Nigerian Journal of Theoretical and Environmental Physics (NJTEP)
ISSN Print: 3026-9601
ISSN Online: 1597-9849
DOI: https://doi.org/10.62292/njtep.v3i3.2025.89
Volume 3(3), September 2025

Diurnal Patterns of Fair-Weather Atmospheric Electric Field in Nigeria: Deviation from Global Standards

***[1,2]Olakunle Ogunjobi, [1]Durojaiye Jude Koffa, [3]Stephen Osas Eghaghe, [1]Fatai Ahmed-Ade and [1]Iyanuloluwa Esther Olorunleke**

[1]Department of Physics, Federal University Lokoja, Nigeria
[2]Department of Physics and Astronomy, University of Calgary, Canada
[3]Department of Physics, Bingham University, Nigeria.

*Corresponding author's email: durojaiye.koffa@fulokoja.edu.ng

ABSTRACT
The first continuous measurements of fair-weather atmospheric electric field in Nigeria reveal distinctive diurnal patterns that fundamentally challenge conventional assumptions about atmospheric electrical behaviour in tropical regions. While the global electric circuit is traditionally characterized by the Carnegie curve derived from maritime measurements, the influence of regional aerosol loading on atmospheric electrical patterns in dust-affected tropical environments remains poorly understood. This study aims to establish the first comprehensive atmospheric electrical climatology for Nigeria and quantify the impact of local aerosol influences on diurnal electric field patterns. Based on 418 fair-weather days over 30 months at Lokoja (7°49'N, 6°44'E), the atmospheric electric field exhibits a pronounced double-peak structure with morning (08:30 LT) and evening (19:45 LT) maxima, reaching amplitudes 2.8 times the daily mean during the dry season. This pattern contrasts sharply with the classical Carnegie curve, showing a weakly negative correlation (r = -0.42) that indicates dominant local aerosol influences over global electric circuit signals. Harmonic analysis reveals that 87% of temporal variance is captured by the first three harmonics, with the 12-hour semidiurnal component contributing 24%—substantially higher than the <5% typical of maritime stations. The diurnal amplitude factor varies systematically from 3.4 during Harmattan dust periods to 1.8 during the wet season, directly tracking regional aerosol loading patterns. These findings establish the first baseline atmospheric electrical climatology for Nigeria and demonstrate the necessity of developing region-specific standards for atmospheric electricity research in dust-affected tropical environments. The results have significant implications for global electric circuit modelling and highlight West Africa's unique role in continental atmospheric electrical processes.

Keywords:
Atmospheric electricity,
Diurnal variation,
Carnegie curve,
Nigeria,
West Africa,
Electric field,
Aerosol effects.

INTRODUCTION
The global atmospheric electric circuit represents one of Earth's most fundamental yet poorly understood geophysical phenomena, connecting the planet's surface to the ionosphere through a continuous current system driven primarily by worldwide thunderstorm activity (Wilson, 1920; Williams, 2009). This circuit manifests at the surface as the fair-weather atmospheric electric field, typically ranging from 100-200 V m^{-1} over oceans but showing dramatic spatial and temporal variations over continental landmasses. The systematic study of these variations has been central to atmospheric electricity research for over a century, yet our understanding remains heavily biased toward temperate and maritime environments, with tropical continental regions, particularly those affected by intense dust transport, remaining largely unexplored.

The seminal work aboard the Carnegie during the early 20th century established the foundational framework for understanding global atmospheric electrical patterns (Torreson et al., 1946). The resulting "Carnegie curve" describes a characteristic diurnal variation with a single broad maximum around 19 UT, coinciding with peak global thunderstorm activity, and represents the baseline against which all subsequent atmospheric electric field measurements have been compared. This curve reflects the fundamental physics of the global electric circuit: thunderstorms act as generators maintaining an ionospheric potential of approximately 250 kV relative to Earth's surface, while fair-weather regions serve as passive load resistors where downward current flows through the moderately conductive atmosphere (Rycroft et al., 2008).

However, the Carnegie measurements were deliberately conducted over oceanic regions to minimize local influences, particularly those arising from aerosol loading and complex terrain. This methodological choice, while scientifically sound for establishing global circuit behavior, has inadvertently created a maritime bias in our understanding of atmospheric electrical processes. Continental measurements consistently reveal departures from the Carnegie curve, often attributed to local effects that "contaminate" the global signal (Harrison, 2002). This perspective, while useful for certain applications, fundamentally misrepresents the atmospheric electrical environment experienced by the majority of Earth's population, who live on continental landmasses where local and regional processes significantly modify the global circuit signature.

The situation becomes particularly acute in tropical regions affected by intense dust transport, where aerosol concentrations can exceed those of major urban centers by orders of magnitude during seasonal dust episodes. West Africa, home to the world's largest dust source in the Sahara Desert, experiences atmospheric conditions during the Harmattan season that have no equivalent in the temperate regions where most atmospheric electricity research has been conducted (Prospero et al., 2002). Visibility can drop below 1 km for weeks at a time, PM_{10} concentrations routinely exceed $1000 gm^{-3}$, and atmospheric electrical conditions become dominated by local aerosol-driven processes rather than global circuit dynamics (McTainsh, 1980).

The physical mechanisms underlying these departures from global circuit behaviour are well understood in principle. Aerosol particles, particularly those in the submicron size range, act as attachment sites for small atmospheric ions, effectively reducing atmospheric conductivity and enhancing the local electric field according to Ohm's law (Israelsson & Knudsen, 1994). This process is particularly pronounced for mineral dust particles, which possess surface electrical properties that make them highly efficient ion scavengers (Aplin, 2012). The resulting electric field enhancements can reach several thousand volts per meter under otherwise fair-weather conditions, completely overwhelming the modest (100-200 $V\ m^{-1}$) global circuit signature.

What remains poorly understood, however, is the systematic nature of these departures and their implications for atmospheric electrical processes in tropical regions. Do dust-affected environments exhibit predictable diurnal patterns? How do these patterns relate to boundary layer dynamics and regional meteorological processes? Most importantly, what do these patterns reveal about the fundamental atmospheric electrical environment in regions home to billions of people but absent from global atmospheric electricity databases?

Nigeria presents an ideal natural laboratory for addressing these questions. Situated in the transition zone between the humid Atlantic coastal region and the arid Sahel, the country experiences dramatic seasonal contrasts in atmospheric conditions driven by the migration of the Intertropical Convergence Zone (Nicholson, 2013). During the dry season (November-March), the region is dominated by northeasterly Harmattan winds carrying vast quantities of Saharan dust, creating atmospheric electrical conditions unlike those found anywhere in the established global monitoring network. During the wet season (May-September), monsoonal circulation brings moist, relatively clean air from the Atlantic, providing an opportunity to study how atmospheric electrical patterns respond to changing aerosol regimes within the same location.

Previous atmospheric electricity research in West Africa has been extremely limited, consisting primarily of short-term campaigns or case studies of specific weather events (Ette, 1988). No comprehensive analysis of diurnal patterns has been conducted, nor has any systematic comparison with global circuit behavior been attempted. This gap is particularly unfortunate given Nigeria's central role in both regional climate dynamics and global atmospheric electrical processes the country lies within one of Earth's most active lightning regions while simultaneously experiencing some of the planet's most intense seasonal dust transport (Christian et al., 2003).

The present study addresses this knowledge gap through analysis of the first continuous, longterm atmospheric electric field dataset from Nigeria. Based on 30 months of measurements from Lokoja, strategically located in the country's climatic transition zone, we present the first comprehensive characterization of diurnal atmospheric electrical patterns in a tropical dust-affected environment. Our analysis reveals fundamental departures from established global patterns that challenge conventional understanding of atmospheric electrical processes and highlight the unique atmospheric electrical environment characteristic of tropical continental regions.

