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SEASONAL POLLUTION PATTERNS IN WEST AFRICA: A REVIEW OF ATMOSPHERIC CHEMICAL PROCESSES DURING THE MONSOON AND HARMATTAN

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ABSTRACT

The West African atmosphere is a dynamic chemical reactor, governed by the dramatic seasonal alternation between the dry, dust-laden Harmattan winds from the Sahara and the humid, rain-bearing West African Monsoon. These regimes create profoundly different environments for the emission, transformation, and removal of pollutants, yet a synthesized understanding of the resulting seasonal chemistry remains scattered across discipline-specific studies. This narrative review consolidates current knowledge to elucidate the distinct atmospheric chemical processes that define pollution patterns in West Africa. During the Harmattan season, the atmosphere is dominated by long-range transport of mineral dust and biomass burning aerosols, which interact with anthropogenic pollutants under intense solar radiation, driving distinctive photochemical pathways and leading to severe particulate matter (PM) episodes. In contrast, the monsoon season introduces high humidity, frequent precipitation, and active biosphere emissions. This shifts the chemical regime towards aqueous-phase processes, efficient wet deposition, and complex oxidation chemistry fueled by biogenic volatile organic compounds (BVOCs), often resulting in lower aerosol burdens but a more reactive gaseous environment. We critically examine the interactions and feedbacks between meteorology and chemistry, highlight the unique challenges of observation and modeling in this under-instrumented region, and identify key gaps in our understanding of transition periods and integrated climate-air quality impacts. This synthesis underscores the necessity of considering West African pollution through a lens of seasonal duality, providing a crucial foundation for improved regional air quality management, health impact assessments, and climate modeling.

Keywords: Atmospheric Chemistry, Air Pollution, Seasonal Variation, West African Monsoon, Harmattan, Aerosol, Biogenic Emissions, Sahel, Long-Range Transport

INTRODUCTION

The composition of the Earth's atmosphere is a fundamental determinant of both climate and public health. While global pollution trends are often studied, regional atmospheric systems possess unique characteristics driven by local emissions, topography, and, most powerfully, meteorology. Nowhere is this meteorological dominance more starkly illustrated than in West Africa, home to one of the planet's most vigorous seasonal climate phenomena (Redelsperger *et al.,* 2006). Here, the atmosphere oscillates between two starkly contrasting states: the dry, dusty Harmattan and the humid, energetic West African Monsoon. This seasonal pendulum does not merely change the weather; it fundamentally rewrites the rulebook for atmospheric chemistry, alternately activating and suppressing different emission sources, chemical reaction pathways, and pollutant removal mechanisms (Knippertz *et al.*, 2015).

The Harmattan, a persistent northeasterly flow from the Sahara Desert between November and March, transforms the regional atmosphere into a vast transport highway for mineral dust. This dust, often mingling with smoke from widespread seasonal biomass burning, creates a pervasive haze that dramatically reduces air quality and visibility (Prospero *et al.*, 2014). Under clear, dry skies, intense solar radiation fuels photochemical activity, yet the chemical interactions on the surface of the abundant dust and smoke particles remain a complex and active area of research (Formenti *et al.,* 2011). Conversely, the summer months are governed by the West African Monsoon, a southwesterly flow of moist oceanic air. The monsoon brings profound change: dust transport is curtailed, rainfall scrubs the atmosphere, and the landscape erupts with vegetative growth. This growth releases a different suite of chemicals biogenic volatile organic compounds (BVOCs) setting the stage for a distinct chemical regime dominated by humidity-driven and aqueous-phase processes (Guenther *et al.,* 2012). The rapid transitions between these seasons further create ephemeral periods of unique chemical dynamics that are poorly observed and understood.

Despite the recognized importance of these processes, scientific understanding has progressed in fragments. Major international field campaigns such as the African Monsoon Multidisciplinary Analysis (AMMA) and the Dynamics-aerosol-chemistry-cloud interactions in West Africa (DACCIWA) project have provided invaluable snapshots (Lebel *et al.,* 2010; Knippertz *et al.,* 2015). However, a cohesive narrative that ties together the chemical processes across the complete seasonal cycle contrasting the dry and wet regimes, synthesizing findings from ground-based, airborne, and satellite studies, and integrating them with regional climate dynamics is conspicuously absent from the literature. This gap impedes efforts to predict how the system will respond to dual pressures of changing climate and accelerating anthropogenic development in West Africa (IPCC, 2022).

The primary objective of this narrative review is, therefore, to synthesize and articulate the current state of knowledge regarding the atmospheric chemical processes that govern pollution patterns in West Africa, with explicit focus on the contrasting monsoon and Harmattan seasons. We aim to move beyond a simple catalog of observations to construct an integrated picture of how meteorology drives chemistry, and how chemistry, in turn, may influence regional climate and health. To achieve this, we first establish the essential climatological framework. We then outline the general principles of atmospheric chemistry relevant to the region before delving into a detailed, season-by-season analysis of dominant processes, key pollutants, and major findings. The review culminates in a synthesis comparing the regimes, a frank discussion of persistent observational and modeling challenges, and finally, a forward-looking perspective on the most pressing research needs to secure a clearer understanding of this vital component of the Earth system.

MATERIALS AND METHODS

This article adopts a narrative review methodology to synthesize a broad and interdisciplinary body of literature. The goal is not to provide a statistical meta-analysis but to construct a coherent, explanatory synthesis of atmospheric chemical processes in West Africa, structured around the dominant seasonal meteorological forcings (Ferrari, 2015). This approach is particularly suited to the topic, where evidence is derived from diverse methodologies including field campaigns, satellite remote sensing, ground-based monitoring, and modeling studies and requires integration into a compelling seasonal framework.

To ensure a comprehensive and representative foundation, a structured literature search was conducted. Primary databases included Web of Science Core Collection, Scopus, and Google Scholar. The search strategy employed keyword combinations and Boolean operators tailored to capture the regional and thematic scope. Core search strings included:

(West Africa OR Sahel) AND (atmospheric chemistry OR air pollution OR aerosol OR ozone) AND (monsoon OR Harmattan OR seasonal), (African Monsoon Multidisciplinary Analysis OR AMMA OR DACCIWA).

