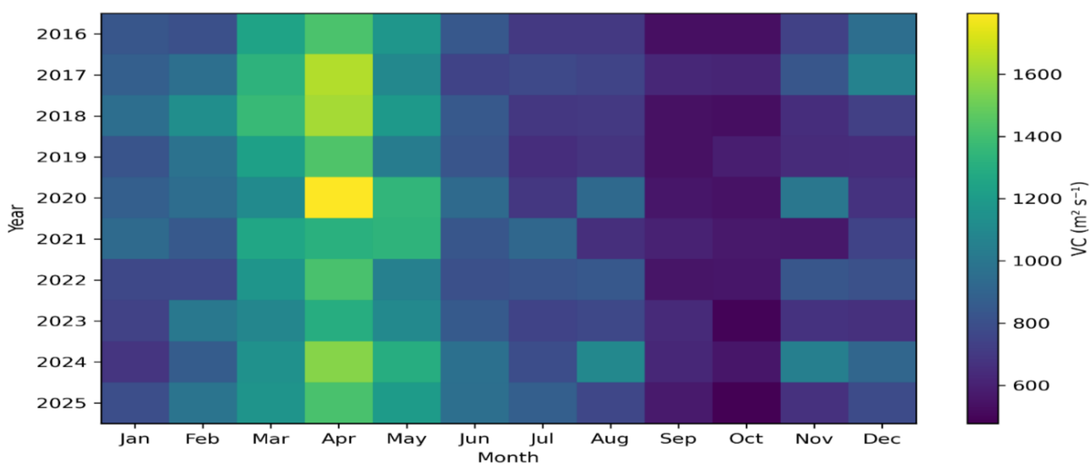

Fig. 2: **Monthly climatology heatmap of ventilation coefficient (VC) over Abuja during 2016–2025.**

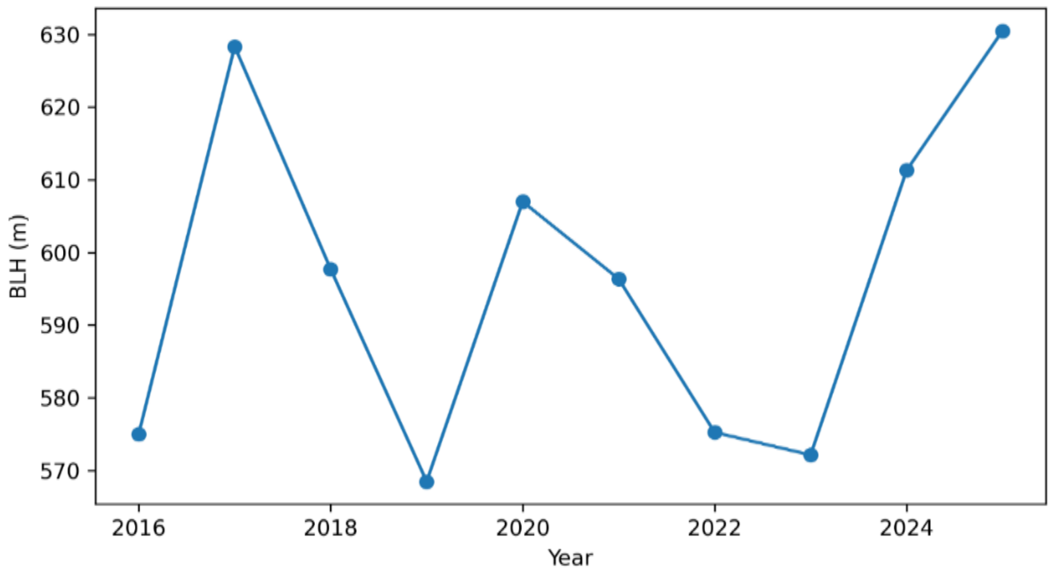

Fig. 3: **Interannual variability of annual mean boundary-layer height (BLH) over Abuja during 2016–2025.**

