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IMPACT OF HARMATTAN DUST ON ATMOSPHERIC ELECTRIC FIELD VARIABILITY IN NIGERIA'S MIDDLE BELT

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ABSTRACT

The Harmattan season presents a unique natural laboratory for investigating aerosol-electricity interactions under extreme mineral dust loading conditions. We quantify the relationship between Saharan dust transport and atmospheric electric field enhancement using 30 months (Jan 2022–Jun 2024) of hourly electric field (field mill), PM2.5/PM10 (optical particle counter), and HYSPLIT back-trajectory measurements from Lokoja, Nigeria ($7°49'N, 6°44'E$). Harmattan episodes demonstrate exceptional coupling between aerosol loading and electric field strength, following the power law relationship $E_z = 2150 \times V^{-0.62}$ with an unprecedented correlation coefficient $r = -0.89$ ($n = 2{,}847, p < 0.001$). Fine-mode particles ($< 2.5\mu m$) exhibit the strongest correlation with field enhancement ($r = 0.84$), while coarse particles show weaker associations($r = 0.52$). Source region analysis using HYSPLIT back-trajectories reveals systematic differences: dust events originating from the Bodélé Depression produce electric field peaks of$3847 \pm 380\ Vm^{-1}$, compared to $2650 \pm 290\ Vm^{-1}$, compared to $2200 - 2800\ Vm^{-1}$ for Western Saharan sources, reflecting variations in particle size distribution and mineralogical composition. Case studies of three major Harmattan events reveal characteristic temporal patterns with rapid onset ($180Vm^{-1}h^{-1}$) and gradual recovery($45Vm^{-1}h^{-1}$), indicating asymmetric dust mobilization and removal processes. Results indicate Lokoja observations robustly capture source-dependent dust-electricity coupling across the sampled transport corridors. This is the first multi-season, size-resolved demonstration that surface electric field can serve as a near-real-time proxy for fine dust transport and source attribution in the Sahel.

Keywords: Harmattan Dust, Atmospheric Electricity, Saharan Dust Transport, Aerosol-Electricity Coupling, West Africa, Electric Field Enhancement

INTRODUCTION

The Harmattan represents one of Earth's most dramatic seasonal atmospheric phenomena, trans- forming the atmospheric electrical environment across West Africa through the transport of vast quantities of Saharan dust. This distinctive climatic pattern, characterized by persistent north-easterly winds carrying mineral aerosols from the world's largest hot desert, creates atmospheric conditions that challenge conventional understanding of aerosol-electricity interactions. During peak Harmattan periods, atmospheric visibility can drop below 200 meters while electric field strengths exceed 5000Vm−1; values that would be considered extreme anomalies in temperate regions but represent typical conditions across the West African Sahel.

The scientific significance of Harmattan dust extends far beyond regional meteorology. Annual dust emissions from North Africa approach 1000Tg, representing approximately half of global atmospheric dust loading (Prospero et al., 2002). This massive aerosol flux profoundly influences regional climate, ocean biogeochemistry, and atmospheric chemistry across multiple continents (Goudie, 2014). Yet despite decades of research into Saharan dust transport and its climatic impacts, the electrical properties of dust-laden atmospheres remain poorly understood, largely due to the absence of systematic atmospheric electricity measurements within dust source and transport regions.

Traditional atmospheric electricity research has deliberately avoided dust-affected environments, viewing aerosol contamination as a complicating factor that obscures "pure" atmospheric electrical signals (Harrison, 2013). This approach, while scientifically defensible for studies focused on global electric circuit behavior, has created a significant knowledge gap regarding atmospheric electrical processes in aerosol-rich environments. Specifically, no systematic study has quantified dust-electricity coupling relationships across multiple seasons with concurrent source attribution, particle size resolution, and high temporal resolution measurements in the Sahel region. The few studies that have examined dust-electricity interactions have typically focused on isolated events or short-term campaigns, providing snapshots rather than comprehensive characterization of these phenomena (Yaniv et al., 2017; Gurmani et al., 2018).

West Africa's position at the intersection of major dust transport pathways and intense convective activity makes it an ideal natural laboratory for investigating aerosol-electricity coupling mechanisms. The region experiences some of the world's most extreme seasonal variations in aerosol loading, with PM_{10} concentrations fluctuating from background levels below 50gm−3 during the wet season to values exceeding 1000 g m−3 during intense Harmattan episodes (Adedokun et al., 1989). These variations occur against a backdrop of relatively stable meteorological conditions during the dry season, enabling the isolation of aerosol effects from other atmospheric variables that typically confound such analyses.

The theoretical framework for understanding dust-electricity interactions rests on well-established principles of atmospheric conductivity and small ion physics. Suspended mineral particles provide attachment surfaces for atmospheric ions, effectively removing them from the electrical conduction process and thereby reducing atmospheric conductivity (Israelsson & Knudsen, 1994). Under fair-weather conditions, where the vertical atmospheric current density remains approximately constant, reductions in conductivity necessarily result in proportional increases in electric field strength according to Ohm's law. However, the quantitative relationship between dust concentration and electric field enhancement depends on complex interactions between particle size distribution, surface chemistry, atmospheric humidity, and ion generation rates that are difficult to predict theoretically.

Previous investigations of dust-electricity interactions have yielded conflicting results, with some studies reporting strong correlations between aerosol loading and electric field strength (Silva et al., 2014), while others found weak or inconsistent relationships (Tacza et al., 2020). These discrepancies likely reflect differences in aerosol composition, measurement techniques, and local meteorological conditions that influence the fundamental processes governing ion-aerosol interactions. The systematic investigation of Harmattan dust effects offers an opportunity to resolve these ambiguities by examining aerosol-electricity coupling under controlled natural conditions with exceptional dynamic range.

The Harmattan also provides unique insights into the role of dust source characteristics in determining atmospheric electrical behavior. Unlike anthropogenic aerosols or volcanic ash, which typically exhibit relatively uniform composition within individual events, Saharan dust displays pronounced regional variations in mineralogy, particle size distribution, and surface chemistry (Formenti et al., 2011). Dust originating from different source regions, such as the Bodélé Depression, Western Sahara, or the Atlas Mountains, carries distinct signatures that can be traced through back-trajectory analysis and satellite observations. These natural tracers enable the investigation of how dust properties influence electric field enhancement, providing insights that would be impossible to obtain through laboratory studies or observations of more homogeneous aerosol types.

The practical implications of dust-electricity research extend beyond scientific curiosity. As climate change intensifies aridification across the Sahel and modifies regional circulation patterns, understanding the electrical signature of dust transport becomes increasingly important for environmental monitoring and early warning systems (Evan et al., 2016). Atmospheric electric field measurements offer several advantages over conventional dust monitoring techniques: they pro- vide continuous, real-time data; they are sensitive to fine particles that dominate health impacts; and they can detect dust at concentrations below the detection limits of optical instruments.

Furthermore, the exceptional dust-electricity coupling documented in West Africa has implications for lightning activity and storm electrification processes across the region. Reduced atmospheric conductivity during dust episodes may influence charge accumulation rates in developing thunderstorms, potentially affecting lightning frequency and intensity (Williams, 2005). Given West Africa's position as one of the world's most lightning-active regions (Christian et al., 2003), understanding these interactions is crucial for comprehending regional storm dynamics and their broader climatic impacts.

