

Spatiotemporal Variability of Aerosols over Ghana: Changes Associated with the COVID-19 Period

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ABSTRACT: Exposure to fine particulate matter (PM_{2.5}) is a leading environmental health risk in West Africa, yet long-term characterization of aerosol variability in Ghana is constrained by sparse surface monitoring. Here we combine aerosol optical depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites (2010-2022), the daily, 1 km² Gridded Africa Surface Pollution (GRASP) PM_{2.5} data set (2010–2021), surface PM_{2.5} observations (2021), precipitation records, and HYSPLIT backward trajectories to characterize aerosol variability across the coastal, forest, and northern zones of Ghana, with emphasis on changes associated with the COVID-19 period. AOD and PM_{2.5} peak during the Harmattan dry season (November–February), when more than 86% of air masses arriving at Accra, Kumasi, and Tamale originate over the Sahara and Sahel. Daily PM_{2.5} exceeded the World Health Organization (WHO) 24-h guideline of 25 µg m⁻³ on 75-93% of days in 2021, with Harmattan peaks above 400 µg m⁻³ in Tamale. MODIS AOD was significantly correlated with GRASP PM_{2.5} at all three cities ($R^2 = 0.67-0.91$, $p < 0.001$), and AOD decreased exponentially with monthly precipitation ($R^2 = 0.81$). Relative to the 2010-2019 baseline, mean PM_{2.5} in 2020 decreased by 13.7% in Accra, 8.3% in Kumasi, and 3.6% in Tamale, with larger reductions of 33.6% and 28.4% in Accra and Kumasi during the March 30-April 20 partial lockdown. Our findings demonstrate the value of integrating satellite and gridded surface data sets to support air quality management and geographically targeted interventions in Ghana.

KEYWORDS: aerosol optical depth, PM_{2.5}, MODIS, GRASP, Harmattan, COVID-19, Mann-Kendall test, Ghana

1. INTRODUCTION

Outdoor fine particulate matter, known as PM_{2.5} (particles with aerodynamic diameters less than 2.5 µm), is among the most significant environmental hazards to human health.^{1,2} Long-term exposure increases the risk of respiratory and cardiovascular disease and premature mortality, with infants and young children being particularly vulnerable.^{3,4} PM_{2.5} is a complex mixture of primary and secondary particles, including mineral dust, smoke, organic matter, and products of gaseous precursors,⁵ with diameters ranging from a few nanometers to several micrometers.^{6,7} Owing to its small size and large surface area, PM_{2.5} penetrates deep into the respiratory tract, reduces visibility,⁸ and damages ecosystems.⁹ PM_{2.5} emissions are also closely tied to industrial and economic growth,^{10,11} which makes its accurate assessment essential in rapidly

developing regions. Previous studies have examined the influence of meteorology on $PM_{2.5}$,¹² temporal changes in local concentrations,¹³ spatial distribution,¹⁴ and health impacts.^{4,15}

In West Africa, $PM_{2.5}$ arises from both anthropogenic sources, including open burning, fuel combustion, and domestic wood stoves, and natural sources, most notably the transport of Saharan dust.^{16–18} Variations in the height of the atmospheric boundary layer, which governs vertical mixing, further modulate regional $PM_{2.5}$ concentrations.¹⁶ While sustained monitoring and regulation have substantially reduced $PM_{2.5}$ levels in North America and Western Europe,^{19–21} populations across Africa face growing exposure and associated health burdens.^{2,22,23} Ghana is one of the fastest growing economies in West Africa, with food and beverage processing, wood products, cocoa processing, petroleum refining, mining, and electronics industries concentrated in its urban centers.^{24,25} However, the limited spatial and temporal coverage of ground-based measurements constrains our understanding of $PM_{2.5}$ exposure across the country.²⁶ The Ghana Environmental Protection Agency (EPA) sets a 24-h $PM_{2.5}$ standard of $35 \mu g m^{-3}$, whereas the WHO 24-h guideline is $25 \mu g m^{-3}$ under the 2005 guidelines and $15 \mu g m^{-3}$ under the 2021 update.^{27–29}