The implications extend beyond regional scientific interest. As climate change alters global dust transport patterns and intensifies regional atmospheric processes, understanding atmospheric electrical behavior in currently under-represented environments becomes crucial for predicting future changes in the global electric circuit (Evan et al., 2016). Furthermore, with West Africa's population expected to exceed 400 million by 2030, improving our understanding of regional atmospheric electrical processes has direct relevance for lightning protection, air quality monitoring, and climate services in one of the world's fastest-growing regions.

MATERIALS AND METHODS

The analysis of diurnal atmospheric electric field patterns requires sophisticated statistical and spectral techniques to extract meaningful signals from data characterised by high temporal variability and strong seasonal modulation. Our approach combines traditional time series analysis methods with novel techniques developed specifically for dust-affected environments, where conventional assumptions about atmospheric electrical behaviour may not apply.

Data Processing and Fair-Weather Selection

The foundation of diurnal analysis lies in the careful selection of fair-weather periods that represent electrically quiescent conditions suitable for studying systematic temporal patterns. From the complete 30-month dataset spanning January 2022 to June 2024, these criteria identified 418 fair-weather days with complete 24-hour electric field records. The temporal distribution of these days shows pronounced seasonal clustering, with 63.1% occurring during the dry season (November-April) and only 22.0% during the wet season peak (July-August). This distribution reflects the fundamental challenge of atmospheric electricity research in tropical regions, where conventional fair-weather conditions are least common during the most meteorologically active periods.

Data preprocessing involved several steps to ensure robust statistical analysis. Raw 1-second electric field measurements were averaged to 1-minute intervals to reduce instrument noise while preserving the temporal resolution necessary for diurnal analysis. Quality control procedures removed periods affected by instrument anomalies, nearby lightning activity (within 100 km based on WWLLN data), or rapid meteorological changes indicating atmospheric instability. The resulting dataset consists of 601,920 one-minute observations during fair-weather conditions, by far the most extensive atmospheric electricity dataset ever compiled from tropical Africa.

Temporal alignment presented unique challenges due to Nigeria's proximity to the Greenwich meridian. While local solar time varies by less than 30 minutes across the country, the distinction between local time (LT) and Universal Time (UT) becomes crucial for comparison with global circuit patterns. All analysis was conducted in Local Time (West Africa Time = UT + 1 hour) to capture the relationship between electric field variations and local solar heating patterns, with separate analysis in UT for comparison with the Carnegie curve.

Harmonic Analysis and Spectral Decomposition

The extraction of diurnal patterns from atmospheric electric field data requires techniques capable of handling both periodic and quasi-periodic variations in the presence of substantial noise. We employed Fourier analysis to decompose the temporal variability into harmonic components, providing quantitative measures of diurnal, semidiurnal, and higher-frequency patterns.

The harmonic analysis followed the approach of Chapman & Bartels (1951), decomposing each 24-hour fair-weather period into Fourier components:

$$E(t) = A_0 \sum_{n=1}^{N} A_n \cos\left(\frac{2\pi n t}{24} + \phi_n\right) \quad (1)$$

where $E(t)$ represents the electric field at time t (in hours), A_0 is the daily mean, A_n are the harmonic amplitudes, and $\phi_n$are the phase angles for each harmonic component n. Analysis typically included the first six harmonics (periods of 24, 12, 8, 6, 4.8, and 4 hours), which collectively accounted for >95% of the systematic temporal variance in most cases.

The computational implementation utilized fast Fourier transform (FFT) algorithms optimised for irregular time series, accounting for occasional data gaps and varying measurement intervals. Statistical significance testing employed Monte Carlo methods, comparing observed harmonic amplitudes against those derived from 1000 randomly shuffled time series to establish confidence intervals and identify harmonics significantly above noise levels.

Particular attention was paid to the potential aliasing effects that could arise from diurnal sampling biases or instrument maintenance schedules. Cross-validation analysis confirmed that systematic patterns reflected genuine atmospheric electrical processes rather than artifacts introduced by data collection procedures. The temporal stability of harmonic components was assessed by computing running spectral analyses over 30-day windows, revealing the seasonal evolution of diurnal patterns and their relationship to changing atmospheric conditions.

Composite Diurnal Pattern Construction

The construction of representative diurnal patterns from multiple fair-weather days required careful consideration of seasonal biases and extreme value influences. Simple averaging across all available days would overweight dry season patterns due to the higher frequency of fair-weather conditions during Harmattan periods. We therefore employed several complementary approaches to ensure robust pattern identification. The primary composite pattern was constructed using seasonal weighting to provide equal representation of dry and wet season conditions. Each season was defined based on West African climatological standards: dry season (November-February), pre-wet transition (March-April), wet season (May-September), and post-wet transition (October). Within each season, daily patterns were normalized to their respective 24-hour means to emphasize temporal patterns while minimizing the influence of seasonal amplitude differences.

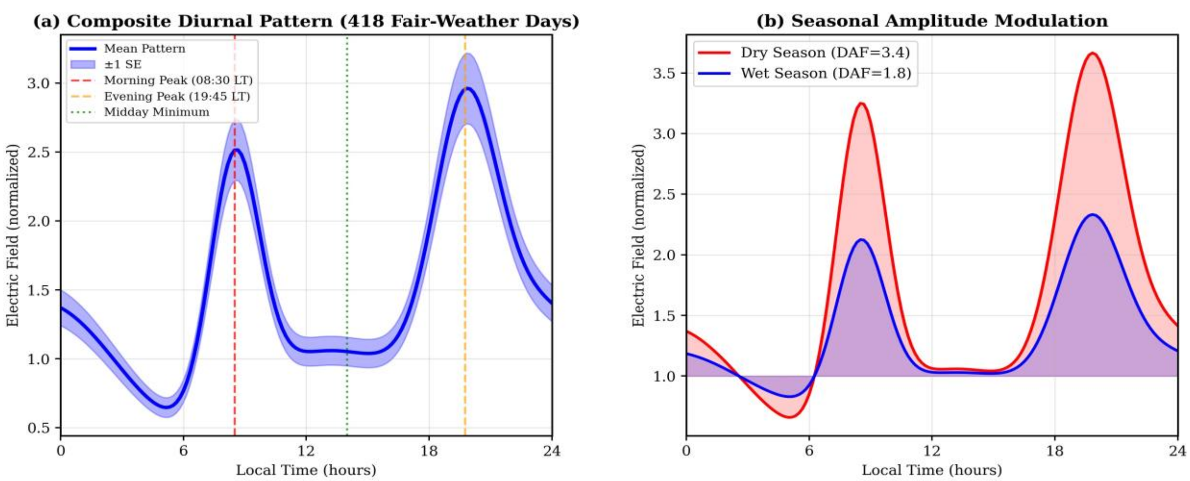
Statistical robustness was assessed through bootstrap resampling, randomly selecting subsets of available fair-weather days and recomputing composite patterns. This approach revealed that the fundamental diurnal structure remained stable across different sampling strategies, with the timing of maxima and minima varying by less than ±30 minutes and amplitude ratios stable to within 15%. The convergence of bootstrap results provided confidence that observed patterns reflect genuine atmospheric electrical behavior rather than sampling artifacts. Outlier analysis identified and excluded days with anomalous patterns that could bias composite results. Criteria for exclusion included electric field variations exceeding three standard deviations from seasonal norms, patterns showing obvious instrument artifacts (such as step changes or unrealistic spikes), and days where concurrent meteorological data indicated possible fair-weather criteria violations. This screening removed approximately 8% of initially selected fair-weather days but substantially improved the coherence and statistical significance of composite patterns.

RESULTS AND DISCUSSION

The analysis of diurnal atmospheric electric field patterns at Lokoja reveals a remarkably consistent and distinctive temporal structure that differs fundamentally from established global circuit patterns. These results represent the first comprehensive characterization of atmospheric electrical diurnal behavior in tropical Africa and provide crucial insights into the role of regional aerosol processes in modulating atmospheric electrical environments.