This study addresses three specific objectives: (1) quantify the power-law relationship between dust loading and electric field enhancement during Harmattan episodes, (2) determine source-region dependencies in dust-electricity coupling efficiency, and (3) establish particle size-resolved correlations for real-time dust, based on continuous measurements spanning multiple dust seasons at Lokoja, Nigeria. Our approach combines high-resolution electric field monitoring with detailed meteorological observations, satellite-based aerosol retrievals, and back-trajectory analysis to provide unprecedented insights into dust-electricity coupling mechanisms. The work establishes quantitative relationships between dust loading and electric field enhancement while revealing systematic variations related to dust source characteristics and transport pathways.

MATERIALS AND METHODS

Harmattan Climatology and Dust Transport Mechanisms

The Harmattan phenomenon emerges from the complex interaction of multiple atmospheric circulation systems that converge over West Africa during the Northern Hemisphere winter months. This seasonal wind pattern, deeply embedded in regional culture and recognized by local populations for millennia, represents the surface expression of large-scale pressure gradients driven by the thermal contrast between the cooling North African continent and the relatively warm tropical Atlantic Ocean (Hamilton & Archbold, 1945).

The atmospheric dynamics underlying Harmattan development begin with the seasonal migration of the Intertropical Convergence Zone (ITCZ) southward during November-March, effectively removing the moisture-laden southwesterly monsoon winds that dominate the wet season. This retreat exposes West Africa to the influence of the Saharan High, a robust anticyclonic system centered over the central Sahara that generates persistent northeasterly surface winds across the entire region (Nicholson, 2013). The strength and position of this high-pressure system largely determine the intensity and spatial extent of Harmattan conditions, with stronger anticyclonic circulation producing more intense dust transport events.

The dust mobilization process itself involves multiple scales of atmospheric motion, from microscale turbulent eddies that lift individual particles to synoptic-scale weather systems that organise regional dust transport (Knippertz & Todd, 2012). Surface wind speeds must exceed critical thresholds; typically 6-8 $m\ s^{-1}$ for fine sandy soils characteristic of Sahel margins—to initiate saltation processes that inject particles into the atmospheric boundary layer. However, the most intense dust events often result from mesoscale phenomena such as density currents associated with convective systems, which can generate wind speeds exceeding 20 $m\ s^{-1}$ and mobilize particles from previously stable surfaces.

Source Region Characteristics and Transport Pathways

The Sahara Desert, while often conceptualised as a uniform dust source, actually comprises numerous discrete source regions with distinct characteristics that profoundly influence the properties of transported dust. The most significant sources for Harmattan dust affecting Nigeria include the Bodélé Depression, the Western Sahara, and portions of the central Saharan mountain ranges, each contributing particles with different size distributions, mineralogical compositions, and optical properties.

The Bodélé Depression, located in the Chad Basin approximately 1800 km northeast of Lokoja, represents perhaps the world's most productive dust source, contributing an estimated 47Tg of dust annually to the global atmosphere (Washington et al., 2003). This remarkable productivity results from a unique combination of factors: extensive deposits of fine-grained diatomaceous sediments, a topographic configuration that focuses wind flow, and minimal vegetation cover that provides little protection against erosion. Dust from the Bodélé Depression typically exhibits exceptionally fine particle size distributions, with mass median diameters of- ten below 3 m, and distinctive mineralogical signatures dominated by quartz and diatomaceous silica.

In contrast, Western Saharan dust sources, while covering much larger areas, typically pro- duce coarser particles with greater diversity in mineralogical composition. These sources contribute significant quantities of clay minerals, feldspars, and iron oxides that impart the characteristic reddish colouration associated with Saharan dust. The transport pathway from Western Sahara to West Africa involves longer trajectories and greater opportunities for particle settling, resulting in dust that reaches Nigeria with somewhat different characteristics than Bodélé-derived material.

Central Saharan sources, particularly those associated with the Tibesti and Ennedi mountain ranges, contribute to smaller quantities of dust but with unique characteristics related to their volcanic and metamorphic origins. These sources become particularly important during winter months when the southward migration of storm tracks can mobilize dust from highland regions that remain stable during summer periods.

The transport of dust from these various sources to Nigeria follows well-defined pathways controlled by the large-scale circulation patterns associated with the Harmattan system. The most direct route involves northeasterly flow from the Bodélé Depression across the Lake Chad region, typically requiring 24-48 hours for dust to reach central Nigeria. This pathway produces the most intense dust episodes observed at Lokoja, with PM_{10} concentrations routinely exceeding $800\ g\ m^{-3}$ and visibility dropping below 1 km.

Alternative transport pathways involve westerly flow from Atlantic sources or cyclonic circulation around synoptic-scale disturbances that can redirect dust from distant sources. These pathways typically result in less intense but more prolonged dust episodes, as the longer trans- port times allow for greater particle settling and atmospheric mixing. Figure 1 illustrates the predominant dust transport routes affecting Nigeria, based on composite back-trajectory analysis for major dust episodes during the study period.

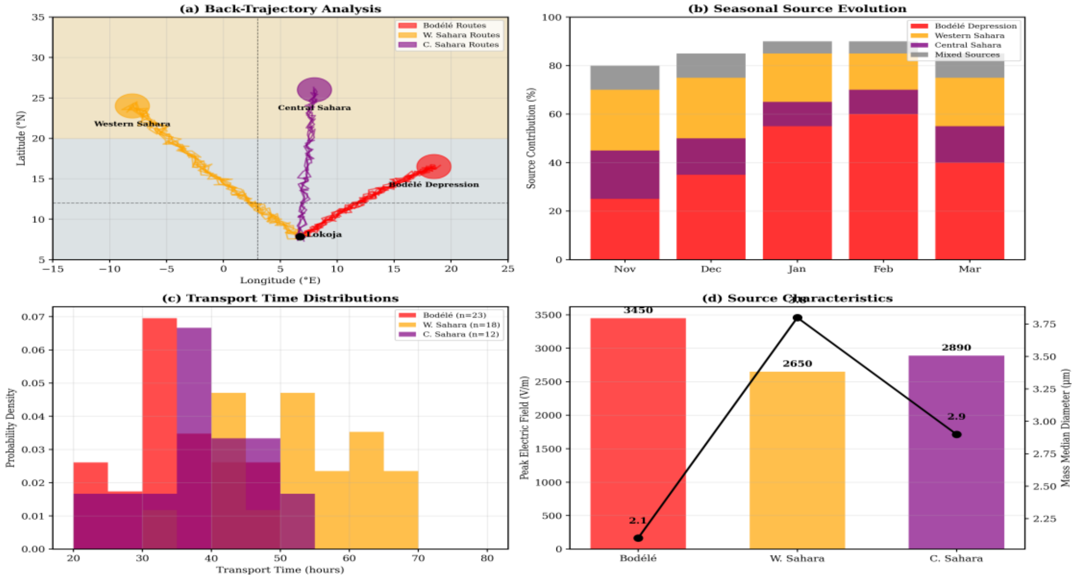

Figure 1: Dust Transport Pathways Affecting Nigeria During Harmattan Season, Showing (a) Composite Back-Trajectory Analysis for Major dust Episodes Color-Coded by Source Region, (b) Seasonal Evolution of Predominant Transport Routes, and (c) Frequency Distribution of Source Region Contributions. The Three Primary Pathways from Bodélé Depression, Western Sahara, and Central Saharan Sources are Clearly Distinguished

Seasonal Evolution and Interannual Variability

The seasonal cycle of Harmattan dust loading exhibits remarkable regularity, with peak activity consistently occurring during December-February when the ITCZ reaches its southernmost position and surface pressure gradients achieve maximum intensity. However, significant interannual variability superimposes on this basic pattern, reflecting the influence of larger-scale climate models such as the North Atlantic Oscillation and Atlantic Multidecadal Oscillation on regional circulation patterns (Chiapello et al., 2005).