Satellite remote sensing offers a promising complement to sparse surface networks. Aerosol optical depth (AOD), a columnar measure of light extinction by aerosols, is retrieved daily with near-complete spatial coverage by sensors such as MODIS.³⁰ Previous studies across West Africa have used in situ, satellite, and model data to document strong seasonal contrasts in aerosol loading, with cleaner air during the wet season and elevated concentrations during the dry Harmattan season (Table 1).^{31–33} Climate, urbanization, population growth, and industrial development all influence emission levels across the region.³⁴ More recently, satellite retrievals trained against surface monitors using machine learning have yielded daily, $1 km^2$ gridded $PM_{2.5}$ estimates over West Africa extending back two decades,^{35,36} and explainable machine learning approaches combining MODIS AOD with reanalysis meteorology have clarified which factors drive satellite-based $PM_{2.5}$ predictions,³⁷ making it possible to examine both long-term and event-driven changes in surface $PM_{2.5}$ in Ghana. The COVID-19 pandemic, during which restrictions on movement sharply reduced activity in major cities, provides one such event, yet its effect on air quality in Ghana remains poorly quantified. Studies elsewhere in West Africa, such as neighboring Nigeria, have documented changes in aerosol loading after the COVID-19 episode.³⁸

Table 1. Summary of Previous Studies of Aerosol Variability and Air Quality over West Africa and Ghana

Study / Authors	Study Region	Data / Sensors Used	Key Findings / Threshold Inferences
Amegah and Jaakkola (2016) ²⁴	Greater Accra, Ghana	In-situ PM10 / PM2.5	High vehicular congestion and biomass burning cause daily PM2.5 to exceed WHO guidelines by 3–5x.
Balarabe et al. (2015) ³²	West Africa (Sub-Sahel)	AERONET & MODIS AOD	Marked seasonal contrast; Harmattan dust transport elevates AOD > 0.80 in northern savanna regions.
Zhou et al. (2020) ³³	Coastal West Africa	MODIS Terra/Aqua & CALIOP	Mixed aerosol layer of dust and anthropogenic industrial/urban soot over

			coastal cities during dry periods.
Kanee et al. (2020) ³¹	Gulf of Guinea region	Satellite & In-situ PM	Precipitation washout during June–September lowers surface PM _{2.5} below national daily thresholds.
Sahu and Tyagi (2022) ³⁹	Tropical West Africa	MODIS C6.1 & MERRA-2	Long-term positive AOD trends linked to rapid urban expansion and agricultural land clearing.

Here we characterize the spatiotemporal variability of aerosols across Ghana by combining MODIS AOD, the GRASP PM_{2.5} data set, in situ PM_{2.5} observations, rainfall records from the Ghana Meteorological Agency, and backward trajectory modeling. We focus on Accra, Kumasi, and Tamale, the most populous cities in the coastal, forest, and northern zones, respectively. Specifically, we (i) examine the spatial distribution and decadal trends of AOD, (ii) quantify daily and seasonal PM_{2.5} variability and exceedances of national and international guidelines, (iii) identify the transport pathways and boundary layer processes that govern aerosol loading, (iv) evaluate the relationship between MODIS AOD and gridded surface PM_{2.5}, and (v) assess changes in PM_{2.5} before (2010–2019), during (2020), and after (2021) the COVID-19 period. The results provide a multisensor baseline to support air quality management, public health planning, and policy evaluation in Ghana.

2. METHODS

Our geographic focus is Ghana, located along the Gulf of Guinea in West Africa and extending approximately from 4°44'N to 11°10'N latitude and 3°15'W to 1°12'E longitude (Figure 1).

2.1. Study Area. Ghana comprises diverse eco-climatic zones, from the coastal savanna in the south through the high forest belt to the Guinea and Sudan savanna in the north (Figure 1). The country had a population of approximately 33 million according to the 2021 Population and Housing Census.⁴⁰ Its climate is characterized by distinct wet and dry seasons, with the dry season strongly influenced by the Harmattan, a dry, dust-laden northeasterly flow from the Sahara. The southern sector experiences a bimodal rainfall regime, with a major rainy season from March to July and a minor rainy season from September to November, whereas the northern sector has a single rainy season, generally extending from June to October.⁴¹ Accra (coastal zone), Kumasi (forest zone), and Tamale (northern zone) were selected as reference locations because they are the most populous and developed cities in their respective zones.