The search was initially conducted for the period from 2000 to the present, with a focus on capturing the pivotal studies following major field campaigns. Seminal earlier works identified through citation tracking were also included. The review prioritizes peer-reviewed journal articles, authoritative book chapters, and comprehensive reports from significant international research programs. Gray literature and non-English publications were excluded to maintain a focus on widely accessible and vetted science.

This narrative is organized thematically to highlight the cause-and-effect relationships between meteorology and chemistry. After establishing the climatological context, the core of the review is structured around the two primary seasonal regimes Harmattan and Monsoon with dedicated subsections for their defining processes, key pollutants, and major findings. This structure allows for clear comparison and contrast, facilitating the integrated synthesis presented in the later sections. The evidence is interpreted to not only describe what is observed but to explain how and why these seasonal pollution patterns emerge, identifying consistent mechanisms, unresolved contradictions, and critical knowledge gaps that define the frontier of research in this region.

Climatology of the West African Monsoon and Harmattan

The atmospheric chemistry of West Africa cannot be deciphered without first understanding the powerful meteorological engine that drives it: the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) and the associated wind reversal. This migration creates two diametrically opposed atmospheric regimes, each with its own distinct source regions, thermodynamic structure, and removal processes for pollutants (Nicholson, 2013).

The Harmattan Season (November–March)

The Harmattan is a synoptic-scale feature characterized by the persistent flow of the northeasterly trade winds, known as the Harmattan flow, from the Sahara Desert southward into the Gulf of Guinea region. This period coincides with the boreal winter when the ITCZ is at its southernmost position. The air mass is exceptionally dry (relative humidity often below 25%), stable, and laden with fine particulate matter, primarily mineral dust lifted from the Bodélé Depression in Chad and other Saharan source regions (Washington *et al.,* 2003). A prominent feature is the elevated, warm Saharan Air Layer (SAL), which rides atop a shallow, cooler marine boundary layer near the coast, effectively capping vertical mixing and trapping local pollutants (Parker *et al.,* 2005). During the Harmattan (roughly November to March), there is a significant increase in AOD due to the transport of mineral dust from the Sahara Desert and smoke from biomass burning. The weather conditions during this period facilitate greater dust emission and distribution (Balarabe, & Isah, 2019). Additionally, the season is marked by high insolation, minimal precipitation, and reduced visibility, often to less than a kilometer during intense dust outbreaks. Concurrently, widespread agricultural and savanna fires in the Sahelian band add biomass burning aerosols (e.g., black carbon, organic carbon) to the dust-laden flow, creating a complex mixture of natural and anthropogenic aerosols (Roberts *et al.,* 2009).

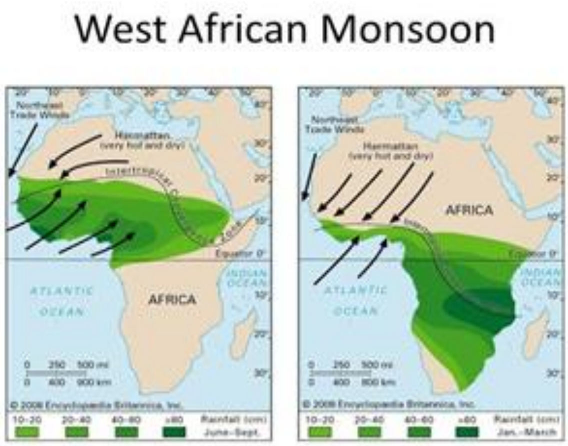
The West African Monsoon Season (June–September)

The onset of the West African Monsoon (WAM) around June represents a dramatic climatic shift. The ITCZ moves northward, and the dominant low-level flow reverses to southwesterlies, channeling moist, maritime air from the tropical Atlantic onto the continent. This moist inflow is part of the broader monsoonal circulation, interacting with the African Easterly Jet and fostering the development of deep convection and widespread rainfall (Redelsperger *et al.,* 2006). The moisture and precipitation during the monsoon season affect aerosol levels. It utilizes Artificial Neural Networks (ANN) to model how meteorological variables like relative humidity and visibility explain over 71% of the variation in atmospheric aerosols (Balarabe, & Isah, 2019).

The atmosphere becomes deeply mixed, with a high and variable boundary layer. Humidity is high, cloud cover frequent, and precipitation acts as a potent cleansing mechanism via wet deposition. The greening of the landscape from the Sahel to the Guinea Coast leads to a surge in biogenic emissions from vegetation, while dust uplift is largely suppressed due to increased soil moisture and vegetative cover, though not completely eliminated in the northern Sahel (Guenther *et al.,* 2012; Marsham *et al.,* 2011).

Transition Periods (April–May and October)

The transitions between the dominant seasons are brief but dynamically intense. The spring (April–May) transition sees the gradual weakening of the Harmattan flow, increasing humidity, and the northward advance of the monsoon front, often accompanied by convective "pre-monsoon" storms. The autumn (October) transition involves the rapid southward retreat of the ITCZ and the re-establishment of northeasterly flows. These periods are characterized by high variability in wind direction, moisture, and convection, leading to potentially unique but poorly documented chemical environments where processes from both main seasons can interact transiently (Ramel *et al.,* 2006).