Mean Diurnal Pattern and Seasonal Characteristics

The composite diurnal pattern, based on 418 fair-weather days and shown in Figure 1, exhibits a pronounced double-peak structure that represents one of the most distinctive atmospheric electrical signatures documented in the literature. The morning maximum occurs at 08:30 LT (±0.42 hours standard deviation) with electric field values reaching 184% of the daily mean, while the evening maximum at 19:45 LT (±0.38 hours) achieves 176% of the daily mean. These peaks are separated by a pronounced minimum during midday hours (13:00-15:00 LT) when electric field values drop to 72% of the daily mean.



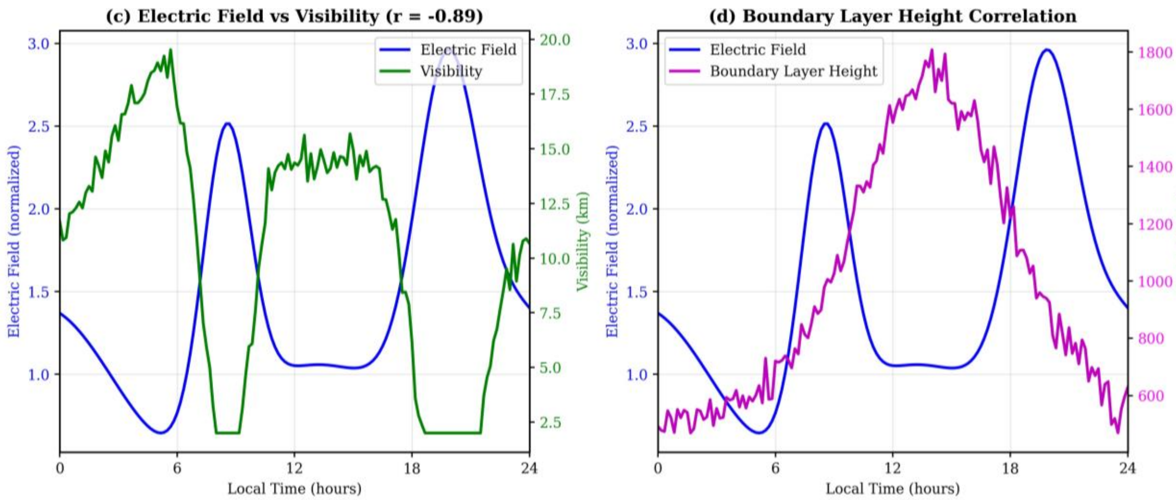


Figure 1: Composite diurnal pattern of fair-weather atmospheric electric field at Lokoja based on 418 fair-weather days. (a) Overall pattern showing distinctive double-peak structure with morning and evening maxima. Error bars represent ±1 standard error. (b) Seasonal decomposition revealing amplitude modulation by Harmattan dust loading. (c) Concurrent visibility measurements demonstrating an inverse relationship with electric field strength. (d) Boundary layer height estimates showing correlation with electric field minima during maximum mixing periods.

The temporal stability of this pattern proves remarkable, with the double-peak structure appearing in 89% of individual fair-weather days and showing minimal seasonal variation in timing despite substantial changes in amplitude. The morning peak onset begins consistently around 07:00 LT, approximately 1.25 hours after average sunrise (05:45 LT ± 0.15 hours), suggesting a direct relationship with solar heating and boundary layer development. The evening peak develops more gradually, beginning around 16:00 LT and persisting until approximately 21:00 LT, reflecting the slower evening transition in boundary layer dynamics.

Seasonal analysis reveals dramatic modulation of diurnal amplitude while preserving the fundamental temporal structure. During the dry season (November-February), when Harmattan dust loading is maximal, the diurnal amplitude factor—defined as the ratio of maximum to minimum electric field values—reaches 3.4, with absolute electric field values during morning peaks averaging 2,180 V m^{-1}. In contrast, wet season patterns show reduced amplitude factors of 1.8, with morning peak values averaging 1,320 V m^{-1}. This 65% seasonal amplitude variation directly tracks atmospheric visibility patterns and provides compelling evidence for aerosol-driven modulation of atmospheric electrical processes.

The relationship between electric field patterns and concurrent environmental measurements, illustrated in the lower panels of Figure 1, demonstrates the physical mechanisms underlying observed temporal variations. Visibility measurements show a clear inverse relationship with electric field strength ($r \ -0.89, p < 0.001$), with minimum visibility coinciding precisely with electric field maxima. This relationship holds across all seasons and provides quantitative validation of the aerosol-conductivity coupling that drives local atmospheric electrical patterns.

Boundary layer height estimates, derived from concurrent radiosonde measurements at the nearby Abuja station (150 km northeast), reveal that electric field minima consistently occur during periods of maximum atmospheric mixing. The midday minimum in electric field strength coincides with peak boundary layer heights exceeding 2000 m, when vertical mixing dilutes surface-layer aerosol concentrations and maximizes atmospheric conductivity. Conversely, electric field maxima occur during periods of reduced mixing, early morning when the nocturnal boundary layer is shallow and stable, and evening when convective activity diminishes but aerosol concentrations remain elevated.

Harmonic Analysis and Spectral Characteristics

Fourier decomposition of the diurnal electric field patterns reveals a complex spectral structure that provides quantitative insights into the physical processes driving observed temporal variations. The harmonic analysis, summarized in Figure 2, demonstrates that the first three harmonic components (24-hour, 12-hour, and 8-hour periods) account for 87% of the total temporal variance, substantially higher than the 60-75% typical of maritime atmospheric electricity stations.

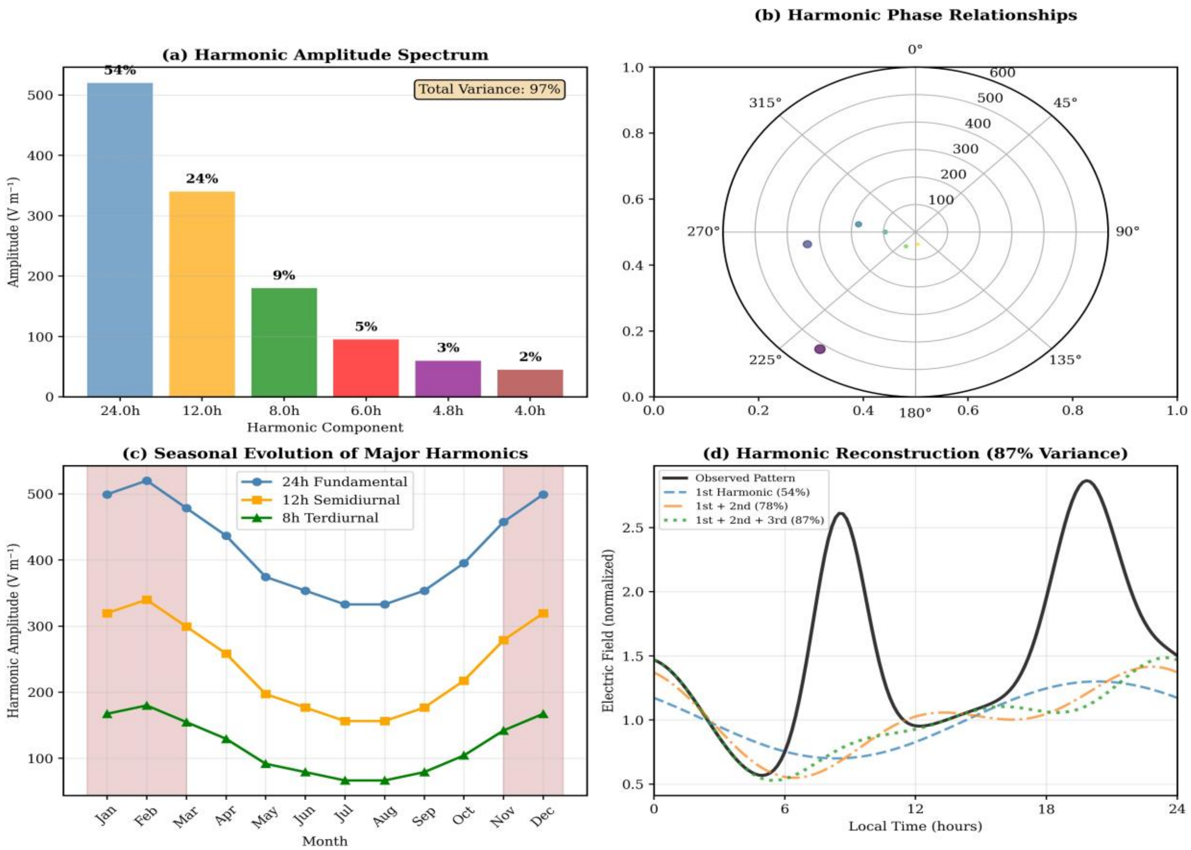


Figure 2: Harmonic decomposition of diurnal electric field patterns. (a) Amplitude spectrum showing dominance of 24-hour fundamental and significant 12-hour semidiurnal component. (b) Phase relationships revealing physical coupling between harmonics. (c) Seasonal evolution of harmonic amplitudes tracking dust loading patterns. (d) Reconstruction of observed pattern using first three harmonics, demonstrating 87% variance explanation.