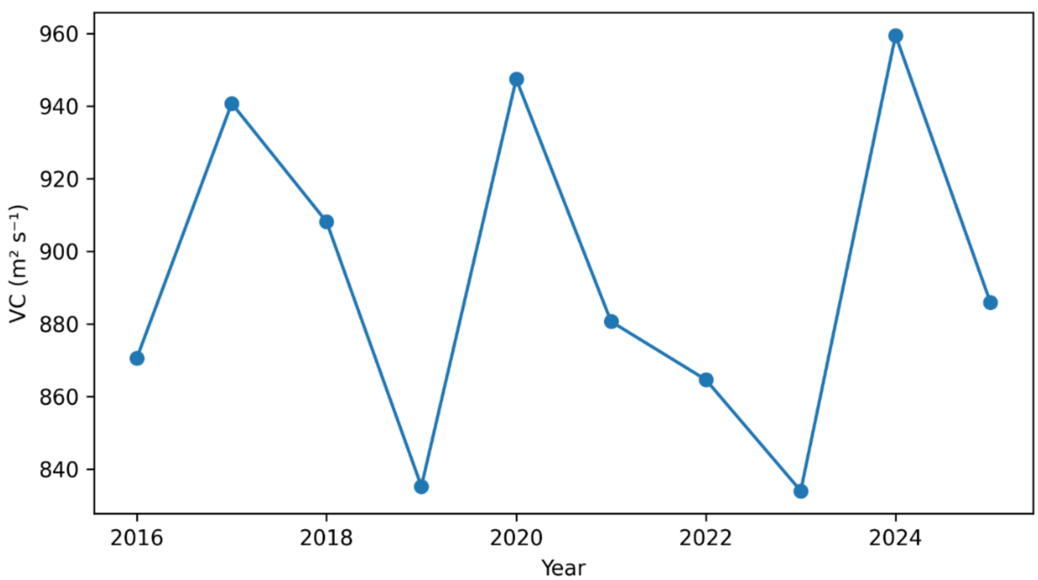

Fig. 4: **Interannual variability of annual mean ventilation coefficient (VC) over Abuja during 2016–2025**.

The temporal trend analysis indicated differing rates of change among the atmospheric variables during 2016–2025. BLH showed a weak positive tendency of 1.59 m yr^{-1}, but the trend was not statistically significant (R^2 = 0.044, p = 0.562). WS exhibited a weak negative tendency of −0.0021 m s^{-1} yr^{-1}, which was also not statistically significant (R^2 = 0.024, p = 0.671). Similarly, VC showed a negligible negative tendency of −0.47 m^2 s^{-1} yr^{-1} (R^2 = 0.001, p = 0.931), indicating that interannual variability substantially exceeded the linear change over the study period. In contrast, T2M showed a statistically significant positive linear trend of 0.091 °C yr^{-1} (R^2 = 0.473, p = 0.028). Given the relatively short ten-year record, this result is interpreted as a significant temporal warming tendency during the study period rather than definitive evidence of a long-term climate trend.