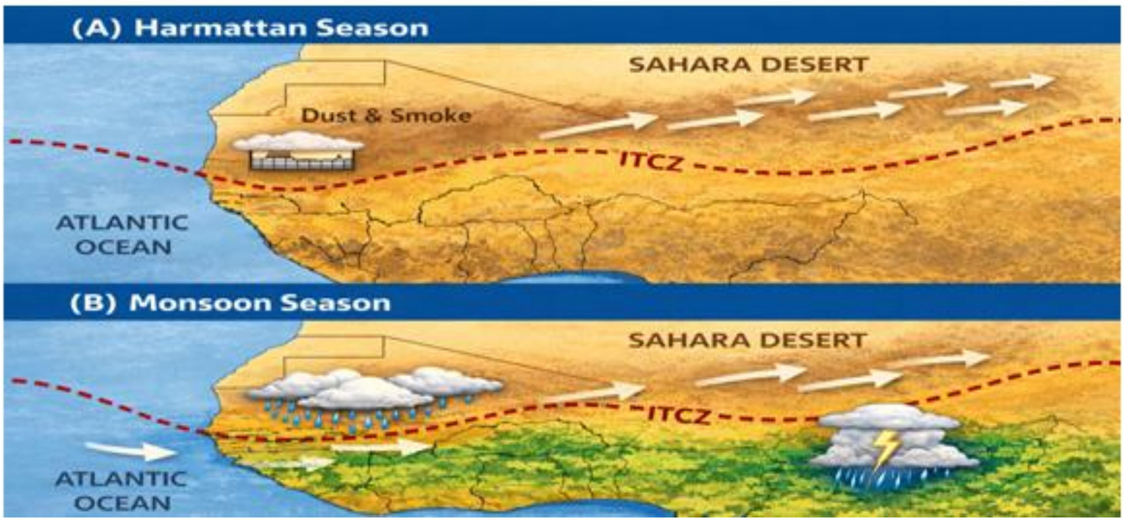


Figure 1: Schematic Representation of Seasonal Atmospheric Circulation over West Africa. Panel (A) Illustrate Harmattan Season Conditions, Characterized Bynorthesterly Continental Winds, Enhanced Dust and SMOK transport (Brown Haze), and a Shallowboundary Layer. Panel (B) shows Monsoon Season Conditions, Marked by Southeasterly Maritime Flow, Widespread Cloud Formation, Increased Rainfall, Greener Vegetation Cover, and Deep Convective Activity. The Approximate Position of Intercontinental Convergence Zone (ITCZ) is Indicated for Each Season

Atmospheric Chemical Processes

General Framework

To understand the distinct seasonal chemistries of West Africa, one must first consider the universal processes that govern the life cycle of atmospheric constituents. These processes emission, chemical transformation, transport, and deposition form a conceptual toolkit. Their relative importance, however, is dramatically modulated by the meteorological parameters that define the Harmattan and Monsoon regimes, such as humidity, solar radiation, temperature, and boundary layer dynamics (Seinfeld & Pandis, 2016).

Gas-Phase Chemistry and Photochemical Ozone Production

The oxidative capacity of the atmosphere is largely driven by gas-phase photochemistry,initiated by the solar photolysis of key species like ozone (O_3), nitrogen dioxide (NO_2), and formaldehyde (HCHO). This produces highly reactive radicals, most notably the hydroxyl radical (OH), which acts as the primary atmospheric "detergent" (Levy II, 1971). Tropospheric ozone, a key pollutant and greenhouse gas, is not directly emitted in significant quantities but is formed through complex nonlinear photochemical cycles involving nitrogen oxides ($NOx = NO + NO_2$) and volatile organic compounds (VOCs). The balance between NOx and VOCs determines whether a chemical regime is NOx-sensitive or VOC-sensitive, controlling the efficiency of ozone production a balance that shifts profoundly with season in West Africa (Sillman, 1999).

Aerosol Lifecycle: Emissions, Transformation, and Removal

Atmospheric aerosols (particulate matter, PM) are a critical component of the West African atmosphere, influencing health, visibility, and climate. Their lifecycle begins with primary emissions (e.g., mineral dust from wind erosion, black carbon from combustion) or secondary formation via the condensation of gases that have undergone chemical reactions (e.g., sulfate from SO_2, organic aerosols from oxidized VOCs) (Poschl, 2005). Once airborne, aerosols can undergo aging through coagulation and, importantly, through heterogeneous or multiphase chemistry where gases react on or within particle surfaces. This can alter their composition, hygroscopicity (ability to uptake water), and optical properties. For instance, the coating of dust with sulfate or nitrate can significantly enhance its ability to act as a cloud condensation nucleus (CCN) (Usher *et al.,* 2003). Finally, aerosols are removed by dry deposition (settling and impaction) or wet deposition, the latter being the most efficient scavenging mechanism via in-cloud and below-cloud processes.

Multiphase and Aqueous-Phase Chemistry

When relative humidity is high and clouds or fog are present,chemistry extends into the aqueous phase. Water droplets provide a medium for unique, often faster, reactions. The dissolution of soluble gases like sulfur dioxide (SO_2), hydrogen peroxide (H_2O_2), and organic carbonyl compounds is followed by oxidation, primarily by dissolved ozone and radicals, leading to the in-situ production of sulfate and secondary organic aerosol (SOA) (Ervens, 2015). This pathway is negligible during the dry Harmattan but becomes a dominant chemical factory during the humid Monsoon season, particularly in convective clouds.

Deposition Processes

The ultimate sink for atmospheric pollutants is deposition to the Earth's surface. Dry deposition depends on surface characteristics and atmospheric turbulence, which is limited during the stable Harmattan but vigorous during the mixed Monsoon. Wet deposition includes rainout (incorporation into clouds) and washout (scavenging by falling precipitation). Its efficiency is a first-order control on aerosol and soluble gas lifetimes, making it the single most important seasonal switch in West Africa's atmospheric cleansing mechanism (Textor *et al.,* 2006).

The Role of Meteorology

Integrating The Framework

These fundamental processes do not operate in isolation. They are intricately linked through meteorology. Solar radiation intensity drives photolysis rates; temperature influences reaction kinetics and emission rates (e.g., of biogenic VOCs); wind speed and direction control transport and dilution; humidity governs aqueous-phase chemistry and aerosol water content; and boundary layer depth determines the volume available for mixing, thereby concentrating or diluting pollutants. It is this pervasive meteorological control that makes the West African seasonal cycle such a powerful natural experiment for studying atmospheric chemistry.

Seasonal Pollution Patterns and Processes

Armed with the general framework of atmospheric chemistry, we can now dissect how the starkly different meteorological conditions of the Harmattan and Monsoon seasons activate distinct sets of processes, leading to the characteristic pollution patterns of each regime.