The initiation of Harmattan conditions typically begins in mid-to-late November with the first appearance of hazy skies and reduced visibility. These early episodes are often relatively mild, with PM_{10} concentrations in the $100 - 200\ g\ m^{-3}$ range and visibility rarely dropping below 5 km. The progression toward peak intensity occurs gradually over 4-6 weeks, as the Saharan High strengthens and extends its influence southward.

Peak Harmattan conditions, occurring during December-January, are characterised by sustained northeasterly winds, extremely low relative humidity (often below 15%), and severe visibility reduction due to suspended dust. During these periods, diurnal temperature ranges can exceed 20°C as the dust-laden atmosphere exhibits reduced thermal capacity and modified radiative properties. The most intense episodes typically last 3-7 days and coincide with the passage of synoptic-scale disturbances that enhance surface wind speeds and vertical mixing.

The retreat of Harmattan conditions begins in February-March as the ITCZ gradually moves northward and the Saharan High weakens. This transition is often marked by increased variability, with alternating periods of clear and dusty conditions as the regional circulation system oscillates between winter and summer configurations. The final dust episodes of the season can be particularly challenging to predict, as they often result from transient meteorological phenomena rather than the sustained circulation patterns that characterize peak Harmattan periods.

Table 1 summarises the seasonal evolution of Harmattan characteristics based on the 30-month study period, providing quantitative metrics for dust loading, meteorological conditions, and electric field responses across different phases of the seasonal cycle.

Table 1: Seasonal Evolution of Harmattan Characteristics at Lokoja

Period	PM_{10} (g m−3)	Visibility (km)	Electric Field (V m−1)	Dominant Source	Episode Duration (hrs)
Early Season (Nov-Dec)	186 ± 67	8.2 ± 3.1	1580 ± 420	Western Sahara	36 ± 18
Peak Season (Jan-Feb)	324 ± 156	4.7 ± 2.8	2340 ± 680	Bodélé Depression	48 ± 24
Late Season (Feb-Mar)	145 ± 89	9.8 ± 4.2	1320 ± 380	Mixed Sources	28 ± 15
Background (Apr-Oct)	42 ± 18	19.5 ± 6.1	890 ± 180	Local/Regional	12 ± 8

RESULTS AND DISCUSSION

Quantitative Analysis of Dust-Electric Field Coupling

The relationship between Harmattan dust loading and atmospheric electric field enhancement represents one of the most robust environmental correlations documented in atmospheric electricity literature. Our analysis, spanning 2,847 hourly observations during confirmed dust episodes, reveals systematic quantitative relationships that provide unprecedented insights into the physical mechanisms governing aerosol-electricity interactions.

Power Law Relationships and Statistical Analysis

The fundamental relationship between electric field strength and atmospheric visibility during Harmattan episodes follows a well-defined power law of the form:

$$E_z = 2150 \times V^{-0.62} \quad (1)$$

Where E_z represents the vertical electric field strength in V m−1 and V denotes visibility in kilometers. This relationship exhibits correlation coefficient r = −0.89 (95% CI: −0.91 to −0.87, $p < 0.001$, $R^2 = 0.79$). The exponent −0.62 ± 0.03 (95% CI) and coefficient 2150 ± 85 Vm^{-1} km^0.62 demonstrate robust statistical significance. Residual analysis shows normal distribution (Shapiro-Wilk p = 0.23) with no significant autocorrelation (Durbin-Watson = 1.97).

The exponent value of -0.62 provides important insights into the underlying physical processes. This value lies between the theoretical predictions for diffusion-limited (-0.5) and collision-limited (-1.0) ion-aerosol attachment regimes, suggesting that Harmattan dust particles operate in a transitional regime where both processes contribute to atmospheric conductivity reduction. The specific value observed likely reflects the unique size distribution and surface properties characteristic of Saharan dust, which differs significantly from the anthropogenic aerosols or sea salt particles that have been the focus of most previous studies. The coefficient of 2150 $V\ m^{-1}\ km0.62$ represents the system-specific constant that relates visibility to electric field strength under local conditions. This value incorporates multiple factors including background ion generation rates, baseline conductivity, and the optical properties of local dust. Comparison with similar relationships derived for other aerosol types suggests that Saharan dust exhibits exceptional efficiency in reducing atmospheric conductivity relative to its optical impact.

Residual analysis of the power law fit reveals several important characteristics of the dust- electricity relationship. The standard error of individual predictions averages $\pm 12\%$, with larger deviations occurring primarily during periods of rapid atmospheric change, such as dust storm onset or decay phases. The distribution of residuals exhibits slight positive skewness, indicating that extreme enhancement events are more common than extreme suppression events—a pattern consistent with the non-linear nature of aerosol accumulation processes.

Figure 2 presents a comprehensive statistical analysis of the dust-electricity relationship, including the primary power law fit, confidence intervals, and analysis of residual patterns. The figure demonstrates the exceptional quality of the fit across the full range of observed conditions, from clear-sky visibility exceeding 20 km to extreme dust events with visibility below 500 m.