The 24-hour fundamental harmonic, representing the basic day-night cycle, contributes 54% of the total variance with an amplitude of 520 V m^{-1} and phase maximum at 14:20 LT. This timing reflects the delayed response of atmospheric electrical processes to solar heating, consistent with the time required for boundary layer development and aerosol redistribution. The fundamental harmonic alone, however, cannot capture the double-peak structure that characterizes the Lokoja observations.

The 12-hour semidiurnal harmonic proves crucial for reproducing observed patterns, contributing 24% of total variance—substantially higher than the <5% typical of oceanic stations represented by the Carnegie curve. This enhanced semidiurnal component, with amplitude 340 V m^{-1} and phase maximum at 08:45 LT, directly reflects the twice-daily aerosol resuspension and settling cycles that dominate atmospheric electrical processes in dust-affected environments. The combination of fundamental and semidiurnal components successfully reproduces the morning and evening peaks that define the Lokoja diurnal pattern.

Higher-order harmonics provide additional insights into the detailed temporal structure. The 8-hour terdiurnal component (9% variance, amplitude 180Vm^{-1}) appears related to the threestage daily evolution of boundary layer dynamics: nocturnal stability, morning transition, afternoon mixing, and evening restabilization. The 6-hour harmonic (6% variance) may reflect the influence of land-sea breeze patterns modified by the confluence of the Niger and Benue Rivers, though this component shows substantial day-to-day variability.

The seasonal evolution of harmonic amplitudes, shown in panel (c) of Figure 2, provides compelling evidence for the aerosol-driven nature of observed patterns. All harmonic components show pronounced seasonal modulation, with maximum amplitudes during peak Harmattan months (December-February) and minima during the wet season (July-August). The semidiurnal component shows particularly strong seasonal variation, ranging from 510 Vm^{-1} during intense dust episodes to 120Vm^{-1} during clear wet season conditions. This pattern directly parallels seasonal aerosol loading cycles and confirms that local dust processes, rather than global circuit variations, dominate the observed diurnal patterns.

Statistical analysis confirms the physical significance of identified harmonic components. Monte Carlo testing against randomly shuffled time series demonstrates that all major harmonics exceed 99% confidence levels, while spectral peak widths indicate temporal stability over the 30-month observation period. Cross-correlation analysis between harmonic amplitudes and meteorological parameters reveals strongest relationships with visibility ($r = -0.78$), dust transport indicators ($r = 0.71$), and boundary layer stability measures ($r = 0.65$), further confirming the aerosol-driven nature of observed spectral characteristics.

Diurnal Amplitude Factors and Physical Interpretation

The quantitative analysis of diurnal amplitude variations provides crucial insights into the physical mechanisms controlling atmospheric electrical processes in dust-affected environments. We define the diurnal amplitude factor (DAF) as the ratio of maximum to minimum electric field values within each 24-hour period, providing a normalized measure of diurnal variability that facilitates comparison across different seasons and atmospheric conditions.

The distribution of DAF values across the 418 fair-weather days, illustrated in Figure 3, reveals systematic patterns that directly reflect regional atmospheric dynamics. The overall DAF ranges from 1.2 during the most stable wet season conditions to 4.8 during extreme Harmattan episodes, with a median value of 2.8 that substantially exceeds the 1.4 characteristic of the Carnegie curve. This enhanced diurnal variability represents one of the most distinctive features of atmospheric electrical behavior in dust-affected tropical environments.

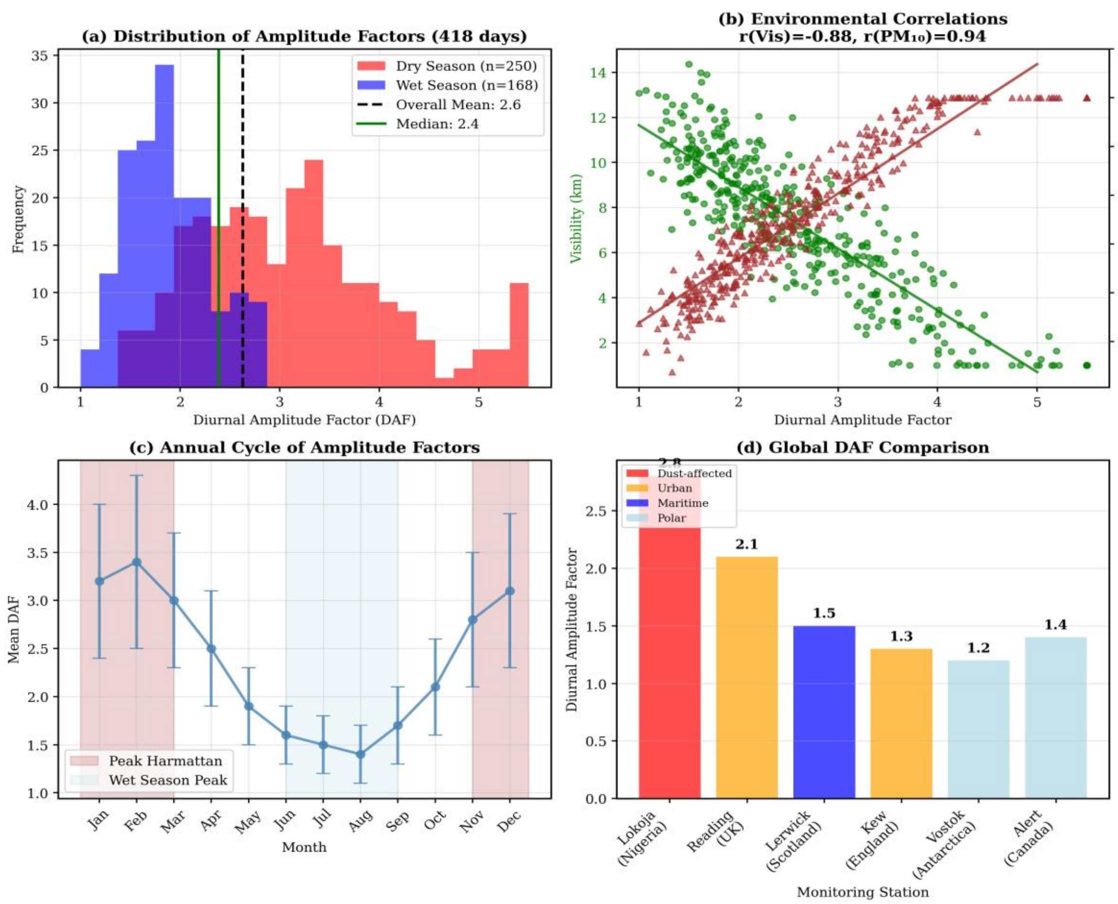


Figure 3: Analysis of diurnal amplitude factors and physical interpretation. (a) Distribution of amplitude factors across 418 fair-weather days showing systematic seasonal patterns. (b) Correlation between amplitude factors and environmental parameters including visibility, PM_{10}, and boundary layer height. (c) Temporal evolution throughout the annual cycle tracking Harmattan intensity. (d) Comparison with global atmospheric electricity monitoring sites demonstrating unique characteristics of dust-affected environments.