The Harmattan Season

The Harmattan transforms West Africa into a receptor for one of the planet's largest annual aerosol plumes. The chemical environment is defined by three dominant features: an abundance of mineral dust, the mixing of biomass burning emissions, and a dry, stable atmosphere under intense solar radiation.

The Dust Load And Its Chemical Role

Saharan dust is the primary atmospheric constituent during the Harmattan,with daily mean PM 10 concentrations routinely exceeding 1000 µg m^{-3} in the Sahel and several hundred µg m^{-3} as far south as the Gulf of Guinea (Anuforom *et al.,* 2007). This dust is not chemically inert. Its mineralogical composition, rich in clays, carbonates, and iron oxides, provides vast surfaces for heterogeneous chemical reactions. Key processes include:

i. The Uptake and Oxidation of SO_2: The alkaline nature of carbonate minerals in dust promotes the efficient uptake and oxidation of anthropogenic SO_2 to form sulfate, often observed as a coating on dust particles. This process is a significant sulfate production pathway in the region, reducing SO_2 lifetime and altering dust hygroscopicity (Bauer *et al.,* 2007).
ii. Modification of NOy Chemistry: Dust surfaces can catalyze the decomposition of peroxides (H_2O_2) and uptake nitrogen acids (HNO_3), effectively acting as a sink for odd hydrogen (HOx) and nitrogen (NOy) radicals. This can suppress the local photochemical production of ozone by scavenging the precursors needed for its formation (Tang *et al.,* 2004).
iii. Photocatalysis: Iron oxides (e.g., hematite) in dust can act as photocatalysts under UV light, driving "photo-fenton" reactions that contribute to the oxidative processing of organic compounds adsorbed on the particle surfaces, potentially forming secondary organic aerosol (George *et al.,* 2015).

Biomass Burning Aerosols and their Mixture with Dust

From December to February, widespread agricultural and savanna fires in the Sahel inject massive amounts of biomass burning aerosols (BBA) into the Harmattan flow. This creates a persistent, complex mixture where absorbing black carbon and organic carbon aerosols co-exist with scattering mineral dust. This internal mixing has critical implications:

i. Radiation and Climate: The mixture modifies the single-scattering albedo (SSA) of the plume. While pure dust scatters sunlight (cooling effect), the addition of absorbing black carbon can reduce the SSA, leading to atmospheric warming and potentially influencing the stability of the Saharan Air Layer and its southward penetration (Wilcox *et al.,* 2010).
ii. Gas-Particle Partitioning: The thick organic smoke coating on dust particles can alter gas-phase partitioning for semi-volatile organic compounds, affecting the budget of secondary organic aerosols in ways that are not yet fully quantified (Chakrabarty *et al.,* 2010).
iii. Health Impacts: The PM 2.5 fraction of this mixture, laden with toxic combustion by-products (e.g., polycyclic aromatic hydrocarbons), penetrates deep into the respiratory system, contributing to a well-documented peak in respiratory illnesses during the Harmattan season across the region (Nana *et al.,* 2022).

Photochemistry in a Dry, Nox-Limited Environment

Despite high actinic flux,the photochemical production of ozone during the core Harmattan period is often observed to be lower than expected or even suppressed. This is attributed to a NOx-limited regime. Sources of NOx (lightning, soils) are minimal, and anthropogenic sources are sparse outside cities. The little available NOx is efficiently titrated by high levels of peroxy radicals from VOC oxidation and, as noted, is also subject to uptake on dust surfaces (Stewart *et al.,* 2008). However, in localized plumes downwind of urban centers like Lagos, Accra, or Abidjan, the introduction of fresh anthropogenic NOx and VOCs into the dusty, sunlit air can trigger intense, episodic ozone production events, creating significant pollution hotspots within the broader regional haze (Aboh *et al.,* 2009).

The Suppressed Boundary Layer and Pollutant Accumulation

The stable stratification of the Harmattan atmosphere,particularly the shallow marine boundary layer along the coast capped by the warm SAL, severely restricts vertical mixing. This leads to the accumulation of both imported (dust, BBA) and locally emitted pollutants (e.g., from urban traffic, domestic fuel use), resulting in extremely high surface concentrations. This "lid effect" is a defining characteristic of Harmattan air quality, distinguishing it from more well-mixed polluted environments (Deroubaix *et al.,* 2018).

Table 1: Summary of Key Pollutants, Typical Concentration Ranges, and Dominant Processes during the Harmattan Season

Parameter	Typical Range / Dominant Feature	Key Processes & Implications
Meteorology	NE winds, RH < 30%, Stable BL, Shallow ML (coast)	Trapping of pollutants, long-range transport
Key Aerosol	Mineral Dust (PM10)	300 – >1000 µg m⁻³
Co-Aerosol	Biomass Burning Aerosol (PM2.5)	20 – 150 µg m⁻³
Key Gas-Phase	Ozone (O3)	20 – 50 ppbv
Key Gas-Phase	Nitrogen Oxides (NOx)	< 0.1 – 1 ppbv (background)
Chemical Regime	Dry, Dust-Surface Mediated, Photochemical	Heterogeneous uptake (SO2, HNO3), radical sink, potential O3 suppression
Removal	Slow Dry Deposition	Long aerosol lifetime, regional haze persistence
Radiative Effect	Net Warming (TOA over ocean/forest)	Due to absorption by dust-BBA mixtures

Table 1. Synthesis of dominant meteorological conditions, key atmospheric constituents, typical concentration ranges, and primary chemical processes during the Harmattan season (November–March) in West Africa. Ranges are compiled from literature and represent surface-level conditions in the Sahel and coastal regions.

The Monsoon Season

The arrival of the West African Monsoon initiates a profound chemical cleansing and regime shift. The atmosphere transitions from a transport-dominated, dusty reactor to a wet, vertically dynamic system where removal processes and biologically driven emissions take center stage. While aerosol loads diminish, the chemical complexity of the gas phase may increase.