3.1.3 Variability and Distribution Characteristics of Atmospheric Ventilation Conditions

The temporal stability of atmospheric conditions over Abuja during 2016–2025 was evaluated using summary statistics and coefficients of variation (CV), as presented in Table 3. The frequency distributions of BLH and VC are shown in Figs. 6 and 7, respectively. As shown in Table 3, the mean BLH during the study period was 596.21 m, with values ranging from 18.98 m to 3563.48 m. The corresponding standard deviation was 669.52 m, resulting in a coefficient of variation of 112.30%. Wind speed exhibited a mean value of 1.49 m s^{-1}, a standard deviation of 0.73 m s^{-1}, and a coefficient of variation of 48.88%. The mean ventilation coefficient was 892.65 m^2 s^{-1}, with a minimum value of 0.36 m^2 s^{-1} and a maximum value of 10,529.37 m^2 s^{-1}. The standard deviation of VC was 1027.58 m^2 s^{-1}, corresponding to a coefficient of variation of 115.12%. Air temperature exhibited a mean value of 28.22 °C, with values ranging from 16.07 °C to 41.28 °C and a coefficient of variation of 14.66%. The distributional statistics indicate pronounced right-skewed distributions in both BLH and VC. The mean BLH of 596.21 m was considerably higher than the median of 309.06 m, while the mean VC of 892.65 m^2 s^{-1} exceeded its median value of 498.38 m^2 s^{-1}. The large differences between the means and medians, together with the high maximum values of 3563.48 m for BLH and 10,529.37 m^2 s^{-1} for VC, indicate that occasional episodes of very deep boundary layers and strong ventilation substantially influenced the overall distributions. Consequently, median and percentile-based measures provide useful complementary information to the mean when characterizing atmospheric ventilation over Abuja. Generally, the results demonstrate differing degrees of temporal variability among the atmospheric variables, with BLH and VC exhibiting the largest relative fluctuations and T2M showing the lowest variability during the study period.

Table 2: **Linear trend statistics for BLH, WS, VC, and T2M over Abuja during 2016–2025**.

Variable	Trend Slope	R^2	p-value	Trend Direction
BLH (m)	+1.59 m yr^{-1}	0.044	0.562	Increasing
WS (m s^{-1})	−0.0021 yr^{-1}	0.024	0.671	Decreasing
VC (m^2 s^{-1})	−0.47 m^2 s^{-1} yr^{-1}	0.001	0.931	-Decreasing
T2M (°C)	+0.091 °C yr^{-1}	0.473	0.028	Increasing*