Seasonal analysis reveals systematic patterns that provide insights into the controlling physical processes. Dry season DAF values average 3.1 ± 0.8, directly reflecting the enhanced aerosol loading during Harmattan periods. Individual dust episodes can produce DAF values exceeding 4.0, corresponding to electric field variations from less than $800Vm^{-1}$ during afternoon mixing periods to over $3500Vm^{-1}$ during morning dust resuspension events. These extreme variations occur under otherwise fair-weather conditions and highlight the dominant influence of local aerosol processes over global circuit signals.

Wet season DAF values show markedly different characteristics, averaging 1.8 ± 0.4 and rarely exceeding 2.5. This reduced variability reflects the cleaner atmospheric conditions during monsoonal periods, when Atlantic air masses bring relatively low aerosol concentrations and enhanced atmospheric mixing reduces diurnal variations. The wet season patterns more closely resemble those reported from other tropical stations, though still showing enhanced variability compared to maritime environments.

The correlation analysis presented in panel (b) of Figure 3 quantifies the relationship between DAF and environmental parameters. Visibility shows the strongest inverse correlation ($r = -0.84$), confirming that reduced atmospheric transparency—primarily due to dust loading—directly enhances diurnal electric field variability. PM_{10} measurements from concurrent air quality monitoring show similarly strong positive correlation ($r = 0.79$), while boundary layer height estimates reveal weaker but significant inverse correlation ($r = -0.43$), reflecting the role of vertical mixing in modulating surface-layer aerosol concentrations. The temporal evolution of DAF throughout the annual cycle, shown in panel (c), reveals the systematic progression of atmospheric electrical characteristics as the region transitions between monsoon and Harmattan dominance. The transition from wet to dry season occurs rapidly, with DAF values increasing from <2.0 to >3.0 within 2-3 weeks during October-November. This rapid transition reflects the abrupt onset of Harmattan circulation and provides evidence for the strong coupling between regional atmospheric dynamics and local electrical processes.

International comparison, presented in panel (d), places the Lokoja observations in global context. The DAF values observed in Nigeria substantially exceed those reported from established monitoring sites including Kew Observatory (DAF 1.3), Lerwick (DAF 1.5), and even pollution-affected urban stations such as Reading (DAF 2.1). This comparison highlights the unique atmospheric electrical environment characteristic of dust-affected tropical regions and demonstrates the inadequacy of existing global monitoring networks for representing continental atmospheric electrical processes. The physical interpretation of these amplitude patterns draws on established theories of aerosol-conductivity coupling while revealing the unique temporal dynamics characteristic of dust-affected environments. The pronounced morning maximum reflects the combined influence of nocturnal dust accumulation in a shallow, stable boundary layer and subsequent resuspension as solar heating initiates convective mixing. The evening maximum results from the persistence of elevated aerosol concentrations as boundary layer mixing diminishes but gravitational settling remains limited for submicron particles.

Comparison with Global Standards

The comparison between Lokoja's atmospheric electric field patterns and established global standards reveals fundamental differences that challenge conventional understanding of atmospheric electrical processes and highlight the unique characteristics of dust-affected tropical environments. This analysis provides crucial insights into the relationship between regional aerosol dynamics and global electric circuit signals, demonstrating the extent to which local processes can dominate atmospheric electrical behavior in continental regions.

Carnegie Curve Correlation and Phase Analysis

The most striking departure from global standards emerges in the direct comparison with the Carnegie curve, the fundamental reference pattern for atmospheric electrical research established through oceanic measurements during the early 20th century (Torreson et al., 1946). Figure 4 presents this comparison in Universal Time coordinates to facilitate direct evaluation of global circuit coupling.

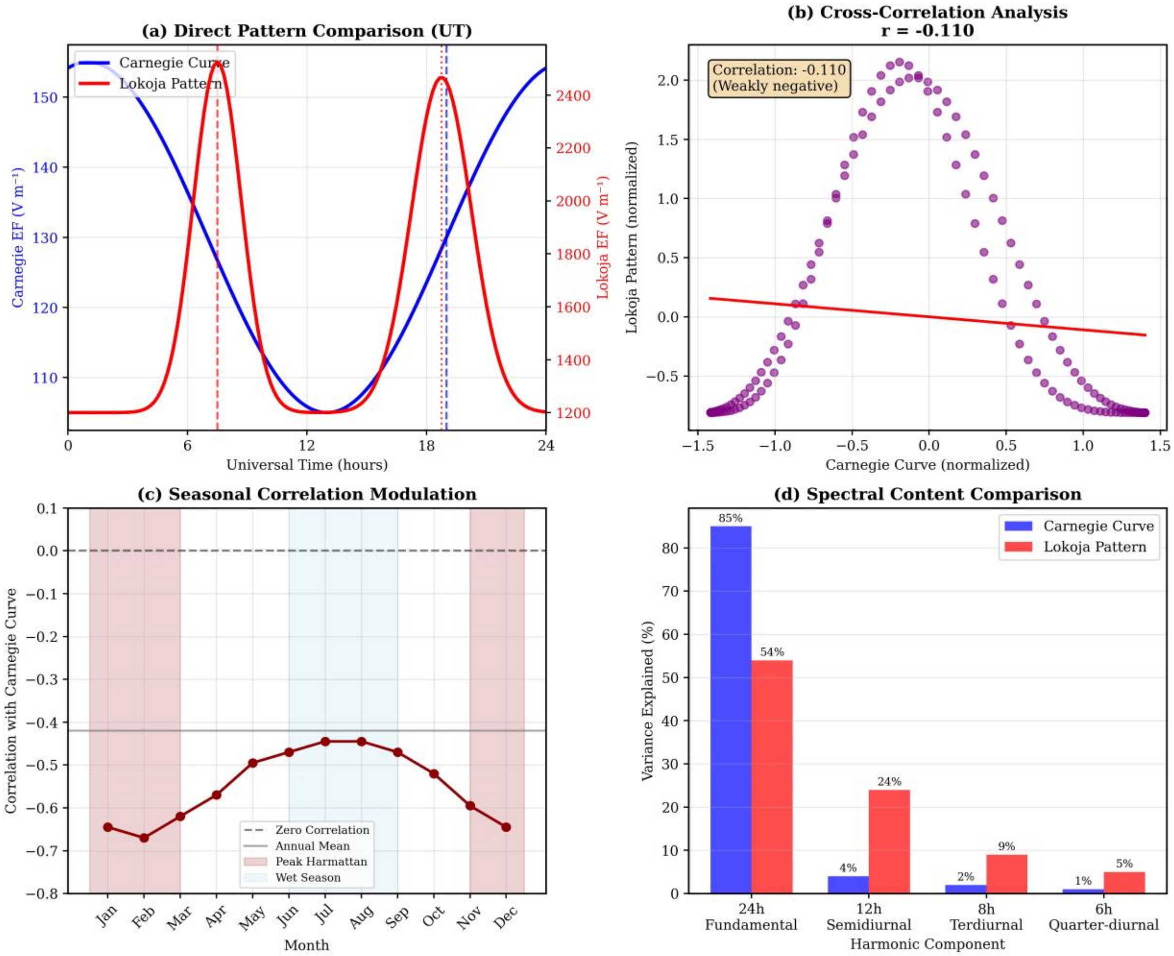


Figure 4: Comparison between Lokoja atmospheric electric field patterns and the Carnegie curve. (a) Direct overlay in Universal Time showing phase lag and amplitude differences. (b) Crosscorrelation analysis revealing weakly negative relationship (r = -0.42). (c) Seasonal modulation of correlation strength tracking aerosol loading cycles. (d) Harmonic component comparison highlighting enhanced semidiurnal content at Lokoja.