Wet Deposition as the Dominant Cleansing Mechanism

The most immediate and visible impact of the monsoon is the dramatic reduction in aerosol optical depth. Frequent and often intense convective rainfall acts as an efficient wet scrubber. This wet deposition removes a significant fraction of accumulation-mode aerosols (both dust and particulate pollution) through in-cloud nucleation scavenging and below-cloud impaction scavenging (Flamant *et al.,* 2018). Studies following the onset of the monsoon document a precipitous drop in PM 10 and PM 2.5 concentrations, often by an order of magnitude compared to Harmattan peaks, leading to vastly improved visibility and surface air quality (Liousse *et al.,* 2010). However, this cleansing is selective; coarse dust particles are more efficiently removed than fine combustion aerosols, and the process is intermittent, leading to a "pulse-and-clean" cycle tied to individual storm systems.

The Surge of Biogenic Volatile Organic Compounds (BVOCS)

The greening of the Sahel and savannas with the rains triggers a massive biological response. Vegetation, particularly trees like isoprene-emitting species common in the Sudanian woodlands, releases large fluxes of BVOCs, primarily isoprene (C_5H_8) and monoterpenes ($C_{10}H_{16}$) (Murphy *et al.,* 2021). These highly reactive hydrocarbons become the dominant non-methane VOC source in the region during the monsoon. Their oxidation, initiated by OH radicals and ozone, proceeds through complex multigenerational pathways that can lead to:

i. ***The Formation of Secondary Organic Aerosol (SOA):*** While traditionally considered less efficient than anthropogenic precursors, the high flux of BVOCs under intense oxidative conditions can generate significant biogenic SOA, contributing to the residual fine aerosol background during the monsoon (Carlton *et al.,* 2009).

ii. ***Modification of the Oxidative Capacity:*** The rapid oxidation of BVOCs consumes OH radicals. However, under low-NOx conditions (typical of the remote monsoon background), the degradation pathways can also produce HOx radicals (OH and HO_2), potentially recycling the oxidizing power of the atmosphere in a complex feedback loop (Whalley *et al.,* 2021).

Aqueous-Phase Chemistry

The ubiquitous cloud cover and high humidity open a major chemical pathway that was dormant during the Harmattan:aqueous-phase chemistry. Within cloud and raindrops, soluble gases undergo rapid oxidation.

Sulfate Production

The dissolution and oxidation of SO_2 by H_2O_2 and O_3 in cloud water is a primary mechanism for sulfate production during the monsoon, contributing to aerosol mass even in a season of overall cleansing (Alexander *et al.,* 2005).

Secondary Organic Aerosol (SOA) from Cloud Processing

Water-soluble organic gases (WSOC), including oxidation products of BVOCs like glyoxal and methylglyoxal, can dissolve in droplets and undergo further reaction to form low-volatility, highly oxidized organic molecules that remain as SOA after droplet evaporation (Ervens *et al.,* 2011).

Impact on Radical Budgets

Clouds also act as temporary sinks and reactors for radicals (OH, HO_2, NO_3), modifying photolysis rates and gas-phase chemistry below and around them, adding another layer of complexity to regional photochemical models (Lelieveld *et al.,* 2016).

Photochemical Ozone Production in a Humid, Bvoc-Rich Environment

Contrary to the often-suppressed ozone production of the Harmattan,the monsoon season can foster active photochemistry, but of a different character. The chemical regime is typically VOC-limited or in a transitional state due to the high BVOC fluxes. Key features include:

Lightning Nox
Widespread deep convection generates prolific lightning, which is a major regional source of nitrogen oxides (LNOx). This injection of NOx into the humid, BVOC-laden upper troposphere and outflow regions can be a highly efficient driver of ozone production on regional scales, contributing to the tropical ozone maximum (Mari *et al.,* 2011).

Soil NOx Emissions
Wetted soils following rain events can become a pulsed source of biogenic NOx emissions, further fueling near-surface photochemistry in vegetated areas (Jaeglé *et al.,* 2005).

Urban Plume Processing
Anthropogenic pollution from coastal cities, while subject to more efficient dispersion and wet removal, can still mix with the abundant BVOCs and LNOx, creating potent ozone production mixtures downwind, though their spatial extent is more limited than during the stable Harmattan (Haslett *et al.,* 2019).

The Deep Convective Boundary Layer and Vertical Redistribution
The monsoon boundary layer is deep, turbulent, and frequently overturned by convection. This promotes rapid dilution of surface emissions but also enables the efficient vertical transport of gases and aerosols from the surface to the middle and upper troposphere. This vertical mixing is crucial for redistributing short-lived climate forg like ozone precursors and aerosols, linking surface processes to upper-level chemistry and radiation budgets on a continental scale (Barret *et al.,* 2008).

Table 2: Summarizing Key Pollutants, Typical Concentration Ranges, and Dominant Processes during the Monsoon Season

Parameter	Typical Range / Dominant Feature	Key Processes & Implications
Meteorology	SW winds, RH > 70%, Deep Convective BL, Frequent Rain	Efficient vertical mixing and wet removal
Key Aerosol	Secondary Organic Aerosol (PM2.5)	5 – 30 μg m⁻³
Residual Aerosol	Fine Mode Sulfate, Nitrate	1 – 10 μg m⁻³
Key Gas-Phase	Biogenic VOCs (Isoprene)	1 – 5 ppbv (canopy level)
Key Gas-Phase	Lightning NOx (LNOx)	Pulsed, elevated in UT
Chemical Regime	Humid, Aqueous-Phase, Biogenic	Cloud processing, wet deposition, VOC-limited O3 production
Removal	Rapid Wet Deposition (Rainout/Washout)	Short aerosol lifetime, episodic "pulse-and-clean" cycles
Radiative Effect	Net Cooling (Direct & Indirect)	Scattering by fine aerosols, cloud adjustment effects

Table 2. Synthesis of dominant meteorological conditions, key atmospheric constituents, typical concentration ranges, and primary chemical processes during the Monsoon season (June–September) in West Africa. Ranges are compiled from literature, noting high spatial and temporal variability due to convection.

Transition Periods
The brief interludes between the dominant seasons (April–May and October) are not merely meteorological transitions but periods of unique and rapidly evolving chemistry. These windows see the coexistence and interaction of processes characteristic of both main seasons, yet they remain critically understudied.