***Significant at $p < 0.05$.**

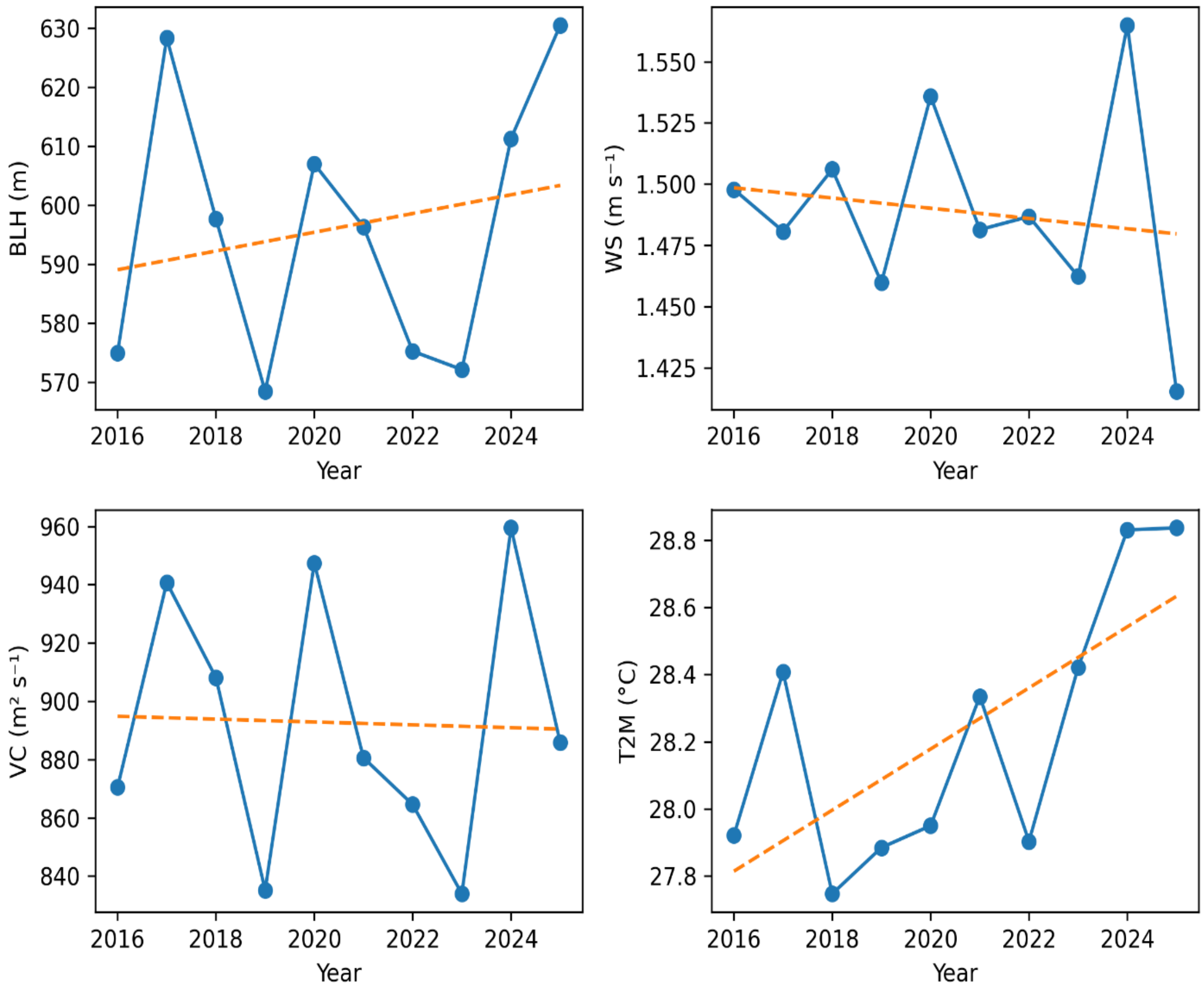

Fig. 5: Long-term trends in annual mean over Abuja during 2016–2025 (a) boundary-layer height (BLH), (b) wind speed (WS), (c) ventilation coefficient (VC), and (d) 2-m air temperature (T2M). Dashed lines represent linear regression trends

Table 3: Summary Statistics and Temporal Stability of Atmospheric Variables over Abuja (2016–2025)

Variable	Mean	Median	SD	Min	Max	CV (%)
BLH (m)	596.21	309.06	669.52	18.98	3563.48	112.3
WS ($m\ s^{-1}$)	1.49	1.42	0.73	0.01	4.67	48.88
VC ($m^2\ s^{-1}$)	892.65	498.38	1027.58	0.36	10529.4	115.12
T2M (°C)	28.22	27.53	4.14	16.07	41.28	14.66

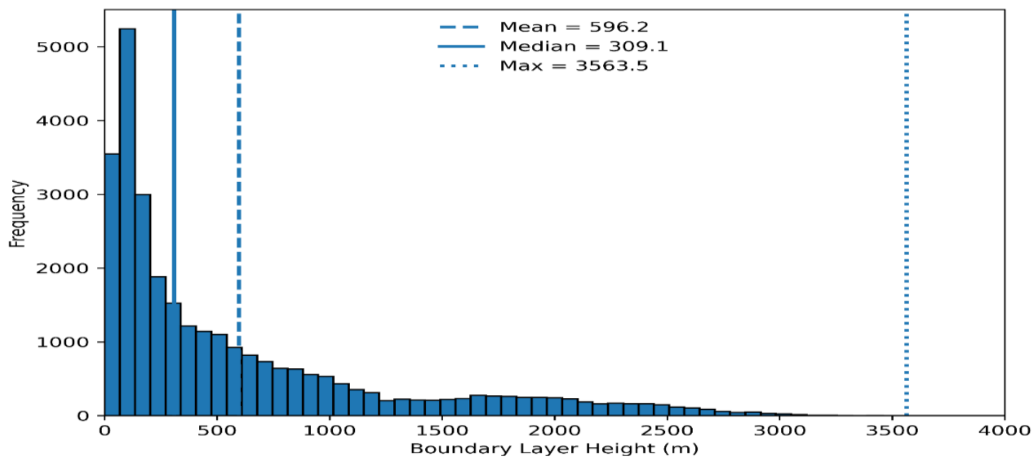

Fig. 6: Frequency distribution of boundary-layer height (BLH) over Abuja during 2016–2025