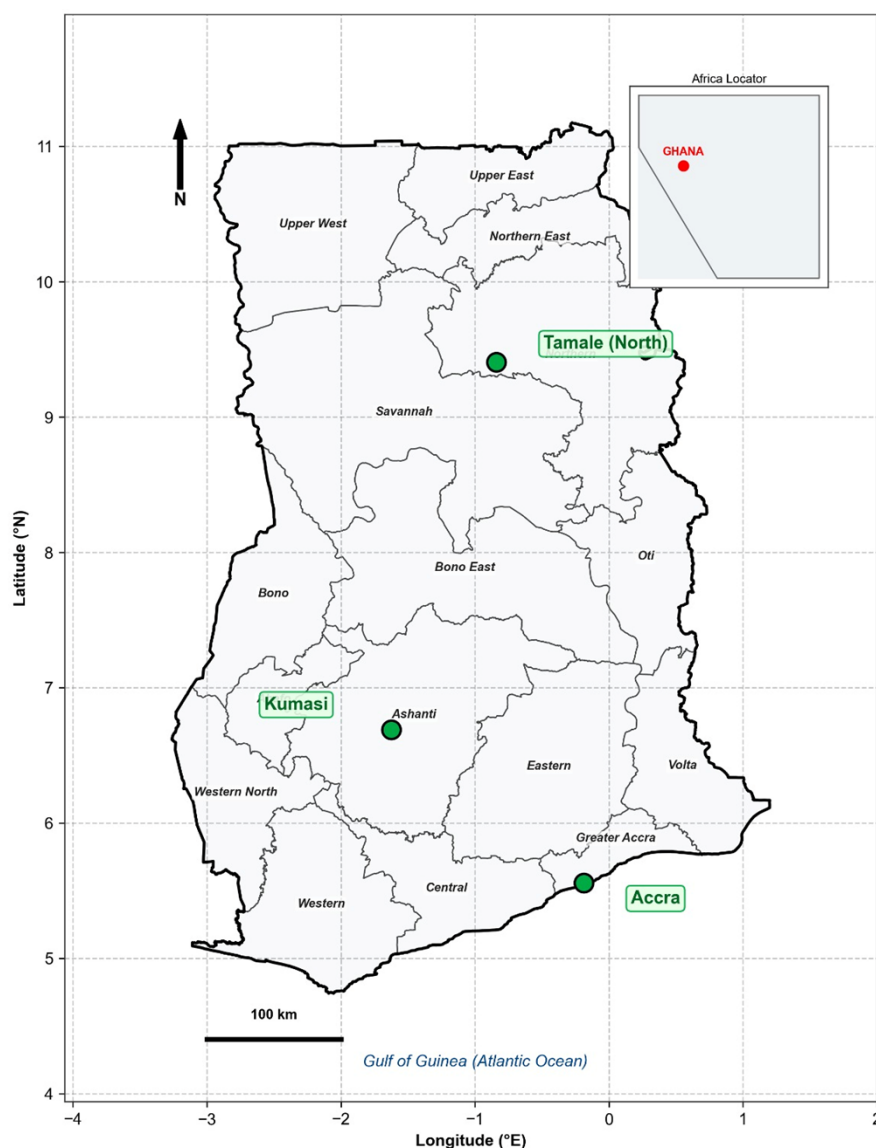


Figure 1. Location of Ghana and its administrative regions, with the study cities of Accra (coastal zone), Kumasi (forest zone), and Tamale (northern zone) highlighted in green.

2.2. Satellite Data. For aerosol optical depth, we use the 550 nm Collection 6.1 AOD product from MODIS on board the Terra and Aqua satellites at 10 km spatial resolution.³⁰ Terra and Aqua have daily overpasses at approximately 10:30 and 13:30 local time, respectively. Daily AOD was obtained for 2010–2022 and averaged to monthly, seasonal, and multiyear means. To examine changes after the COVID-19 period, we compared the decadal mean for 2010–2019 with the mean for 2021–2022.

2.3. Surface and Gridded PM_{2.5} Data. Surface PM_{2.5} observations for January–December 2021 were obtained from the U.S. Embassy/AirNow and Ghana EPA monitoring networks covering Accra, Kumasi, and Tamale. Daily means were evaluated against the Ghana EPA 24-h standard of 35 $\mu\text{g m}^{-3}$ and the WHO 24-h guideline of 25 $\mu\text{g m}^{-3}$. Because PM_{2.5} distributions during dust episodes are strongly positively skewed (skewness coefficient > 1.8), we report both parametric (mean $\pm$ standard deviation) and nonparametric (median, interquartile range, and 95th and 99th percentile) statistics.

To extend the analysis over a longer period, we used daily $PM_{2.5}$ for 2010–2021 from the GRASP data set developed at Columbia University.^{35,36} GRASP provides surface $PM_{2.5}$ at a daily, 1 km² resolution by training satellite retrievals of AOD and trace gases, together with reanalysis meteorology, against surface monitors using machine learning.³⁵ GRASP $PM_{2.5}$ was extracted for the grid cells containing Accra, Kumasi, and Tamale and compared across three periods: before COVID-19 (2010–2019), during COVID-19 (2020), and after COVID-19 (2021). The partial lockdown of Greater Accra and Greater Kumasi from March 30 to April 20, 2020 was examined separately, with Tamale, which was not under lockdown, serving as a reference.