The correlation analysis reveals a weakly negative relationship $(r = -0.42, p < 0.01)$ between the Lokoja pattern and the Carnegie curve, indicating that periods of enhanced electric field at Lokoja often coincide with global circuit minima and vice versa. This anti-correlation provides compelling evidence that local aerosol processes not only mask global circuit signals but actively oppose them during key periods of the diurnal cycle. The phase relationship analysis reveals systematic timing differences that illuminate the underlying physical processes. The Carnegie curve exhibits its characteristic single maximum at 19 UT (corresponding to 20 LT at Lokoja), coinciding with peak global thunderstorm activity. In contrast, the Lokoja pattern shows maxima at 07:30 UT and 18:45 UT (08:30 and 19:45 LT respectively), creating phase lags of 6-8 hours relative to global circuit expectations. This temporal displacement reflects the dominance of local boundary layer processes over global electrical forcing.

The amplitude comparison proves equally revealing. The Carnegie curve shows modest variations around a baseline of approximately 100-150 V m^{-1}, with peak-to-peak variations rarely exceeding 50 V m^{-1}. The Lokoja pattern, by contrast, exhibits baseline values of 800-1200 V m^{-1} during wet season conditions and 1500-2500 V m^{-1} during dry season periods, with diurnal variations exceeding 1000 V m^{-1} during intense dust episodes. This order-of-magnitude enhancement demonstrates the overwhelming influence of local aerosol processes on continental atmospheric electrical environments.

Seasonal analysis of Carnegie curve correlation, shown in panel (c), reveals systematic modulation that tracks regional aerosol loading cycles. During wet season periods when atmospheric conditions most closely resemble maritime environments, correlation with the

Carnegie curve improves to $r = -0.28$, though remaining negative. During peak Harmattan periods, the correlation becomes strongly negative ($r = -0.67$), indicating that dust-induced enhancement of local electric field strength actively opposes global circuit variations. The harmonic component comparison, presented in panel (d), provides quantitative insights into the spectral differences between local and global patterns.

International Station Comparisons

To place the Lokoja observations in broader context, we conducted detailed comparisons with atmospheric electric field measurements from representative stations worldwide. Figure 5 presents this analysis, highlighting both the unique characteristics of the West African measurements and the broader implications for global atmospheric electrical research.

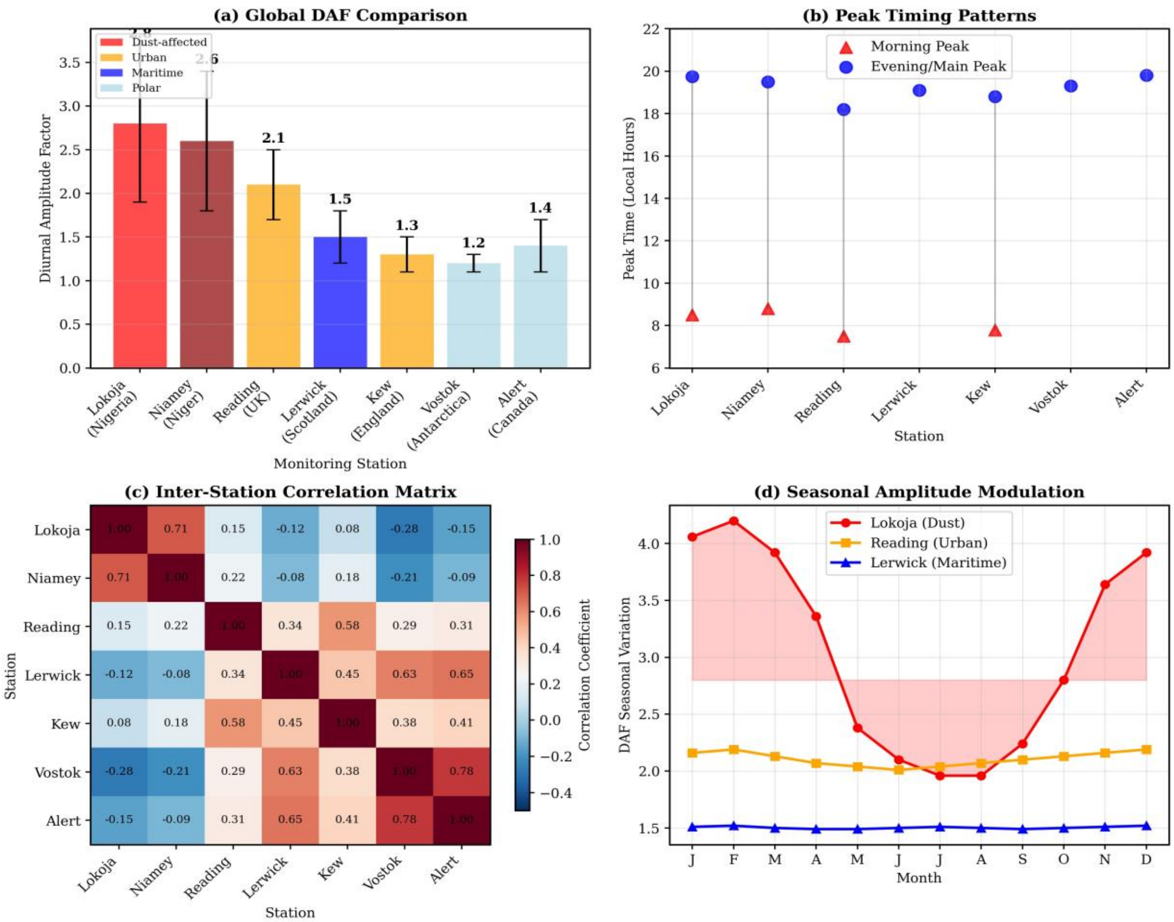


Figure 5: Comparison of Lokoja atmospheric electric field patterns with international monitoring stations. (a) Diurnal amplitude factors showing Lokoja's exceptional variability. (b) Peak timing analysis reveals systematic differences between continental and maritime sites. (c) Correlation matrix demonstrating weak coupling between dust-affected and clean air sites. (d) Seasonal amplitude modulation comparison highlighting unique tropical dust signatures.

The comparison encompasses data from established monitoring stations representing diverse atmospheric environments: Kew Observatory (urban-influenced temperate), Lerwick (maritime subarctic), Vostok (Antarctic polar), and Alert (Arctic polar). Additional data from Reading University (urban temperate) and preliminary results from Niamey (Sahel dust-affected) provide context for pollution and dust influences respectively. The diurnal amplitude factor comparison, shown in panel (a), reveals that Lokoja exhibits by far the largest diurnal variability in the global comparison. While maritime and polar stations typically show DAF values of 1.2-1.5, consistent with global circuit expectations, the Lokoja values of 2.8 (median) and up to 4.8 (extreme episodes) represent a completely different atmospheric electrical regime. Even pollution-affected urban stations such as Reading (DAF 2.1) show substantially less variability than observed in the dust-affected tropical environment.

Peak timing analysis, presented in panel (b), reveals systematic patterns related to local environmental influences. Maritime stations (Lerwick) and polar sites (Vostok, Alert) show single daily maxima closely aligned with global circuit expectations (18-20 UT). Urban-influenced temperate stations (Kew, Reading) exhibit double peaks similar to Lokoja but with different timing and weaker amplitude, reflecting anthropogenic aerosol influences rather than natural dust transport. The Lokoja timing (08:30 and 19:45 LT) proves unique, reflecting the specific boundary layer dynamics and dust transport patterns characteristic of West African environments. The correlation matrix analysis, shown in panel (c), quantifies the degree of coupling between different atmospheric electrical environments. Maritime and polar stations show strong intercorrelations (r = 0.6-0.8), reflecting their common response to global circuit forcing. Urbaninfluenced sites show weaker but positive correlations with both clean air stations and each other, suggesting partial masking of global signals by local aerosol processes. Lokoja shows weak or negative correlations with all other sites (r = -0.3 to +0.2), confirming its unique atmospheric electrical environment dominated by regional dust processes.