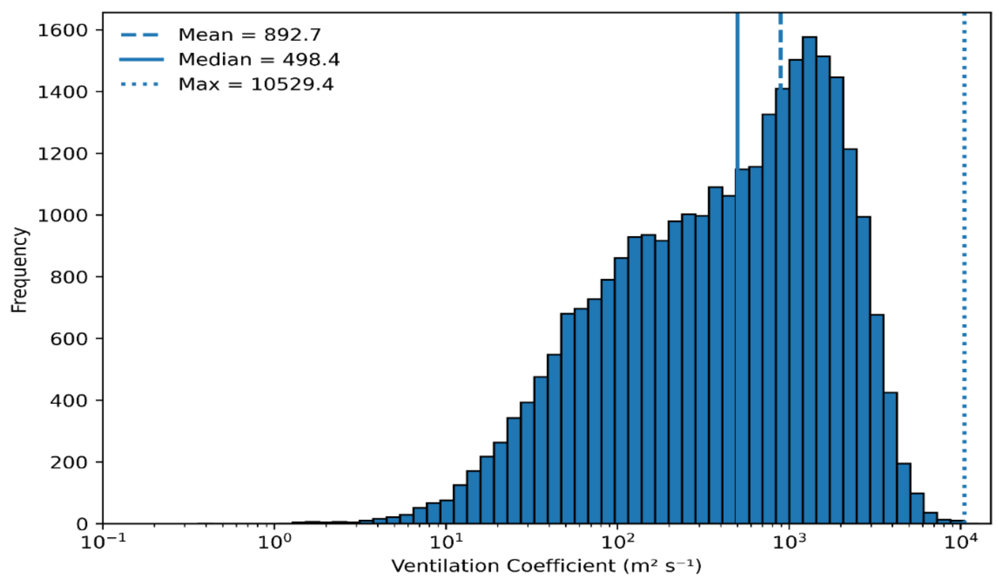

Fig. 7: Frequency distribution of ventilation coefficient (VC) over Abuja during 2016–2025.

3.1.4 Extreme Low-Ventilation Events

Extreme low-ventilation events were identified by ranking all hourly ventilation coefficient (VC) values from lowest to highest during the 2016–2025 study period (Fig. 8). The twenty lowest ventilation events are presented in Table 4.

The twenty lowest ventilation coefficient events recorded during the study period exhibited VC values ranging from 0.36 to 2.31 $m^2 s^{-1}$ (Table 4). The lowest event occurred on the 4th of December 2019 at 21:00 UTC, when the ventilation coefficient decreased to 0.36 $m^2 s^{-1}$ under a boundary-layer height of 32.58 m and a wind speed of 0.011 $m s^{-1}$. The associated boundary-layer heights ranged from 19.52 m to 92.50 m, while wind speeds varied between 0.011 and 0.082 $m s^{-1}$. Air temperatures during these events ranged from 22.53 °C to 31.34 °C. The extreme low-ventilation events occurred throughout the study period and were observed during multiple years. Their occurrence was concentrated during nighttime and early-morning hours, particularly between 21:00 and 06:00 UTC. Several events were recorded during September, October, November, and

December, although occurrences were also observed in other months.

Overall, the results indicate that extreme low-ventilation events were characterized by exceptionally low ventilation coefficients accompanied by shallow boundary layers and very weak winds relative to typical atmospheric conditions over Abuja.

The hourly distribution of the twenty extreme low-ventilation events is summarized in Table 5, while their monthly distribution is shown in Fig. 9. All events occurred between 21:00 and 06:00 UTC, confirming that extreme ventilation deficiencies were confined to nighttime and early-morning periods. The highest frequency occurred at 00:00 UTC (40%), followed by 03:00 UTC (25%), whereas events at 21:00 UTC and 06:00 UTC accounted for 20% and 15%, respectively.