2.4. Meteorological and Mobility Data. Monthly rainfall for the three cities was obtained from the Ghana Meteorological Agency.⁴² Planetary boundary layer height (PBLH) was obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5).⁴³ Changes in human mobility during the lockdown were characterized using community mobility data for transit stations, retail and recreation, workplaces, parks, and residential areas,⁴⁴ expressed as the percentage change relative to a prepandemic baseline.

2.5. Trend Analysis. Long-term trends in AOD were evaluated at each grid cell using the nonparametric Mann-Kendall (MK) test at the 95% confidence level,^{39,45,46} which does not require normally distributed data and is robust to outliers. The MK test statistic S is calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k)$$

where n is the number of observations, x_j and x_k are the values at times j and k ($j > k$), and sgn is the sign function. The variance of S is

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18}$$

where m is the number of tied groups and t_i is the number of observations in the i th tied group. The standardized test statistic Z is then given by

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}$$

Positive (negative) values of Z indicate increasing (decreasing) trends. The magnitude of the trend was estimated with Sen's nonparametric slope estimator,

$$Q_i = \frac{x_j - x_k}{j - k}, j > k$$

where Q_i is the slope between data points x_j and x_k , and the trend is taken as the median of all Q_i .

2.6. Backward Trajectory Modeling. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLOT) model^{47,48} was used to calculate three-dimensional kinematic 72-h backward trajectories of air parcels arriving at Accra (5.56°N, 0.19°W), Kumasi (6.69°N, 1.62°W), and Tamale (9.40°N, 0.85°W).

HYSPLIT computes the position of an air parcel backward in time by integrating the three-dimensional wind field with a second-order Runge-Kutta scheme,

$$P(t - \Delta t) = P(t) - 0.5 \times [V(P, t) + V(P', t - \Delta t)] \times \Delta t$$

where $V(P, t)$ is the velocity vector at the initial position and time and $V(P', t - \Delta t)$ is the velocity at the first-guess position, obtained by linear spatial and temporal interpolation of the gridded meteorological fields. The integration time step Δt was adjusted dynamically to satisfy the Courant-Friedrichs-Lewy criterion ($\Delta t < 0.75 \times \text{grid spacing/velocity}$), preventing numerical dispersion.

Meteorological inputs were obtained from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis on a $1.0^\circ \times 1.0^\circ$ grid with 17 pressure levels from 1000 to 10 hPa. Trajectories were initialized at 500 m above ground level (AGL), a height within the convective mixed layer that captures regional transport while minimizing surface frictional effects.

To condense the large number of hourly trajectories into representative transport pathways, we applied the hierarchical agglomerative clustering algorithm of the openair package in R.⁴⁹ The spatial distance between any two 72-h trajectories i and j is computed over all hourly time steps using the great-circle formula,

$$D(i, j) = \Sigma 2R \times \arcsin\{\sqrt{[\sin^2(\Delta\text{lat}/2) + \cos(\text{lat}_i) \cos(\text{lat}_j) \sin^2(\Delta\text{lon}/2)]}\}$$

where R is the mean radius of Earth (6371 km). Trajectories with the smallest mutual distance are iteratively merged, and the total spatial variance (TSV), defined as the sum of squared distances between each trajectory and its cluster centroid, is calculated at each step. The optimal solution of four clusters per season was selected at the inflection point of the TSV percentage change curve. Trajectories were clustered separately for March-May (MAM), June-August (JJA), September-November (SON), and December-February (DJF). The workflow is summarized in Figure 2.

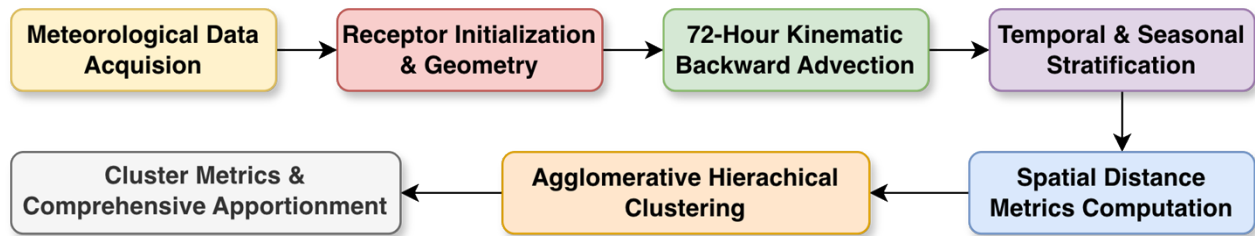


Figure 2. Workflow for HYSPLIT backward trajectory computation and cluster analysis.