Spring (Pre-Monsoon)
As humidity increases and the first convective systems develop, residual Harmattan dust and aerosols can be incorporated into nascent clouds. This may lead to unique multiphase chemistry where dust serves as CCN or ice nuclei in mixed-phase clouds. The increasing biogenic activity begins to emit BVOCs into an atmosphere that may still contain significant aerosol surface area for heterogeneous reactions (Sow *et al.,* 2022).

Autumn (Post-Monsoon)
The rapid retreat of the ITCZ and the re-establishment of northeasterly flows can lead to sporadic, early Harmattan dust events intruding into an atmosphere still possessing moderate humidity and some biogenic activity. This can create short-lived episodes of dust-BVOC interaction that are not seen in the deep Harmattan. The sharp decline in wet deposition also allows pollutants to begin accumulating before the full establishment of the stable Harmattan layer (Deroubaix *et al.,* 2021).
The lack of coordinated, year-round observational campaigns means that the chemical budgets and specific processes active during these transitions represent one of the most significant gaps in our quantitative understanding of the West African atmospheric system.

Synthesis
Comparison, Interactions, and Feedbacks
Having detailed the distinct chemical regimes of the Harmattan and Monsoon, we can now synthesize these patterns into a holistic view of the West African atmospheric system. This involves direct comparison, examination of their interactions particularly during transitions and identification of potential feedback mechanisms that link atmospheric chemistry to the regional climate.

Direct Comparison of Seasonal Regimes
The core contrasts between the Harmattan and Monsoon are profound,affecting every aspect of the atmospheric life cycle (summarized conceptually in Figure 1 and quantitatively in Tables 1 & 2). These contrasts can be distilled into a few fundamental dichotomies:

Source Dominance
Harmattan = transported (Saharan dust, Sahelian biomass burning) vs. Monsoon = local biogenic (BVOCs from vegetation, lightning NOx, biogenic soil emissions).

Removal Efficiency
Harmattan = slow dry deposition (limited by stable layers) vs. Monsoon = rapid wet deposition (driven by frequent convection).
Chemical Environment: Harmattan = dry, heterogeneous, and dust-surface mediated vs. Monsoon = humid, homogeneous, and aqueous-phase dominated.

Oxidative Capacity & Ozone Production
Harmattan often exhibits suppressed ozone production in a NOx-limited, radical-sink-rich environment, while the Monsoon can support active ozone production fueled by LNOx and BVOCs, though often in a VOC-sensitive or transitional regime (Stewart *et al.,* 2008; Mari *et al.,* 2011).

Aerosol Radiative Effect
Harmattan aerosol plumes have a net direct radiative effect that is strongly positive (warming) at the top of the atmosphere over dark surfaces (ocean, forests) due to absorption by dust-BBA mixtures, but can be negative (cooling) over bright deserts. In contrast, the Monsoon features a much lower aerosol burden, typically with a net cooling effect from primarily scattering biogenic SOA and remaining fine particles, though this is modulated by convective cloud adjustments (indirect effects) (Wilcox *et al.,* 2010; Malavelle *et al.,* 2017).

Interactions and Interdependencies
The seasons are not chemically isolated. Their interaction is most apparent during the transition periods, but also through lingering effects:

Chemical Memory via Aerosols
Monsoon rainfall efficiently removes most aerosols, but a residual layer of small, long-lived particles (e.g., aged organics, sulfate) can persist. These can act as cloud condensation nuclei (CCN) for the following season's clouds, potentially influencing cloud microphysics and precipitation efficiency early in the next monsoon cycle (Twohy *et al.,* 2009).

BVOC-Dust Interactions in Transitions
As discussed in Section 5.3, the spring and autumn periods allow for the direct chemical interaction of gas-phase BVOCs with remaining or arriving mineral dust surfaces. Laboratory studies suggest such interactions can lead to the formation of organo-sulfur and organo-nitrogen compounds, but the regional-scale significance of this pathway remains an open question (George *et al.,* 2015; Sow *et al.,* 2022).

Deposition as a Nutrient Source
The massive deposition of Harmattan dust to the tropical Atlantic Ocean and the West African rainforest is a well-known source of limiting nutrients like iron and phosphorus. Similarly, the wet deposition during the monsoon delivers soluble nitrogen (from lightning NOx and ammonia) and other compounds to ecosystems, linking atmospheric chemical cycles directly to terrestrial and marine biogeochemistry (Jickells *et al.,* 2005).

Climate Feedbacks
Chemistry Influencing Meteorology
Perhaps the most significant and uncertain aspects of the system are the potential feedback loops where atmospheric chemical composition influences the very meteorological drivers that define the seasons.

Dust-Monsoon Feedback
This is a hypothesized multiscale feedback. Elevated dust loads during the late spring/early summer can absorb solar radiation, warming the Saharan Air Layer. This enhanced heating can strengthen the meridional temperature gradient that drives the monsoon flow, potentially affecting its northward penetration and intensity. Conversely, a stronger monsoon leads to wetter conditions that suppress dust emission, creating a negative feedback on dust loading (Solmon *et al.,* 2012). The sign and magnitude of this feedback remain active areas of modeling research.

Aerosol-Cloud-Precipitation Feedback
During the monsoon, aerosols from biogenic SOA, residual pollution, or early Harmattan intrusions can modify cloud properties. An increase in CCN can lead to clouds with more numerous but smaller droplets, potentially suppressing warm-rain formation and invigorating deep convection by allowing clouds to loft more water vapor higher. This can alter the spatial and temporal patterns of monsoon rainfall, with complex implications for regional hydrology (Rosenfeld *et al.,* 2008).

BVOC-Climate Feedback
Rising temperatures due to climate change may increase BVOC emissions from West African vegetation. The resulting increase in biogenic SOA could enhance aerosol cooling effects (a negative feedback), while the accompanying changes in ozone production could modify atmospheric heating rates (a positive or negative feedback depending on location and NOx levels). These coupled biogeochemical-climate feedbacks are poorly constrained for the region (Pacifico *et al.,* 2012).