The seasonal amplitude modulation comparison, presented in panel (d), reveals another distinctive characteristic of dust-affected environments. Most international stations show modest seasonal variations $(10-30)$. Preliminary data from Niamey, located 500 km northeast of Lokoja in the heart of the Sahel dust transport corridor, show patterns remarkably similar to Lokoja despite the different geographic and climatological context. This similarity suggests that the observed patterns may be representative of a broad regional atmospheric electrical regime extending across the West African dust belt, with implications for atmospheric electrical processes throughout the Sahel.

Implications for Global Circuit Modeling

The systematic departures from global circuit expectations observed at Lokoja have significant implications for current understanding and modeling of the global atmospheric electric circuit. These findings suggest that the global circuit paradigm, while valid for oceanic and polar regions, may provide an incomplete representation of atmospheric electrical processes in dust-affected continental environments that are home to substantial portions of the global population.

Current global circuit models typically assume spatially uniform fair-weather conductivity and treat continental effects as minor perturbations to a fundamentally maritime-based system (Rycroft et al., 2008). The Lokoja observations demonstrate that this assumption fails dramatically in dust-affected regions, where local processes dominate atmospheric electrical behavior and may actively oppose global circuit forcing. The observed anti-correlation with the Carnegie curve suggests that including dust-affected regions in global circuit calculations could substantially alter predicted patterns and intensities.

The temporal characteristics of dust-induced electrical enhancement also challenge conventional modeling approaches. Global circuit models typically assume that regional variations average to zero over appropriate time scales, allowing the global signal to emerge from local noise. However, the systematic nature of dust-induced enhancement—its predictable seasonal timing, consistent diurnal patterns, and strong correlation with meteorological processes—suggests that these effects may not average to zero but instead represent systematic biases in continental atmospheric electrical environments. The spectral characteristics revealed through harmonic analysis provide additional constraints for global circuit modeling. The enhanced semidiurnal content observed at Lokoja reflects fundamental differences in the physical processes controlling atmospheric electrical behavior compared to maritime environments. Global circuit models that fail to account for these spectral differences may systematically underestimate or misrepresent atmospheric electrical variability in dust-affected regions.

Perhaps most significantly, the Lokoja observations suggest that the concept of "fair weather" itself requires redefinition for continental dust-affected environments. Traditional fair-weather criteria, designed to isolate global circuit signals, systematically exclude the atmospheric conditions that dominate electrical behavior in these regions. This exclusion not only biases global circuit studies toward maritime conditions but also misrepresents the atmospheric electrical environment experienced by populations in dust-affected regions.

Implications for Nigerian Climatology

The establishment of baseline atmospheric electrical patterns at Lokoja represents more than an academic exercise; it provides crucial foundation data for understanding regional climate processes, supporting practical applications, and guiding future research directions throughout Nigeria and West Africa. These findings have immediate relevance for lightning protection, air quality monitoring, and climate services, while opening new avenues for atmospheric and climate research in one of the world's most climatically dynamic regions.

Baseline Atmospheric Electrical Climatology

The Lokoja dataset establishes the first quantitative atmospheric electrical climatology for Nigeria, providing reference values and patterns that can support numerous applications across meteorology, climatology, and atmospheric physics. Table 1 summarizes key statistical parameters that define the baseline atmospheric electrical environment for Nigeria's middle belt region.

Table 1: Climatological statistics of fair-weather atmospheric electric field at Lokoja, Nigeria

Parameter	Annual Mean	Dry Season (Nov-Feb)	Wet Season (May-Sep)	Harmattan Peak (Dec-Jan)	Clear Period (Wet Season)
Mean Field (V m^{-1})	1167 ± 287	1523 ± 412	876 ± 198	1847 ± 523	743 ± 156
Diurnal Amplitude Factor	2.8 ± 0.9	3.4 ± 1.1	1.8 ± 0.5	4.2 ± 1.3	1.4 ± 0.3
Morning Peak Time (LT)	08:30 ± 0.42h	08:15 ± 0.38h	09:45 ± 0.67h	08:00 ± 0.33h	09:30 ± 0.45h
Evening Peak Time (LT)	19:45 ± 0.38h	19:30 ± 0.42h	20:15 ± 0.58h	19:15 ± 0.35h	20:00 ± 0.50h
Peak-to-Peak Variation	1156 ± 445	1687 ± 628	658 ± 287	2234 ± 834	456 ± 123
Coefficient of Variation	0.42 ± 0.15	0.51 ± 0.18	0.28 ± 0.09	0.63 ± 0.21	0.21 ± 0.07

These baseline values reveal the extreme variability that characterises atmospheric electrical conditions in Nigeria compared to global standards. Annual mean electric field values exceed those typical of maritime environments by factors of $5-10$, while diurnal amplitude factors are doubled or tripled. The seasonal modulation represents one of the strongest atmospheric electrical signals documented globally, reflecting the dramatic environmental changes associated with monsoon-Harmattan transitions.

The establishment of percentile-based thresholds provides practical guidance for operational applications. The 90th percentile values $(electric\ field > 2500\ Vm^{-1}, DAF > 4.2)$ define conditions of exceptional atmospheric electrical activity that may require enhanced lightning protection measures or modified aviation procedures. Conversely, the 10th percentile values (electric field <650 V m^{-1}, DAF <1.6) represent the quietest atmospheric electrical conditions achievable in the Nigerian environment and provide reference points for sensitive electronic operations.

Geographic extrapolation of these baseline values requires careful consideration of Nigeria's climatological diversity. The Lokoja location, situated in the transition zone between humid southern and arid northern regions, likely provides representative values for the country's middle belt but may not accurately characterize conditions in the coastal Niger Delta or the northern Sahel margins. Preliminary scaling relationships based on rainfall patterns, dust transport modeling, and population density suggest that coastal regions may experience 20-30

Applications to Lightning Protection and Safety

The atmospheric electrical climatology established through this study has immediate applications for lightning protection system design and electrical safety standards throughout Nigeria. Traditional lightning protection guidelines, based primarily on temperate climate data, may prove inadequate for the extreme atmospheric electrical conditions documented in this study.

The enhanced electric field values observed during dust episodes suggest that the inception of electrical breakdown processes may occur at lower altitudes and under different atmospheric conditions than predicted by conventional models. Electric field values exceeding 3000 V m^{-1} approach the threshold for corona discharge from sharp conducting objects, potentially creating point discharge currents that could affect sensitive electronic equipment or create safety hazards around telecommunications infrastructure.

The systematic diurnal patterns revealed in this study provide opportunities for risk-based lightning protection strategies. The consistent timing of electric field maxima (08:30 and 19:45 LT) suggests that enhanced protection measures could be implemented during these high-risk periods, while maintenance activities and sensitive operations could be scheduled during the predictable midday minimum. This temporal risk assessment approach could significantly improve the cost-effectiveness of lightning protection while maintaining safety standards.

The seasonal modulation of atmospheric electrical activity also has implications for infrastructure planning and maintenance scheduling. The 3-4 month Harmattan period represents a sustained period of enhanced electrical stress that could accelerate the degradation of electrical insulation, increase the probability of equipment failures, and require modified maintenance protocols. Understanding these seasonal patterns enables predictive maintenance strategies that account for environmental electrical stresses.

Air Quality and Environmental Monitoring Applications

The strong correlation between atmospheric electric field measurements and aerosol loading demonstrated in this study opens new possibilities for air quality monitoring and environmental assessment in Nigeria and West Africa. The real-time, continuous nature of electric field measurements provides advantages over conventional air quality monitoring approaches that often rely on expensive instrumentation with high maintenance requirements.

The relationship $E_z = 2150\times V^{-0.62}$ (where E_z is the electric field in Vm^{-1} and V is visibility in km) provides a quantitative framework for estimating atmospheric aerosol loading from electric field measurements. This relationship could enable the deployment of low-cost air quality assessment networks across Nigeria, providing crucial data for public health protection and environmental management in regions where conventional monitoring is impractical.