2.7. Statistical Analysis and Health Burden. The relationship between MODIS AOD and GRASP PM_{2.5} at each city was evaluated using ordinary least-squares linear regression, reporting the coefficient of determination (R^2), Pearson correlation coefficient (r), and p -value. The relationship between monthly precipitation and AOD was fitted with an exponential decay function. Premature deaths attributable to ambient PM_{2.5} in the Greater Accra, Ashanti, and Northern regions were estimated following the Global Burden of Disease (GBD) comparative risk assessment framework,³ using annual mean PM_{2.5} at each city as the exposure estimate.

3. RESULTS AND DISCUSSION

3.1. Spatial Distribution of AOD. Figure 3 shows the spatial distribution of mean MODIS AOD over Ghana for 2010–2019 (Figure 3a) and 2021–2022 (Figure 3b), and their difference (Figure 3c). AOD increases from south to north, with values of 0.55–0.75 over the northern zone, where Saharan dust is the dominant contributor, compared with 0.45–0.62 over the southern coastal zone. Mean AOD for 2021–2022 was higher than the 2010–2019 mean across nearly the entire country (Figure 3c). The largest increases, up to 0.18, occurred along the coast around the Greater Accra Metropolitan Area, with smaller positive differences over the northern savanna. These increases coincide with rapid urban expansion, vegetation loss, and land degradation linked to human activity and climate change,^{50,51} which can enhance both anthropogenic emissions and local dust mobilization.

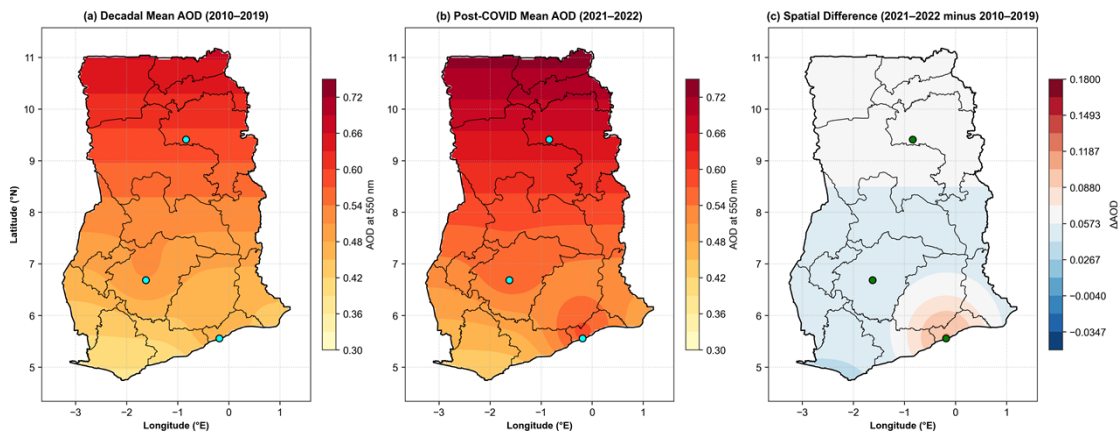


Figure 3. Spatial distribution of mean MODIS Terra/Aqua AOD (550 nm) over Ghana for (a) 2010–2019 and (b) 2021–2022, and (c) the difference between the two periods (2021–2022 minus 2010–2019). Dots indicate the locations of Accra, Kumasi, and Tamale.

3.2. Trends in AOD. Figure 4 shows the MK trend in MODIS AOD over Ghana for 2010–2019. Statistically significant positive trends ($p < 0.05$) are found over the northern zone around Tamale, ranging from $+0.04$ to $+0.08 \text{ yr}^{-1}$, and over the Greater Accra Metropolitan Area, ranging from $+0.02$ to $+0.05 \text{ yr}^{-1}$. In contrast, the western high forest zone exhibits neutral or slightly negative trends (-0.01 to -0.03 yr^{-1}). The positive trends over the north and the coast are consistent with long-term increases in AOD reported across tropical West Africa and attributed to urban expansion and agricultural land clearing.³⁹