Table 4: Top 20 Extreme Low-Ventilation Events Identified over Abuja during 2016–2025

Rank	Date	Time (UTC)	BLH (m)	WS (m s^{-1})	VC (m^2 s^{-1})	T2M (°C)
1	04-Dec-2019	21:00	32.58	0.011	0.36	27.27
2	07-Oct-2024	06:00	21.71	0.053	1.15	24.04
3	25-Sep-2024	00:00	20.58	0.064	1.31	25.10
4	14-Oct-2018	00:00	38.24	0.036	1.39	25.09
5	30-May-2025	00:00	30.73	0.049	1.50	24.79
6	07-Sep-2023	03:00	43.37	0.035	1.51	25.30
7	26-Oct-2018	00:00	25.64	0.060	1.55	24.47
8	26-Sep-2022	00:00	35.09	0.044	1.55	23.49
9	18-Nov-2018	00:00	19.52	0.081	1.59	25.75
10	07-Nov-2016	00:00	31.48	0.053	1.66	23.38
11	20-Oct-2020	06:00	29.28	0.057	1.66	23.51
12	26-Nov-2025	03:00	55.06	0.032	1.74	22.53
13	19-Dec-2023	21:00	23.13	0.082	1.89	26.49
14	27-Jan-2017	03:00	92.50	0.022	2.06	25.19
15	04-Sep-2020	03:00	42.15	0.049	2.06	23.09
16	26-Aug-2020	06:00	43.15	0.048	2.07	24.93
17	26-Dec-2025	21:00	50.15	0.045	2.24	31.34
18	16-Dec-2016	21:00	50.14	0.046	2.29	27.28
19	17-Oct-2017	03:00	38.55	0.060	2.31	24.12
20	14-Jul-2023	00:00	39.90	0.058	2.31	26.18

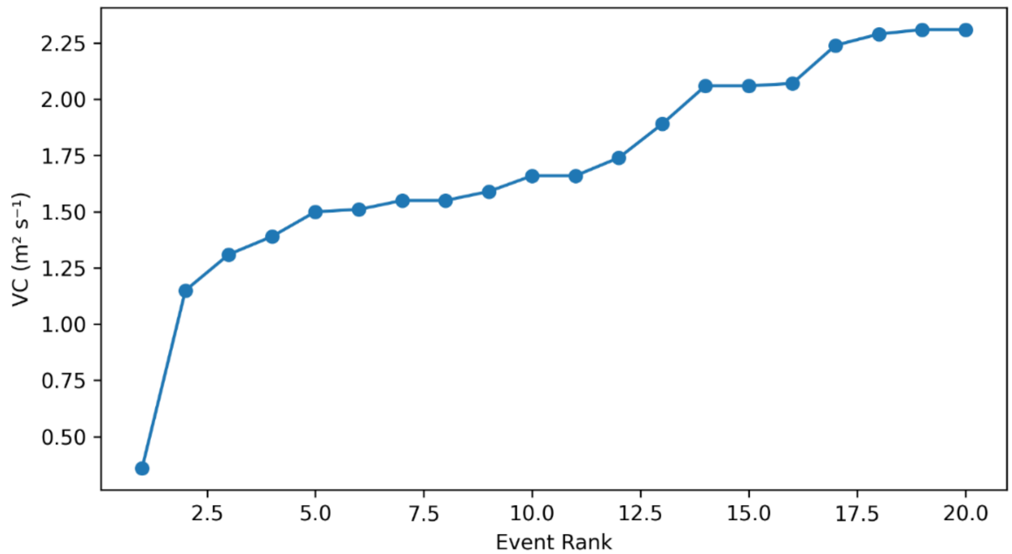

Fig. 8: Ranked ventilation coefficient values for the twenty lowest ventilation events recorded during 2016–2025

Monthly occurrence showed that extreme low-ventilation events were concentrated between September and December, with October recording the greatest frequency (25%), followed by September and December (20% each). Only isolated events were observed during January, May, July, and August. These findings indicate that the most severe ventilation deficiencies over Abuja occur predominantly during nocturnal hours and are more frequent during the late rainy season and early dry season.