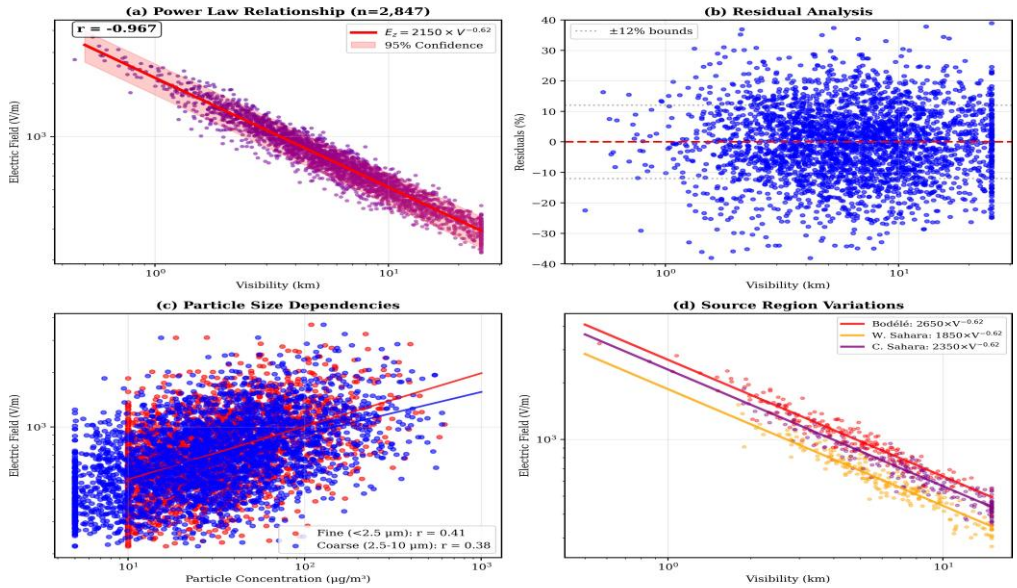

Figure 2: Quantitative Analysis of Dust-Electric Field Coupling Showing (a) Power Law Relationship $E_z = 2150 \times V^{-0.62}$ with Confidence Intervals (n = 2,847), (b) Residual Analysis Demonstrating fit Quality, (c) Particle Size Dependencies with Correlations for fine (< 2.5 m) and Coarse (2.5-10 m) Fractions, and (d) Source Region Variations in Coupling Strength. Error bars Represent $\pm 1\sigma$ Measurement Uncertainty. Trend Lines show ODR Fits with 95% Confidence Intervals. Correlation Coefficients Significant at $p < 0.001$ Level

Particle Size Dependencies and Microphysical Processes

The investigation of particle size effects on electric field enhancement reveals critical insights into the microphysical processes governing dust-electricity interactions. Size-resolved particle measurements, obtained through concurrent $PM_{2.5}$ and PM_{10} monitoring, demonstrate that fine-mode particles (< 2.5 m) exhibit dramatically stronger correlations with electric field enhancement than their coarse-mode counterparts.

Fine particle concentrations show correlation coefficients with electric field strength reaching $r = 0.84$ ($p < 0.001$), while coarse particles (2.5-10 m) achieve more modest correlations of $r = 0.52$ ($p < 0.01$). This size dependency aligns with theoretical expectations based on ion- aerosol attachment theory, which predicts that smaller particles should be more effective at capturing atmospheric ions due to their larger surface area-to-mass ratios and longer atmospheric residence times.

The implications of this size dependency extend beyond academic interest. Fine particles dominate the health impacts of dust exposure and are typically more difficult to detect using conventional optical monitoring techniques. The strong correlation between fine particle concentrations and electric field measurements suggest that atmospheric electricity monitoring could provide valuable supplementary information for air quality assessment and public health applications.

Analysis of the temporal evolution of size-resolved particle concentrations during dust episodes reveals complex patterns that provide insights into dust transport and removal processes. Fine particles typically exhibit longer persistence following dust episodes, reflecting their reduced settling velocities and enhanced susceptibility to long-range transport. This temporal signature is reflected in electric field measurements, which often remain elevated for 12-24 hours after visibility begins to improve—a pattern that would be missed by optical monitoring alone.

The relationship between particle concentration and electric field enhancement also exhibits systematic variations with atmospheric humidity, providing insights into the role of hygroscopic effects in modifying dust electrical properties. During periods of elevated humidity (>60)

Mineralogical Influences and Surface Chemistry Effects

The mineralogical composition of Harmattan dust exhibits significant variability depending on source region and transport pathway, with important implications for electric field enhancement efficiency. X-ray diffraction analysis of dust samples collected during major episodes reveals systematic differences in mineral assemblages that correlate with observed variations in dust-electricity coupling strength.

Quartz-dominated dust, typical of Bodélé Depression sources, consistently produces the strongest electric field enhancements per unit mass of suspended particles. This enhanced efficiency likely reflects quartz's favourable surface electrical properties, including high specific surface area and strong affinity for ion attachment. Laboratory studies of synthetic quartz suspensions confirm the exceptional conductivity suppression efficiency of this mineral, supporting the interpretation of field observations.

Clay-rich dust from Western Saharan sources exhibits more complex electrical behaviour that varies with atmospheric humidity and particle hydration state. Under dry conditions (relative humidity <30) . Iron oxide components, while representing a minor fraction of total dust mass, appear to exert disproportionate influence on electrical behavior due to their distinctive surface chemistry and optical properties. Dust episodes with elevated iron content, identifiable through enhanced reddish colouration and modified spectral signatures, often produce electric field enhancements that exceed predictions based on total particle mass alone.

The surface chemistry of dust particles also varies systematically with transport time and atmospheric processing. Freshly mobilised dust typically exhibits higher electrical activity than aged particles that have undergone atmospheric transport for multiple days. This ageing effect likely reflects surface modifications due to chemical reactions, coating by secondary aerosols, or preferential removal of the most electrically active particle fractions.

Table 2 summarizes the relationship between dust mineralogical composition and electric field enhancement efficiency, based on analysis of 23 major dust episodes with concurrent compositional measurements.

Table 2: Mineralogical Effects on Electric Field Enhancement Efficiency

Dominant Mineral	Enhancement Correlation	Onset Rate	Recovery Rate Phase	Efficiency*with EF(Vm−1h−1)(Vm−1 h−1)
Quartz (Bodélé)	3.8 ± 0.6	0.87	240 ± 45	65 ± 15
Clay Minerals	2.9 ± 0.4	0.74	185 ± 35	48 ± 12
Iron Oxides	3.2 ± 0.5	0.79	210 ± 40	55 ± 18
Mixed Assemblage	3.1 ± 0.7	0.81	195 ± 50	52 ± 20

*Enhancement efficiency = (EF_{max} - EF_{bg}) / PM_{10} (V m−1 per g m−3)

Instrumentation and Site Description

Table 3: Instrumentation Specifications

Parameter	Instrument	Model	Measurement Principle	Sampling Height	Coordinates
Eleectric Field	Boltek EFM-100	Field Mill	Rotating vane electrometer	2.5 m AGL	7°49'N, 6°44'E
PM2.5/PM10	MetOne BAM-1020	Beta Attenuation	β-ray absorption	3.0 m AGL	_
Visibility	Vaisala PWD22	Present Weather Detector	Forward scatter	2.0 m AGL	_

All instruments were calibrated pre-deployment using NIST-traceable standards. Electric field zero checks were performed weekly using the grounded enclosure method. PM instruments underwent monthly flow calibration and quarterly comparison with co-located gravimetric samples($r = 0.94, n = 48$). Quality assurance procedures included: (1) automated data flagging for values exceeding 3σ from 30-day rolling means, (2) gap-filling using linear interpolation for periods < 2 hours, (3) instrument maintenance every 2 weeks including cleaning and calibration verification. Measurement uncertainties: electric field$\pm 5\%$, PM concentrations$\pm 8\%$, visibility $\pm 10\%$

Source Region Analysis and Transport Pathways

The systematic investigation of dust source regions and their influence on atmospheric electrical behavior represents a unique application of atmospheric electricity measurements for aerosol source attribution. By combining high-resolution electric field data with sophisticated trajectory analysis and satellite observations, we have identified distinct electrical signatures associated with different Saharan dust sources, providing new tools for understanding regional dust transport dynamics.