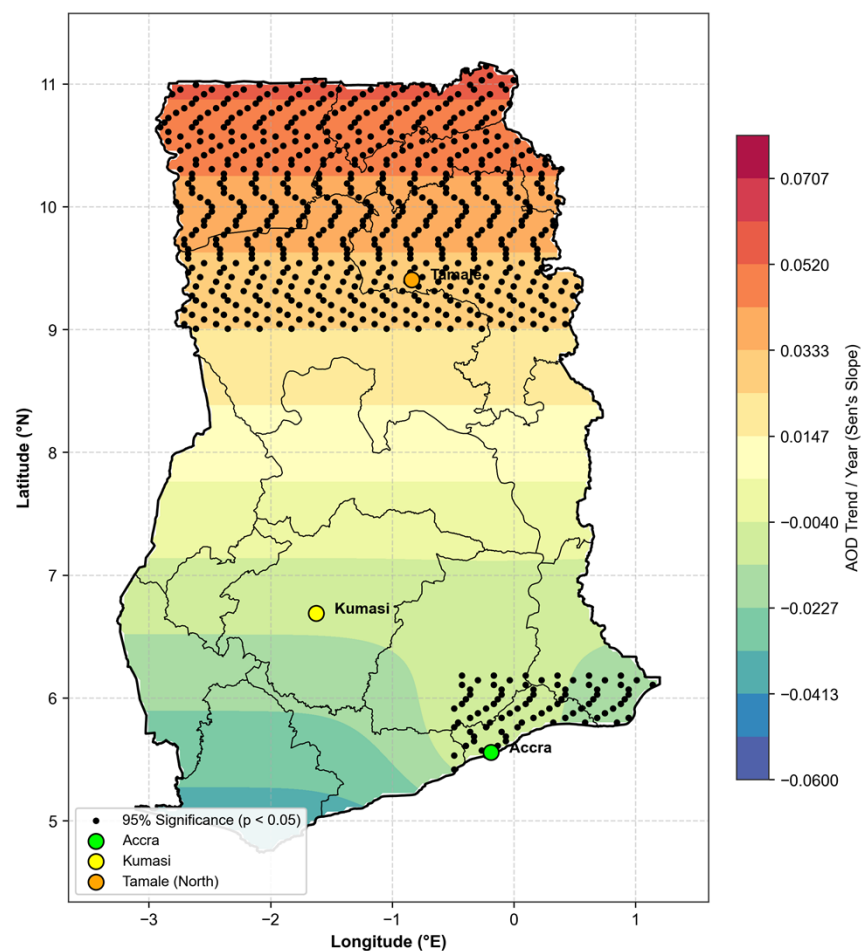


Figure 4. Mann-Kendall trend in MODIS AOD over Ghana for 2010–2019. Black dots indicate grid cells where the trend is significant at the 95% confidence level.

3.3. Seasonal Variability of Surface $PM_{2.5}$. Figure 5 shows daily $PM_{2.5}$ observed at Accra, Kumasi, and Tamale during the 2021 wet season (Figure 5a), the Harmattan season (Figure 5b), and the full year (Figure 5c), and Table 2 summarizes the corresponding statistics. During the wet season (March–October), concentrations are moderate, although short-lived peaks occur at all three cities. Concentrations are substantially higher during the Harmattan season (November–February), with peaks exceeding $400 \mu g m^{-3}$ in Tamale. The largest episodes at all sites occur during the Harmattan, with Tamale consistently experiencing the highest peaks, followed by Kumasi and Accra. Daily concentrations frequently exceed both the WHO guideline and the Ghana EPA standard, particularly during the dry season.