Table 5: Hourly Distribution of the Top 20 Extreme Low-Ventilation Events over Abuja (2016–2025)

Hour (UTC)	Frequency	Percentage (%)
0:00	8	40
3:00	5	25
6:00	3	15
21:00	4	20

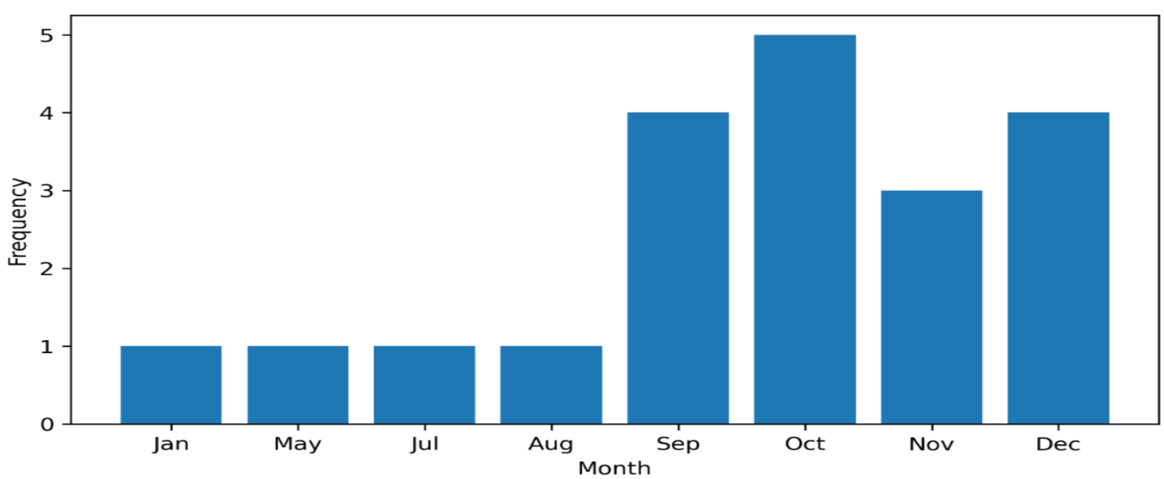

Fig. 9: Monthly distribution of the twenty extreme low-ventilation events identified over Abuja during 2016–2025

3.2 Discussion

3.2.1 Implications of Climatological and Interannual Variability for Atmospheric Ventilation

The monthly climatology revealed pronounced seasonal variations in boundary-layer height (BLH) and ventilation coefficient (VC) over Abuja. Higher BLH values during the dry season indicate enhanced convective development associated with stronger surface heating, whereas lower values during the wet season reflect reduced solar insolation and suppressed boundary-layer growth. Similar seasonal behavior has been reported in urban atmospheric environments, where BLH is strongly controlled by surface energy exchange and turbulent mixing processes. Sujatha *et al.* (2016) reported that seasonal variations in ventilation conditions were primarily governed by changes in boundary-layer development and wind speed, emphasizing the importance of BLH in determining atmospheric dilution potential.

The interannual variability observed in Abuja indicates that atmospheric ventilation fluctuates from year to year, although the magnitude of these changes remains modest relative to seasonal variability. This finding is consistent with previous studies showing that boundary-layer dynamics exhibit substantial short-term variability while maintaining relatively stable long-term climatological characteristics. Li *et al.* (2013) similarly demonstrated that planetary boundary-layer height exhibits strong temporal variability driven by surface forcing and land-atmosphere interactions in tropical urban environments.