Table 3: A Summary Matrix Comparing the Two Seasons across Key Dimensions

Dimension	Harmattan Season	Monsoon Season
Dominant Circulation	Northeasterly Harmattan flow	Southwesterly Monsoon flow
Boundary Layer	Shallow, Stable (coast); Deep SAL	Deep, Well-Mixed, Convective
Humidity	Very Low (< 30%)	Very High (> 70%)
Key Emission Sources	Transported (Saharan dust, Sahelian fires)	Local Biogenic (BVOCs, soils), Lightning
Dominant Aerosol	Mineral Dust & Biomass Burning Mixture	Secondary Organic & Sulfate Aerosols
Primary Chemical Pathway	Heterogeneous/Dust-Surface Chemistry	Aqueous-Phase/Cloud Chemistry
Ozone Production Regime	Often NOx-Limited, Suppressed	Often VOC-Sensitive, Active (with LNOx)
Dominant Removal Process	Inefficient Dry Deposition	Efficient Wet Deposition
Net Direct Radiative Effect	Warming (Absorption-dominated)	Cooling (Scattering-dominated)

Table 3. Direct comparison of the Harmattan and Monsoon seasons across fundamental atmospheric and chemical dimensions, highlighting the contrasting nature of the West African seasonal cycle.

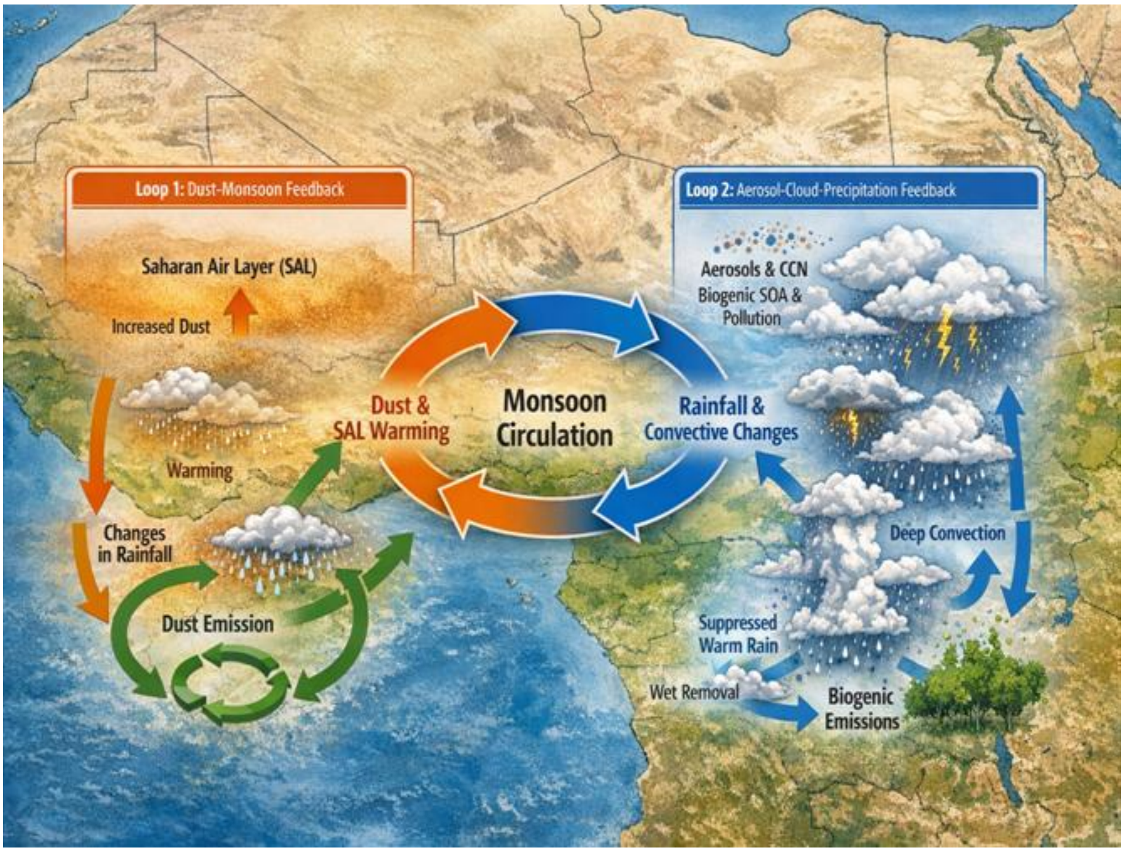


Figure 2**:** Conceptual Diagram of key Climate-chemistry Feedback Loops in West Africa. Loop 1 (Dust-Monsoon Feedback, Orange): Enhanced dust Loading warms the Saharan Air Layer (SAL), Potentially Strengthening the Monsoonal Meridional Gradient and Affecting Rainfall Patterns, which in turn Modulates dust Emission. Loop 2 (Aerosol-Cloud-Precipitation Feedback, blue): Aerosols (e.g., from Biogenic SOA or Residual Pollution) act as Cloud Condensation Nuclei (CCN), Altering Cloud DROPLET number and Size, Potentially Suppressing Warm Rain and Invigorating deep Convection, thereby Modifying the Spatial Pattern of Monsoon Rainfall and Subsequent Aerosol Wet Removal and Biogenic Emissions

This synthesis underscores that the Harmattan and Monsoon are not merely alternating states but are dynamically coupled components of a single integrated system. Perturbations to one season (e.g., changes in Sahelian fire regimes, land use, or global climate) can have cascading effects on the chemistry and climate of the other, highlighting the necessity of a full seasonal-cycle perspective for accurate prediction.

Observational and Modeling Challenges in West Africa

The synthesis presented thus far is built upon a foundation of field campaigns, satellite retrievals, and modeling studies. However, the very nature of the West African environment with its vast spatial scales, extreme meteorological gradients, and complex emission sources poses unique and formidable challenges for both observation and simulation. Acknowledging these limitations is essential for interpreting existing data and for directing future research efforts to reduce the largest uncertainties.

Observational Gaps and Limitations

Despite landmark campaigns like AMMA and DACCIWA, the observational network in West Africa remains sparse and non-continuous, creating a fragmented picture of the atmospheric system.