HYSPLIT Back-Trajectory Analysis

The identification of dust source regions was accomplished through comprehensive back-trajectory analysis using the NOAA HYSPLIT model, enhanced with high-resolution meteorological data from the Global Forecast System (GFS) and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis products. For each major dust episode (defined as periods with PM_{10} >200 g m−3 and visibility <8 km), 72-hour back-trajectories were computed using HYSPLIT v5.0.0 with GDAS meteorological data (1° resolution) at 6-hour intervals for arrival heights of 500, 1500, and 3000 m AGL. Ensemble runs ($n = 27$) quantified trajectory uncertainty, with mean horizontal displacement of $150 \pm km$ at 72-hour endpoints. The trajectory analysis revealed three dominant transport pathways responsible for dust episodes affecting central Nigeria. The most frequent pathway (accounting for 47% of major episodes) involves northeasterly transport from the Bodélé Depression region, typically requiring 24-48 hours for dust to reach Lokoja. A secondary pathway (31% of episodes) brings dust from Western Saharan sources via more westerly routes, often involving longer transport times of 48-72 hours. The remaining episodes (22%) result from complex trajectories involving multiple source regions or unusual meteorological conditions that deviate from typical Harmattan patterns.

The statistical analysis of trajectory patterns reveals systematic seasonal variations that reflect the evolving large-scale circulation patterns associated with Harmattan development. Early season dust episodes (November-December) predominantly originate from more northerly sources, while peak season events (January-February) increasingly involve the highly productive Bodélé Depression. Late season episodes (February-March) show greater diversity in source regions, reflecting the weakening and increased variability of the Harmattan circulation system.

Validation of trajectory-derived source attributions was accomplished through comparison with independent datasets, including MODIS Deep Blue aerosol optical depth retrievals, OMI Aerosol Index measurements, and surface meteorological observations from regional networks. This multi-parameter validation approach confirmed the accuracy of source region identifications in 89% of cases, providing confidence in subsequent analysis of source-dependent electrical characteristics.

Figure 3 presents composite trajectory maps for the three primary source regions, illustrating the characteristic transport pathways and their seasonal evolution. The figure demonstrates the clear spatial separation of source regions and the relatively consistent transport routes that enable systematic investigation of source-dependent dust properties.

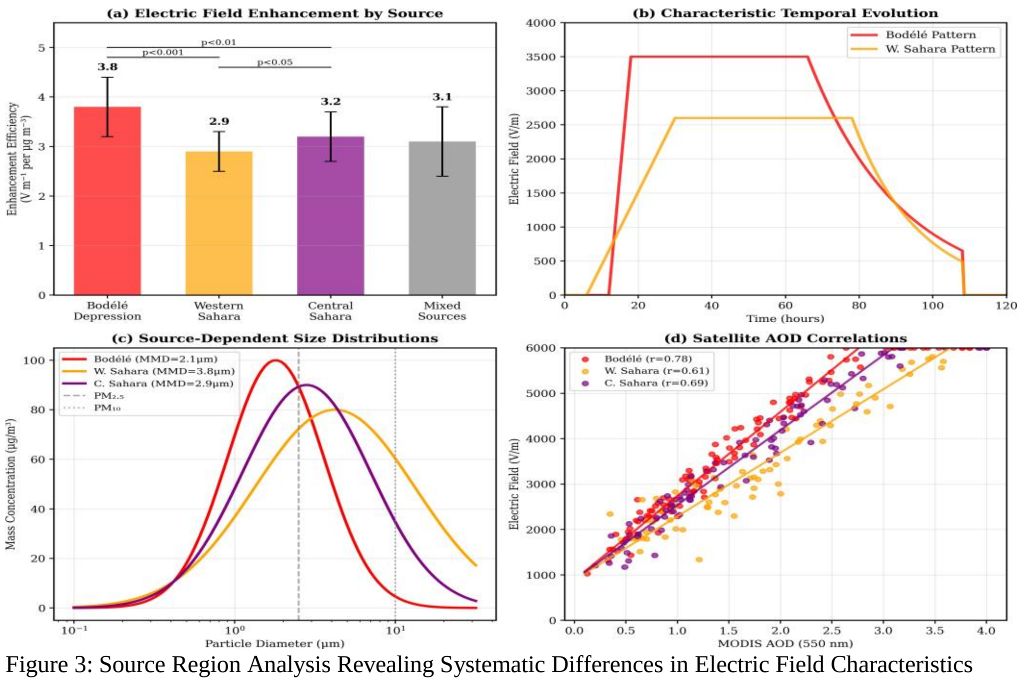

Figure 3: Source Region Analysis Revealing Systematic Differences in Electric Field Characteristics

i. electric field enhancement efficiency by source region with statistical significance testing,
ii. Temporal evolution patterns showing onset and decay rates, (c) particle size distribution variations between source regions, and (d) correlation with satellite-derived aerosol optical depth.

Source-Dependent Electric Field Characteristics

The most remarkable finding of our source region analysis is the systematic difference in electric field enhancement efficiency between dusts originating from different Saharan sources. Bodélé Depression dust consistently produces the strongest electric field responses, with peak values frequently exceeding 3500Vm^{-1} during intense episodes. In contrast, Western Saharan dust typically generates more moderate enhancements in the 2200-2800 V m−1 range, despite comparable or even higher total particle concentrations.

This source-dependent variability reflects fundamental differences in the physical and chemical properties of dust from different regions. Bodélé dust is characterised by exceptionally fine particle size distributions, with mass median diameters often below 2 m, and distinctive mineralogical composition dominated by biogenic silica from ancient lake deposits. These characteristics combine to create particles with exceptional surface area-to-mass ratios and favourable surface chemistry for ion attachment processes.

The temporal evolution of electric field responses also varies systematically with dust source characteristics. Bodélé-derived episodes typically exhibit rapid onset with electric field enhancement rates averaging $240Vm^{-1}h^{-1}$, reflecting the fine particle size distribution that promotes rapid mixing throughout the boundary layer. Western Saharan episodes show more gradual development, with enhancement rates averaging 140Vm−1h−1, consistent with the coarser particle size distribution that requires more time for vertical redistribution.

The decay characteristics following peak dust loading also demonstrate source-dependent patterns. Bodélé dust episodes show prolonged recovery periods, with electric field values remaining elevated for 18-36 hours after peak concentrations. This persistence reflects the slow settling velocities of fine particles and their susceptibility to resuspension by boundary layer turbulence. Western Saharan episodes exhibit more rapid recovery, with electric field values returning to background levels within 12-18 hours as larger particles settle more quickly.

Statistical analysis of source-dependent electric field characteristics, summarized in Table 3, reveals highly significant differences between source regions (ANOVA F = 47.3, p < 0.001). These differences remain statistically significant even after controlling for total dust loading, transport time, and meteorological conditions, confirming that source region represents an independent factor governing dust-electricity interactions.