3.2.2 Implications of Long-Term Ventilation Trends for Atmospheric Dispersion

A notable finding of this study is that despite a statistically significant increase in air temperature during 2016–2025, no significant long-term trends were observed in BLH, wind speed, or VC. This suggests that warming alone may not necessarily translate into measurable changes in atmospheric ventilation conditions over decadal timescales. The absence of significant trends in the ventilation parameters indicates that interannual meteorological variability was substantially greater than the observed linear changes over the study period. Previous studies have emphasized that atmospheric ventilation depends on the combined influence of boundary-layer development and wind speed rather than temperature alone. Sujatha *et al.* (2016) demonstrated that VC is highly sensitive to variations in BLH and transport winds, while Rigby and Toumi (2008) highlighted the critical role of both wind speed and boundary-layer depth in determining urban pollutant dispersion. Consequently, the atmospheric ventilation characteristics and dilution potential of the study area remained broadly stable over the decade.

3.2.3 Implications of Ventilation Stability and Variability for Urban Air Quality

The coefficient-of-variation analysis revealed that BLH and VC exhibited substantially greater variability than wind speed and temperature. The high variability of BLH reflects the strong influence of changing atmospheric stability, surface heating, and turbulent mixing on boundary-layer development. Because VC incorporates both BLH and wind speed, variability in either component can contribute substantially to fluctuations in the ventilation coefficient. Similar observations have been reported elsewhere. Singh (2019) noted that BLH and VC are among the most dynamic meteorological parameters influencing urban air quality because they respond directly to changes in atmospheric stability and turbulence. Likewise, Sujatha *et al.* (2016) reported strong temporal variability in VC associated with changing boundary-layer structure and meteorological conditions. The relatively low variability of temperature compared with BLH and VC further suggests that thermal conditions remain comparatively stable even when atmospheric ventilation undergoes substantial fluctuations.

3.2.4 Implications of Extreme Low-Ventilation Events for Atmospheric Dispersion

The extreme low-ventilation events identified in this study were characterized by very shallow boundary layers and exceptionally weak winds. Most events occurred between 21:00 and 06:00 UTC, indicating a strong association with nocturnal stable atmospheric conditions. Under such conditions, reduced turbulence and suppressed boundary-layer growth limit the atmosphere's ability to disperse pollutants, increasing the likelihood of pollutant accumulation near the surface. The nocturnal concentration of extreme events is consistent with the established understanding of boundary-layer evolution. Li *et al.* (2013) reported that boundary-layer height decreases rapidly after sunset as surface cooling promotes stable stratification. Similarly, studies of urban ventilation have shown that low BLH and weak winds are key contributors to reduced pollutant dispersion and poor air-quality episodes.

Additionally, the concentration of events during September–December may reflect seasonal transitions associated with reduced convective activity and weaker atmospheric mixing. These findings highlight periods when the atmosphere is most vulnerable to pollutant accumulation and therefore provide useful information for air-quality management and environmental planning in Abuja.

4.0 Conclusion

This study provides the first comprehensive ERA5-based climatological assessment of atmospheric ventilation over Abuja, Nigeria, covering the period 2016–2025. The findings demonstrate that atmospheric ventilation is characterized by pronounced temporal variability but exhibits no significant long-term change despite a measurable increase in near-surface air temperature. This indicates that the observed warming over the study period was not accompanied by a statistically detectable change in the ventilation parameters examined. The occurrence of extreme low-ventilation events during nighttime and their concentration between September and December identifies periods when the urban atmosphere is most susceptible to reduced pollutant dispersion and potential pollutant accumulation. These conditions represent critical windows during which meteorological constraints may limit the atmosphere's pollutant-dispersion potential, emphasizing the need for greater consideration of atmospheric ventilation in air-quality management and urban environmental planning. Beyond its regional relevance, this study establishes a climatological baseline against which future changes in atmospheric ventilation can be evaluated under continued urbanization and climate change. The findings also demonstrate the value of ERA5 reanalysis for long-term characterization of atmospheric ventilation in data-sparse tropical environments and provide a scientific foundation for future investigations integrating emission inventories, air-quality observations, and atmospheric dispersion modelling to improve environmental decision-making.

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