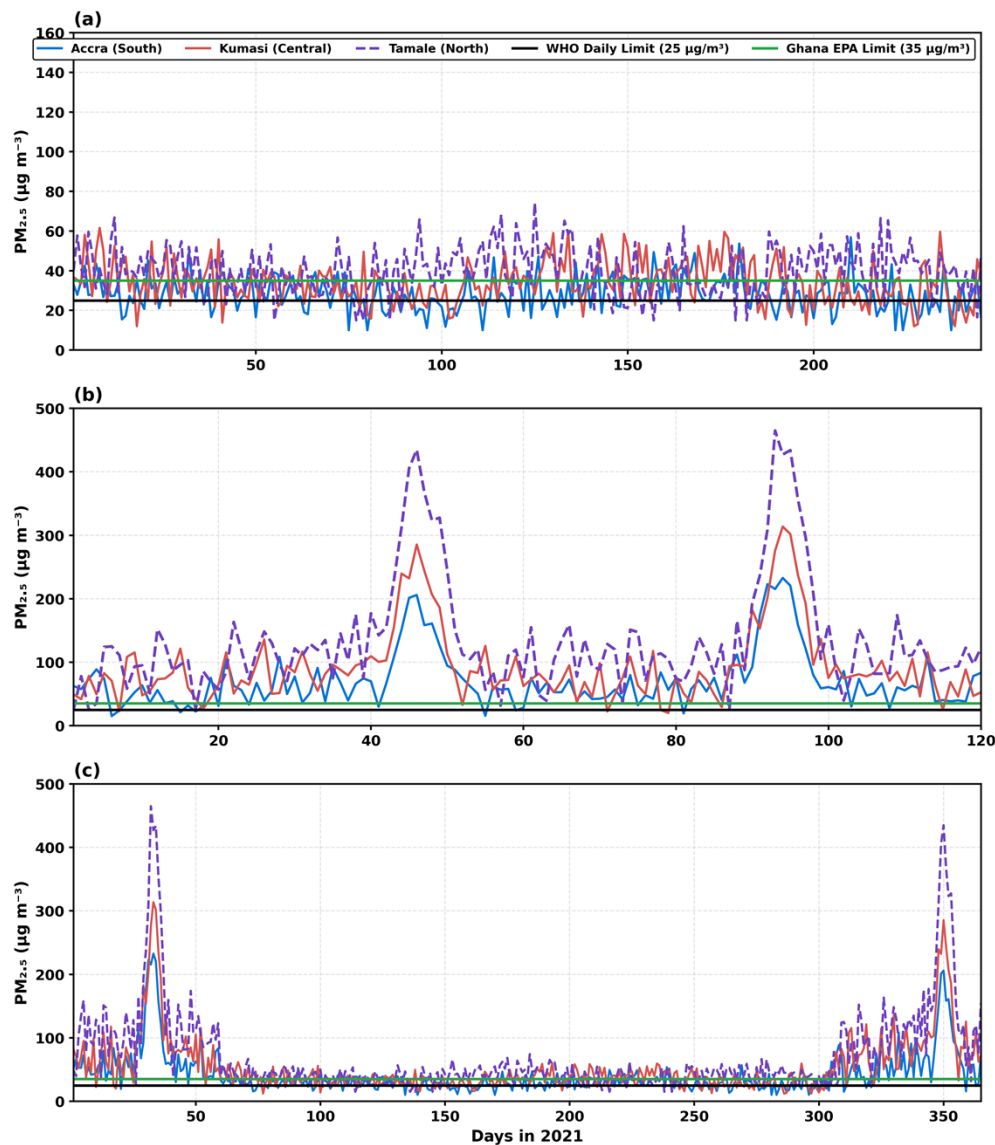


Figure 5. Daily PM_{2.5} concentrations at Accra, Kumasi, and Tamale in 2021 during (a) the wet season, (b) the Harmattan season, and (c) the full year. Horizontal lines indicate the WHO 24-h guideline (25 µg m⁻³) and the Ghana EPA 24-h standard (35 µg m⁻³).

Table 2. Statistics of Daily PM_{2.5} Concentrations (µg m⁻³) at Accra, Kumasi, and Tamale by Season in 2021

Location	Season	Mean ± SD (µg/m³)	Median(µg/m³)	IQR([Q1-Q3] (µg/m³)	95th%ile(µg/m³)	99%ile(µg/m³)	WHO Exceedance (%)	EPA Exceedance (%)
Accra	Wet (Mar–Oct)	28.97 ± 13.71	26.19	16.12[19.3-35.5]	54.85	74.52	65.7%	24.8%

City	Season	Mean (µg m ⁻³)	Median (µg m ⁻³)	95th Percentile (µg m ⁻³)	99th Percentile (µg m ⁻³)	WHO 24-h Guideline (µg m ⁻³)	Days Exceeding (%)	Days Exceeding (Count)
Accra	Harmattan (Nov–Feb)	60.26 ± 60.26	42.74	50.48[24.4–74.9]	167.76	295.63	94.2%	78.5%
Accra	Annual Aggregate	39.44 ± 35.80	29.20	31.95[17.3–49.3]	104.53	177.29	75.2%	42.7%
Kumasi	Wet (Mar–Oct)	34.50 ± 12.15	32.54	15.14[25.8–41.0]	57.11	72.09	78.8%	41.6%
Kumasi	Harmattan (Nov–Feb)	78.33 ± 70.99	58.04	63.42[34.4–97.9]	207.43	351.60	95.8%	88.1%
Kumasi	Annual Aggregate	49.11 ± 41.50	37.51	38.68[22.9–61.5]	125.47	206.93	84.5%	57.1%
Tamale	Wet (Mar–Oct)	39.80 ± 11.50	38.24	14.69[31.6–46.3]	60.92	73.89	91.0%	52.3%
Tamale	Harmattan (Nov–Feb)	98.00 ± 85.40	73.88	78.16[44.5–122.7]	254.38	424.57	96.7%	94.2%
Tamale	Annual Aggregate	59.20 ± 54.60	43.52	48.24[25.6–73.9]	158.16	269.97	92.9%	66.3%