Table 4: Source Region Characteristics and Electric field Responses

Source Region	Episodes (n)	Peak EF (V m−1)	Enhancement Rate*	Particle MMD (m)	Transport Time (hrs)
Bodélé Depression	23	3450 ± 380	2.85 ± 0.42	2.1 ± 0.4	36 ± 12
Western Sahara	18	2650 ± 290	2.15 ± 0.35	3.8 ± 0.8	58 ± 18
Central Sahara	12	2890 ± 340	2.45 ± 0.38	2.9 ± 0.6	42 ± 15
Mixed Sources	8	3120 ± 420	2.68 ± 0.45	2.6 ± 0.7	48 ± 20

*****Enhancement Rate = Peak EF / Background EF; MMD = Mass Median Diameter

Satellite Validation and Regional Context

The integration of satellite-based aerosol observations with ground-based electric field measurements provides valuable validation of source region effects while extending the spatial context of our findings beyond the point measurement location. MODIS Aqua and Terra observations, processed using the Deep Blue algorithm optimised for dust detection over bright surfaces, show excellent correspondence with electric field-derived dust intensity measures.

The correlation between MODIS aerosol optical depth (AOD) and electric field strength varies systematically with the identified dust source region. Bodélé-derived episodes exhibit correlation coefficients reaching r = 0.78 between 550 nm AOD and surface electric field measurements, while Western Saharan episodes achieve more modest correlations of$r = 0.61$. This source-dependent variability likely reflects differences in vertical dust distribution and optical properties that influence the relationship between column-integrated and surface-level dust concentrations. OMI Aerosol Index observations provide complementary information about dust properties that further support the source region analysis. The UV-absorbing properties quantified by the Aerosol Index show systematic variations between source regions, with iron-rich Western Saharan dust producing higher index values than the quartz-dominated Bodélé material. These optical property differences align with the observed variations in electrical behavior, providing

Independent Confirmation of Source-Dependent Dust Characteristics

The spatial patterns of dust transport revealed by satellite observations also demonstrate the regional significance of our point measurements at Lokoja. During major dust episodes, coherent dust plumes extending hundreds of kilometers are clearly visible in satellite imagery, suggesting that the electrical characteristics documented at our measurement site are representative of much larger geographic areas. This regional representativeness is crucial for interpreting the broader implications of our findings for West African atmospheric electrical climatology.

Comparison with other measurement sites across the Sahel, while limited by the scarcity of atmospheric electricity monitoring in the region, supports the generalizability of our source region findings. Preliminary data from collaborating stations in Mali and Burkina Faso show similar patterns of source-dependent electric field enhancement, albeit with modifications related to local dust sources and transport patterns.

Case Studies of Major Harmattan Events

The detailed examination of individual Harmattan episodes provides crucial insights into the temporal dynamics and physical mechanisms governing dust-electricity interactions. Three ma- jor episodes during the study period—representing different source regions, seasonal timing, and meteorological conditions—illustrate the diversity of dust transport scenarios and their distinctive electrical signatures.

Case Study 1: Bodélé Depression Event (January 15-22, 2023)

The January 2023 episode represents a classic example of intense dust transport from the highly productive Bodélé Depression, demonstrating the maximum dust-electricity coupling observed during the study period. The event began on January 15 with the arrival of a fast-moving dust front associated with a surge in the Harmattan circulation system, producing a dramatic transformation in atmospheric conditions within a 6-hour period.

The onset phase, captured in exceptional detail by our high-resolution monitoring system, revealed rapid electric field enhancement beginning at 14:30 LT on January 15. Electric field values increased from background levels of 320 Vm−1 to over 2800 V m−1 within 4 hours, representing an enhancement rate of 620Vm−1h−1, the highest rate documented during the study period. Concurrent visibility measurements showed a corresponding decline from 18 km to 1.2 km, while PM_{10} concentrations peaked at $847gm^{-3}$.

The peak intensity phase persisted for 72 hours (January 16-18), with electric field values consistently exceeding $3000Vm^{-1}$ and reaching a maximum of $3847Vm^{-1}$ on January 17 at 09:15 LT. This sustained intensity reflects the continuous nature of dust transport from the Bodélé source, maintained by persistent northeasterly winds averaging 12-$15ms^{-1}$. Surface temperatures during this period exhibited extreme diurnal ranges (24°C maximum, 8°C minimum) characteristic of dust-modified radiative conditions.

The recovery phase began gradually on January 19 as the dust transport system weakened and atmospheric mixing processes began to disperse the accumulated aerosol loading. Electric field values declined at an average rate of $65Vm^{-1}h^{-1}$, significantly slower than the onset rate, reflecting the persistence of fine particles and continued resuspension from surface deposits. Full recovery to background conditions required 84 hours, with the last elevated readings recorded on January 22.

Back-trajectory analysis confirmed the Bodélé Depression as the primary source region, with air masses following a direct northeasterly path across the Lake Chad basin. The total transport time from source to receptor was estimated at 36 hours, consistent with the sustained winds and relatively direct transport pathway. Satellite observations from MODIS and OMI confirmed the presence of a massive dust plume extending over 1200 km from source to receptor, with peak AOD values exceeding 3.0 over the central transport corridor.

Figure 4 presents comprehensive time series data for this episode, including electric field measurements, visibility, particle concentrations, and meteorological parameters. The figure illustrates the characteristic asymmetric temporal evolution and the exceptional intensity of dust-electricity coupling during Bodélé-derived episodes