Spatial and Temporal Sparsity

Long-term, ground-based monitoring stations measuring comprehensive chemical suites (e.g., speciated aerosols, ozone precursors, VOC spectra) are exceedingly rare outside of short-term campaign periods. This creates a severe data desert, making it difficult to capture the full spatial gradient from the Sahara to the coast, to characterize urban plumes in context, and to establish robust climatologies for trend analysis (Doumbia *et al.*, 2018).

The Vertical Dimension

The vertical structure of pollutants is critical for understanding transport, chemistry, and radiative effects. While satellite lidars (e.g., CALIPSO) provide invaluable global profiles, they have limited temporal resolution over a given location. Intensive airborne campaigns offer detailed vertical snapshots but are inherently brief. The routine vertical profiling of key species, particularly through the Saharan Air Layer and deep convective clouds, remains a major unmet need [(Johnson *et al.*, 2020).

Satellite Retrieval Challenges

Passive satellite sensors face well-known difficulties over West Africa. Retrieving aerosol optical depth and properties over bright desert surfaces is challenging. Cloud cover during the monsoon obscures many passive measurements. Furthermore, retrieving trace gas columns (e.g., NO_2, HCHO) in the presence of high aerosol loads and over varying landscapes requires sophisticated algorithms that can introduce significant uncertainties in this region (Hsu *et al.*, 2012).

Under-constrained Emission Inventories: Bottom-up emission inventories for dust, biomass burning, biogenic VOCs, and anthropogenic sources are plagued by large uncertainties. Dust emission depends critically on soil moisture, vegetation cover, and wind friction velocity—parameters that are poorly resolved. Biogenic VOC emission factors for diverse African ecosystems are not well characterized. Anthropogenic emissions are often extrapolated from outdated proxies and lack verification (Granier *et al.,* 2023). These uncertain emissions are a primary source of error in both regional and global models.

Modeling Complexities and Uncertainties

Numerical models are essential tools for integrating processes and testing hypotheses, but simulating West African atmospheric chemistry accurately requires overcoming several steep hurdles.

Representing Sub-Grid Scale Processes: Many key processes occur at scales finer than typical regional model grid cells (~10-50 km). These include: the initiation of deep convection and its associated lightning NOx production and vertical transport; dust emission "hotspots" like the Bodélé Depression; and the chemistry within individual clouds (aqueous-phase processes). Parameterizations of these sub-grid processes are major sources of model spread and uncertainty (Heinold *et al.,* 2011).

Chemistry-Climate Coupling

To capture the feedbacks discussed in Section 6.3, models must fully couple atmospheric chemistry with dynamic meteorology. This includes the radiative effects of aerosols on temperature profiles and circulation, and the influence of meteorology on chemical rates and emissions. These coupled chemistry-climate models are computationally expensive and their results can be sensitive to the representation of aerosol microphysics and cloud-aerosol interactions (Zanchettin *et al.,* 2021).

Chemical Mechanism Complexity in Unique Environments

Standard chemical mechanisms developed for mid-latitude or marine environments may not adequately represent the specific pathways relevant to West Africa. This includes: the heterogeneous chemistry on complex dust-BBA mixtures; the detailed oxidation mechanisms of major African BVOCs like isoprene under low-NOx conditions; and the multiphase chemistry in intense convective systems. Model evaluations against the limited observational data often reveal systematic biases, pointing to gaps in our process understanding (Archibald *et al.,* 2010).

Boundary Condition Sensitivity

West Africa is a receptor for global pollution and is influenced by remote SST patterns. Therefore, regional model simulations are sensitive to the chemical and meteorological boundary conditions provided by global models, inheriting and potentially amplifying their biases (Stier *et al.,* 2005).

The convergence of these observational and modeling challenges means that while the qualitative seasonal narrative is well established, quantitative prediction of pollutant budgets, radiative forcing, and future changes remains highly uncertain. Progress hinges on strategically addressing these gaps, as outlined in the following conclusions.

CONCLUSION

This review has synthesized the current understanding of atmospheric chemical processes across the dramatic seasonal cycle of West Africa, contrasting the dust-laden, photochemically active Harmattan with the wet, biogenically driven Monsoon. The defining conclusion is that meteorology is the primary architect of pollution patterns in this region. The seasonal pendulum swing of the West African Monsoon system does not merely alter weather; it fundamentally rewires the atmospheric reactor, switching dominant emission sources, activating different chemical pathways (from heterogeneous dust chemistry to aqueous-phase cloud processing), and toggling the primary removal mechanism between inefficient dry deposition and efficient wet scavenging.

We have established that the Harmattan is characterized by a high aerosol burden from long-range transport, creating a complex, multiphase chemical environment where mineral dust interacts with biomass burning emissions and trace gases under intense sunlight, often within a stable atmospheric layer that promotes pollutant accumulation. In stark contrast, the Monsoon season is a period of atmospheric cleansing where chemistry is dominated by local biogenic emissions, rapid oxidation processes fueled by lightning NOx, and efficient wet removal, all occurring within a deep, turbulent, and convective boundary layer. The brief transition periods present a unique, under-sampled chemical milieu where processes from both main seasons interact.

Beyond description, this synthesis reveals an interconnected system ripe with feedbacks, such as the potential influence of dust aerosols on monsoon dynamics and the role of biogenic aerosols in modifying cloud properties. However, as detailed in Section 7, our quantitative grasp of these interactions is hampered by persistent observational gaps and modeling challenges, including sparse ground-based networks, uncertain emission inventories, and the difficulty of simulating coupled chemistry-climate processes at appropriate scales.

In conclusion, the atmosphere of West Africa presents one of the world's most dramatic natural experiments in meteorology-chemistry interaction. As the region faces the dual pressures of rapid urbanization and climate change, a deep, predictive understanding of its atmospheric chemical system is no longer just an academic pursuit it is a prerequisite for effective air quality management, health protection, and climate adaptation. By addressing the synthesis and priorities outlined here, the scientific community can build the knowledge base needed to navigate these challenges and unravel the intricate dance between the Harmattan and the Monsoon.

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