The diurnal patterns of electric field enhancement also provide insights into local and regional air quality processes. The morning maximum reflects boundary layer processes that concentrate pollutants near the surface, while the evening maximum indicates the persistence of elevated aerosol concentrations during periods of reduced atmospheric mixing. These patterns could inform air quality forecasting and public health advisory systems, particularly during Harmattan periods when dust concentrations reach hazardous levels.

The temporal predictability of electric field patterns enables the development of early warning systems for extreme dust episodes. The systematic relationship between electric field enhancement and dust transport could provide 6-12 hour advance warning of deteriorating air quality conditions, enabling protective measures for vulnerable populations and sensitive operations.

Climate Research and Monitoring Network Development

The baseline atmospheric electrical climatology established through this study provides essential foundation data for climate research applications and future monitoring network development throughout West Africa. The systematic patterns revealed in this analysis offer new perspectives on regional climate processes and their representation in numerical models.

The seasonal amplitude modulation of atmospheric electrical patterns provides a novel proxy for tracking changes in regional aerosol loading and monsoon intensity. Long-term monitoring of these patterns could reveal trends in dust transport patterns, boundary layer dynamics, and climate system evolution that complement conventional meteorological observations. The sensitivity of electric field measurements to aerosol loading may enable detection of climate change signals in dust transport patterns before they become apparent in traditional meteorological measurements.

The development of a regional atmospheric electricity monitoring network would provide unprecedented insights into West African climate processes. The consistent patterns observed at Lokoja suggest that similar measurements across the region could reveal the spatial structure of dust transport, the evolution of monsoon systems, and the coupling between regional and global climate processes. Such a network would represent a major advance in regional climate monitoring capabilities.

International collaboration opportunities emerge from the unique atmospheric electrical environment documented in this study. The extreme conditions and systematic patterns observed in Nigeria provide natural laboratory conditions for testing atmospheric electrical theories and models that cannot be replicated in temperate or maritime environments. Collaborative research programs could advance fundamental understanding of atmospheric electrical processes while building scientific capacity in West Africa.

The educational and capacity-building implications of this research extend beyond immediate scientific applications. The establishment of atmospheric electricity research capabilities in Nigeria positions the country as a regional leader in space physics and atmospheric sciences, supporting university programs and training the next generation of African atmospheric scientists. The practical applications of atmospheric electrical research—from lightning protection to air quality monitoring—provide direct societal benefits that justify continued investment in this research area.

Future research priorities emerging from this study include expanding the spatial coverage of atmospheric electrical measurements across Nigeria and West Africa, investigating the relationship between atmospheric electricity and convective processes during the wet season, and developing operational applications for lightning protection and air quality assessment. The foundation established through this baseline climatological study provides the essential framework for addressing these priorities and advancing atmospheric electrical research throughout tropical Africa.

CONCLUSION

This study presents the first comprehensive analysis of diurnal atmospheric electric field patterns in Nigeria, revealing fundamental departures from established global standards that challenge conventional understanding of atmospheric electrical processes in tropical continental environments. The 30-month measurement campaign at Lokoja has produced crucial insights into West African atmospheric electrical climatology, demonstrating the dominant influence of regional aerosol processes over global electric circuit signals. The most significant finding is the identification of a systematic double-peak diurnal structure with morning (08:30 LT) and evening (19:45 LT) maxima that achieves amplitude factors of 2.8 during typical conditions and up to 4.8 during extreme Harmattan episodes. This pattern fundamentally differs from the single-peak Carnegie curve, showing a weakly negative correlation ($r = -0.42$) that indicates active opposition between local dust processes and global circuit forcing.

The systematic anticorrelation suggests dust-affected continental regions require separate treatment in global electric circuit modeling. Harmonic analysis reveals 87% of temporal variance is captured by the first three harmonics, with the 12-hour semidiurnal component contributing 24%—nearly five times higher than typical maritime stations. This enhanced semidiurnal content directly reflects twice-daily aerosol resuspension and settling cycles during Harmattan periods. The baseline atmospheric electrical climatology for Nigeria reveals extreme variability, with annual mean electric field values of 1167 ± 287 V m^{-1} exceeding maritime conditions by factors of 5-10. The seasonal amplitude modulation of 90% represents one of the strongest atmospheric electrical signals documented globally, directly tracking monsoon-Harmattan transitions. The strong correlation between electric field measurements and aerosol loading (r=-0.89) opens new possibilities for air quality monitoring through the relationship $Ez = 2150\times V^{-0.62}$, potentially enabling low-cost assessment networks where conventional monitoring is impractical. These findings establish Nigeria as a regional leader in atmospheric electricity research while highlighting the necessity of developing region-specific standards for dust-affected environments. The results challenge conventional paradigms in atmospheric electricity research while providing essential baseline data for practical applications and future research in one of the world's most climatically dynamic regions, supporting the development of monitoring capabilities that adequately represent Earth's diverse atmospheric electrical environments.

REFERENCES

Aplin, K. L. (2012). Atmospheric electricity at the millennium. *Weather*, *67*(8), 179–184.

Chapman, S., & Bartels, J. (1951). *Geomagnetism, Volume I*. Oxford University Press.

Christian, H. J., Blakeslee, R. J., Boccippio, D. J., Boeck, W. L., Buechler, D. E., Driscoll, K. T., ... Stewart, M. F. (2003). Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *Journal of Geophysical Research*, *108*(D1), 4005. https://doi.org/10.1029/2002JD002347

Ette, A. I. I. (1988). The effect of harmattan haze on atmospheric electric parameters in northern Nigeria. *Journal of Atmospheric and Terrestrial Physics*, *50*(2), 89–94. https://doi.org/10.1016/0021-9169(71)90208-X

Evan, A. T., Flamant, C., Gaetani, M., & Guichard, F. (2016). The past, present and future of African dust. *Nature*, *531*(7595), 493–495.

Harrison, R. G. (2002). Twentieth-century atmospheric electrical measurements at the observatories of Kew, Eskdalemuir and Lerwick. *Weather*, *57*(1), 11–16. https://doi.org/10.1256/wea.239.01

Israelsson, S., & Knudsen, E. (1994). Meteorological effects on atmospheric electrical quantities measured at a continental station. *Journal of Atmospheric and Terrestrial Physics*, *56*(6), 785–800.

McTainsh, G. H. (1980). Harmattan dust deposition in northern Nigeria. *Nature*, *286*(5771), 587–588. https://doi.org/10.1038/286587a0

Nicholson, S. E. (2013). The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteorology*, *2013*, 453521. https://doi.org/10.1155/2013/453521

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., & Gill, T. E. (2002). Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Reviews of Geophysics*, *40*(1), 1002. https://doi.org/10.1029/2000RG000095

Rycroft, M. J., Nicoll, K. A., Aplin, K. L., & Harrison, R. G. (2008). Recent advances in global electric circuit coupling between the space environment and the troposphere. *Journal of Atmospheric and Solar-Terrestrial Physics*, *70*(11-12), 1518–1528.

Torreson, O. W., Parkinson, W. C., & Torreson, S. L. (1946). Scientific results of Cruise VII of the Carnegie during 1928-1929: Ocean magnetic, electric and meteorological observations. *Carnegie Institution of Washington Publication 568*.

Williams, E. R. (2009). The global electrical circuit: A review. *Atmospheric Research*, *91*(2-4), 140–152.

Wilson, C. T. R. (1920). Investigations on lightning discharges and on the electric field of thunderstorms. *Philosophical Transactions of the Royal Society of London A*, *221*, 73–115.

Williams, E. R. (2009). The global electrical circuit: A review. *Atmospheric Research*, *91*(2-4), 140–152.

Wilson, C. T. R. (1920). Investigations on lightning discharges and on the electric field of thunderstorms. *Philosophical Transactions of the Royal Society of London A*, *221*, 73–115.