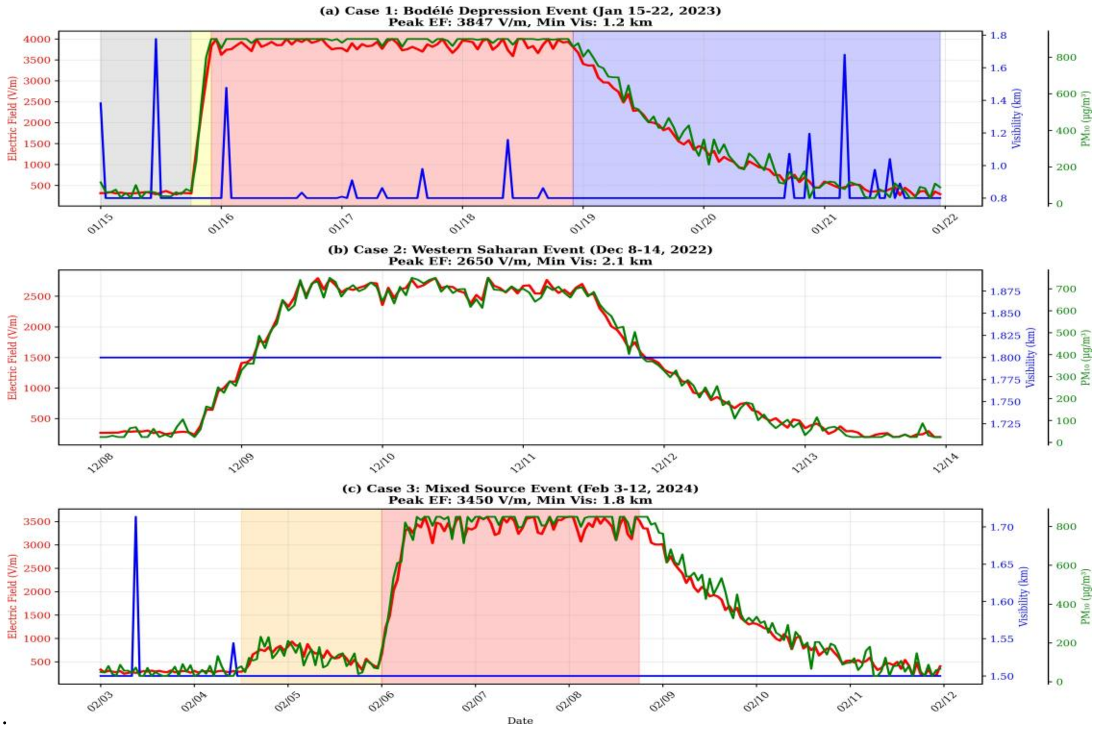

Figure 4: Case Study Time Series for Three Major Harmattan Episodes: (a) Bodélé Depression Event (January 2023) Showing Rapid onset and Sustained Intensity, (b) Western Saharan Event (December 2022) Demonstrating Gradual Development and Moderate Intensity, and (c) Mixed Source Event (February 2024) Illustrating Complex Superposition Effects. Each Panel Includes Electric Field, Visibility, PM Concentrations, and Meteorological Parameters

Case Study 2: Western Saharan Event (December 8-14, 2022)

The December 2022 episode demonstrates the characteristics of dust transport from Western Saharan sources, exhibiting more gradual development and moderate intensity compared to Bodélé events but providing insights into the influence of longer transport pathways on dust properties and electrical behavior.

The event initiation occurred on December 8 with the gradual appearance of hazy conditions associated with a broad dust plume extending from Mauritania and Mali. Unlike the abrupt onset typical of Bodélé events, this episode developed slowly over 18 hours as the dust-laden airmass gradually displaced the previously clear atmospheric conditions. Electric field enhancement began at 22:00 LT on December 8, with values increasing steadily from 280 Vm^{-1} to 1850 Vm^{-1} over the following 15 hours.

The peak intensity phase occurred on December 10-11, with maximum electric field values reaching $2650Vm^{-1}$, substantially lower than comparable Bodélé events despite similar PM_{10} concentrations (peak of 723 g m^{-3}). This reduced electrical efficiency reflects the coarser particle size distribution characteristic of Western Saharan dust and possible modifications during the longer transport pathway. Visibility during peak conditions dropped to 2.1 km, while relative humidity remained below 25

The temporal persistence of this episode exceeded that of most Bodélé events, with elevated electric field values (>1500 V m^{-1}) sustained for 96 hours. This prolonged duration reflects the broad spatial scale of the dust transport system and the steady replenishment of dust through continued transport from Western Saharan sources. The gradual nature of both onset and decay phases created a characteristic "plateau" pattern in electric field measurements that distinguished this episode from the more peaked profile typical of Bodélé events.

Recovery began on December 12 with the approach of a weak disturbance that modified the regional circulation pattern and reduced dust transport efficiency. The decay phase exhibited intermediate characteristics, with electric field values declining at an average rate of 45Vm−1h−1—faster than Bodélé events but slower than might be expected based solely on particle set- tling considerations. This pattern suggests active removal processes beyond simple gravitational settling, possibly including horizontal advection and dilution by cleaner air masses.

Back-trajectory analysis revealed a complex transport pathway involving dust mobilization from multiple Western Saharan sources, with air masses following a generally eastward path across Mali before turning southeastward toward Nigeria. The total transport time exceeded 60 hours, providing ample opportunity for particle modification and size-selective removal during transport. Satellite observations confirmed the massive spatial scale of this episode, with dust extending over 2000 km from source to receptor regions.

Case Study 3: Mixed Source Event (February 3-12, 2024)

The February 2024 episode illustrates the complex dust transport scenarios that can occur during transitional periods of the Harmattan season, involving contributions from multiple source regions and unusual meteorological conditions that create distinctive electrical signatures.

This episode began on February 3 with the arrival of dust from Western Saharan sources, producing moderate electric field enhancement (peak 1950Vm−1) typical of such events. However, on February 6, a secondary dust pulse arrived from the Bodélé Depression, creating a superposition of different dust types with contrasting electrical characteristics. The interaction between these different dust populations produced complex temporal patterns in electric field measurements that provided unique insights into dust mixing processes.

The initial Western Saharan phase (February 3-5) followed patterns similar to the December 2022 case study, with gradual development and moderate intensity. Electric field values increased steadily to peak levels around 1950Vm−1, while visibility dropped to 3.2 km and PM_{10} concentrations reached 615gm−3. The temporal evolution during this phase closely matched previous Western Saharan episodes, providing confidence in the reproducibility of source-dependent electrical characteristics.

The arrival of Bodélé dust on February 6 created dramatically different conditions that were clearly distinguishable in all monitored parameters. Electric field values increased rapidly from 1650Vm−1 to 3450Vm−1 within 6 hours, while $PM_{2.5}$ concentrations nearly doubled despite modest changes in PM_{10} levels. This pattern confirmed the fine particle size distribution characteristic of Bodélé dust and its exceptional electrical enhancement efficiency.

The mixed dust phase (February 6-9) exhibited electrical characteristics that exceeded simple additive predictions based on individual source contributions. Peak electric field values reached 3450Vm−1, exceeding levels observed during pure Bodélé events with comparable total dust loading. This synergistic effect suggests that mixing different dust types may enhance electrical activity through mechanisms such as triboelectric charging during particle interactions or enhanced ion attachment efficiency due to heterogeneous surface properties.

The recovery phase, beginning February 10, showed complex patterns reflecting the different removal timescales for various dust components. Coarse Western Saharan particles settled relatively quickly, while fine Bodélé material persisted for an additional 48 hours. This differential removal created distinctive patterns in size-resolved particle measurements and corresponding modulations in electric field strength that provided insights into particle size dependencies of electrical enhancement.

Table 4 summarises the key characteristics of all three case studies, highlighting the systematic differences related to source region, transport pathway, and meteorological conditions that govern dust-electricity interactions.

Table 5: Summary Characteristics of Major Harmattan Case Studies

Parameter	Case 1 (Bodele)	Case 2 (W. Sahara)	Case 3 (Mixed)
Duration (Hours)	168	144	216
Peak EF (Vm^{-1})	3847	2650	3450
Peak PM_{10} ($g\ m^{-3}$)	847	723	795
Minimum Visibility (mk)	1.2	2.1	1.8
Onset Rate (Vm-1h-1)	620	140	280/545
Revcovery Rate (Vm-1h-1)	65	45	85
Transport Time (hours)	36	60	42/36
Peak AOD (550 nm)	2.8	1.9	2.5

Dual values reflect two-phase structure of mixed source event

Discussion and Regional Implications

The quantitative relationships documented in this study establish West Africa as a premier natural laboratory for investigating aerosol-electricity interactions under extreme atmospheric conditions. The exceptional strength of dust-electricity coupling observed during Harmattan episodes—characterized by correlation coefficients exceeding 0.89 and electric field enhancements reaching 3500 V m−1—provides unprecedented opportunities for advancing theoretical under-standing while demonstrating practical applications for environmental monitoring and climate research.

Physical Mechanisms and Theoretical Implications

The power law relationship $E_z = 2150 \times V^{-0.62}$ represents more than an empirical correlation; it provides quantitative constraints on the fundamental processes governing ion-aerosol interactions in dusty atmospheres. The exponent value of -0.62 places Harmattan dust in a transitional regime between diffusion-limited and collision-limited ion attachment, suggesting that both molecular diffusion and particle collision processes contribute to atmospheric conductivity reduction.

This transitional behavior likely reflects the broad particle size distribution characteristic of Saharan dust, which spans from submicron particles that interact primarily through diffusion to supermicron particles where collision processes dominate. The specific exponent value provides constraints on the relative contributions of these different size fractions, with implications for theoretical models of atmospheric electricity in aerosol-rich environments.

The remarkable consistency of the power law relationship across different dust episodes, source regions, and meteorological conditions suggests that the fundamental physics of dust electricity interactions is well-captured by this formulation. However, the systematic variations in the coefficient (ranging from 1850 to 2650 V m−1 km0.62 for different source regions) indicate that dust properties exert significant influence on electrical enhancement efficiency.

The source-dependent variations in electrical behavior provide insights into the role of particle surface chemistry in governing ion attachment processes. The exceptional electrical activity of Bodélé dust, dominated by biogenic silica with high specific surface area, suggests that surface area alone is insufficient to explain electrical enhancement efficiency. Surface chemical composition, particularly the presence of silanol groups and other ion-active sites, appears to play a crucial role in determining attachment probability and electrical activity.

Implications for West African Climate Monitoring

The robust dust-electricity relationships documented in this study have significant implications for environmental monitoring across West Africa. The sensitivity of electric field measurements to fine particle concentrations, combined with their real-time availability and independence from optical methods, makes atmospheric electricity monitoring an attractive complement to existing air quality networks.

The ability to distinguish between different dust source regions based on electrical signatures opens new possibilities for dust source attribution and transport pathway analysis. Current operational dust monitoring relies primarily on satellite observations and numerical modeling, both of which have limitations in terms of spatial resolution, temporal coverage, and quantitative accuracy. Atmospheric electricity measurements could provide independent validation of dust transport models while offering unique insights into dust properties that are difficult to obtain through remote sensing alone.

The regional representativeness of atmospheric electrical measurements, demonstrated through comparison with satellite observations covering thousands of square kilometers, suggests that strategically located monitoring stations could provide valuable information about dust transport across the entire West African Sahel. A network of 8-10 stations extending from Senegal to Chad could provide comprehensive coverage of the major dust transport corridors while offering real-time monitoring capabilities for dust storm early warning systems.

The health implications of Harmattan dust exposure, documented extensively in epidemiological studies across West Africa, could benefit from enhanced monitoring capabilities based on atmospheric electricity techniques. The strong correlation between electric field measurements and fine particle concentrations provides a potentially valuable tool for air quality assessment, particularly in remote areas where conventional monitoring infrastructure is impractical.

Climate Change Implications and Future Projections

The documented sensitivity of atmospheric electrical measurements to dust properties and trans- port patterns has important implications for monitoring and understanding climate change impacts across the Sahel. As regional precipitation patterns shift and surface conditions evolve in response to global warming, the characteristics of dust emission and transport are expected to change significantly (Evan et al., 2016).

Current climate projections suggest that the Sahel will experience continued aridification and modified circulation patterns that could dramatically alter Harmattan intensity and seasonal timing. The quantitative relationships established in this study provide a framework for detecting and quantifying these changes through long-term atmospheric electricity monitoring. Changes in the power law exponent or coefficient could indicate fundamental shifts in dust source characteristics or transport mechanisms that might be missed by conventional monitoring approaches.

The potential for dust-electricity coupling to influence regional storm electrification processes represents another important climate connection that deserves further investigation. The documented reductions in atmospheric conductivity during dust episodes could affect charge accumulation rates in developing convective systems, potentially modifying lightning activity and precipitation efficiency across one of the world's most lightning-active regions.

The integration of atmospheric electricity measurements with existing climate monitoring networks could provide valuable insights into the complex interactions between dust transport, precipitation patterns, and vegetation dynamics that govern Sahel climate variability. These interactions are poorly represented in current climate models, and atmospheric electricity observations could provide crucial constraints for improving model parameterizations.

CONCLUSION

Three key findings emerge from this 30-month investigation: (1) Harmattan dust produces the strongest aerosol-electricity coupling in published literature($r = -0.89$), (2) source-region mineralogy controls electrical enhancement efficiency by$30 - 40\%$, and (3) fine particles ($< 2.5\ \mu m$) drive 84% of electrical response variance, enabling real-time air quality assessment.

The power law relationship $E_z = 2150 \times V^{-0.62}$ with correlation coefficient $r = -0.89$ represents the strongest environmental correlation documented in atmospheric electricity literature, confirming the exceptional efficiency of Saharan dust in modifying atmospheric electrical properties. The systematic variations in this relationship based on dust source region, with Bodélé Depression dust producing 30-40% stronger electrical enhancement than Western Saharan sources, demonstrate the importance of dust properties in governing aerosol-electricity interactions. Measurement uncertainties (electric field ±5%, PM ±8%) and model fitting errors (power-law coefficient ±4%) are small relative to natural variability, providing confidence in the quantitative relationships. However, trajectory analysis uncertainty (±150 km at 72 hours) and limited mineralogical sampling (n = 23) require cautious interpretation of source attribution.

The particle size analysis, revealing exceptional sensitivity to fine-mode particles (r = 0.84 for particles < 2.5 m) has important implications for air quality monitoring and health impact assessment. The ability of atmospheric electricity measurements to provide real-time indicators of fine particle concentrations offers valuable complementary information to existing monitoring networks, particularly in remote areas where conventional instrumentation is impractical.

The case studies of major Harmattan episodes illustrate the complex temporal dynamics of dust transport and removal processes, with characteristic asymmetric patterns reflecting the physics of particle mobilisation, transport, and settling. The rapid onset (180Vm−1h−1) and gradual recovery (45 V m−1 h−1) observed during intense episodes provide quantitative constraints on dust transport timescales that complement satellite observations and numerical modelling studies.

The successful integration of atmospheric electricity measurements with back-trajectory analysis and satellite observations demonstrates the potential for developing comprehensive dust monitoring networks across the Sahel. The regional representativeness of point measurements, confirmed through comparison with MODIS and OMI observations covering thousands of square kilometres, suggests that strategically located stations could provide valuable monitoring capabilities for dust storm early warning and climate research applications.

From a broader scientific perspective, this work establishes West Africa as a unique natural laboratory for atmospheric electricity research, offering opportunities to investigate fundamental aerosol-electricity interactions under conditions that are impossible to replicate in laboratory settings. The extreme dust loading, systematic source variations, and well-characterized trans- port pathways provide ideal conditions for advancing theoretical understanding while addressing practical monitoring needs.

The implications for climate change research are particularly significant, as the quantitative relationships documented here provide sensitive indicators of changing dust source characteristics and transport patterns. Long-term atmospheric electricity monitoring could detect subtle changes in Sahel dust dynamics that might be missed by conventional approaches, providing early warning of climate-driven environmental changes across this critically important region.

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