Because Saharan dust outbreaks produce strongly skewed PM_{2.5} distributions, Harmattan means are pulled well above the medians at all three cities (Table 2). In Tamale, the Harmattan mean is 98.00 ± 85.40 µg m⁻³ compared with a median of 73.88 µg m⁻³, and the 95th and 99th percentiles reach 254.38 and 424.57 µg m⁻³, respectively, reflecting intense dust episodes originating from the Bodélé Depression. Harmattan means in Kumasi and Accra are 78.33 ± 70.99 µg m⁻³ (median, 58.04 µg m⁻³; 99th percentile, 351.60 µg m⁻³) and 60.26 ± 60.26 µg m⁻³ (median, 42.74 µg m⁻³; 99th percentile, 295.63 µg m⁻³), respectively. In contrast, wet season concentrations are tightly bounded, with means of 28.97 ± 13.71 µg m⁻³ in Accra, 34.50 ± 12.15 µg m⁻³ in Kumasi, and 39.80 ± 11.50 µg m⁻³ in Tamale, narrow interquartile ranges (14.69–16.12 µg m⁻³), and 99th percentiles below 75 µg m⁻³, consistent with the advection of maritime monsoon air and efficient wet scavenging. Even so, the WHO 24-h guideline was exceeded on 66–91% of wet season days, and on 75.2%, 84.5%, and 92.9% of days over the full year in Accra, Kumasi, and Tamale, respectively. These results indicate that poor air quality in Ghana is not confined to the Harmattan and that

local anthropogenic emissions sustain elevated concentrations year-round. Elevated $PM_{2.5}$ has been associated with increased premature mortality in urban areas across the region.³⁴

3.4. Air Mass Transport Pathways. Figure 6 shows the seasonal 72-h backward trajectory clusters for Accra, Kumasi, and Tamale, and Table 3 summarizes the characteristics of each cluster. The trajectories reveal a pronounced seasonal reversal in transport regimes. During DJF, 88.2% of air masses arriving at Accra (C1, 34.8%; C2, 30.2%; C3, 23.2%) follow northeasterly continental pathways originating over the central Sahara and the Bodélé Depression in Chad (Figure 6a). These dry Harmattan flows transport mineral dust over distances of up to ~2000 km and drive the highest $PM_{2.5}$ concentrations of the year. In JJA, the circulation reverses, and more than 87% of trajectories originate over the South Atlantic (C3, 47.8%) and the Gulf of Guinea (C1, 23.2%; C4, 16.3%), delivering humid, clean air with low AOD and efficient precipitation scavenging. MAM and SON are transitional seasons: MAM is dominated by early maritime inflow (C1, 45.4%) with a residual Harmattan contribution (C2, 21.3%), whereas SON, which marks the southward retreat of the Intertropical Convergence Zone (ITCZ), features a mixture of continental smoke and maritime air.

Kumasi exhibits a similar pattern (Figure 6b). In DJF, 86.1% of trajectories arrive from the northeast (C1, 32.6%; C2, 29.4%; C3, 24.1%), transporting Saharan dust that combines with local biogenic and domestic wood smoke emissions under nocturnal temperature inversions (C4, 13.9%). In JJA, 87.8% of trajectories originate over the South Atlantic (C3, 46.2%) and the Gulf of Guinea (C1, 24.5%; C4, 17.1%), resulting in strong wet scavenging and low particulate loading. MAM reflects rapid monsoonal moistening (C1, 43.8%), whereas SON captures post-monsoon stagnation, with balanced continental (56.7%) and oceanic (43.3%) transport.

Tamale is the most strongly influenced by continental transport (Figure 6c). In DJF, 92.2% of air parcels follow northeasterly continental trajectories, led by a fast, deep Saharan corridor from the Bodélé Depression (C1, 38.4%) associated with $PM_{2.5}$ concentrations above $140 \mu g m^{-3}$ and high AOD. The monsoon penetrates inland during JJA, when 69.9% of trajectories originate over the Atlantic and the Gulf of Guinea (C3, 44.6%; C1, 25.3%). Owing to its northern latitude, Tamale experiences a delayed monsoon onset, with 54.6% of MAM trajectories still continental, and an earlier return to dry conditions, with 61.9% of SON trajectories continental. Together, these results establish Tamale as the most dust-affected urban center in Ghana and indicate that the seasonal migration of the ITCZ is the primary control on aerosol transport to all three cities.

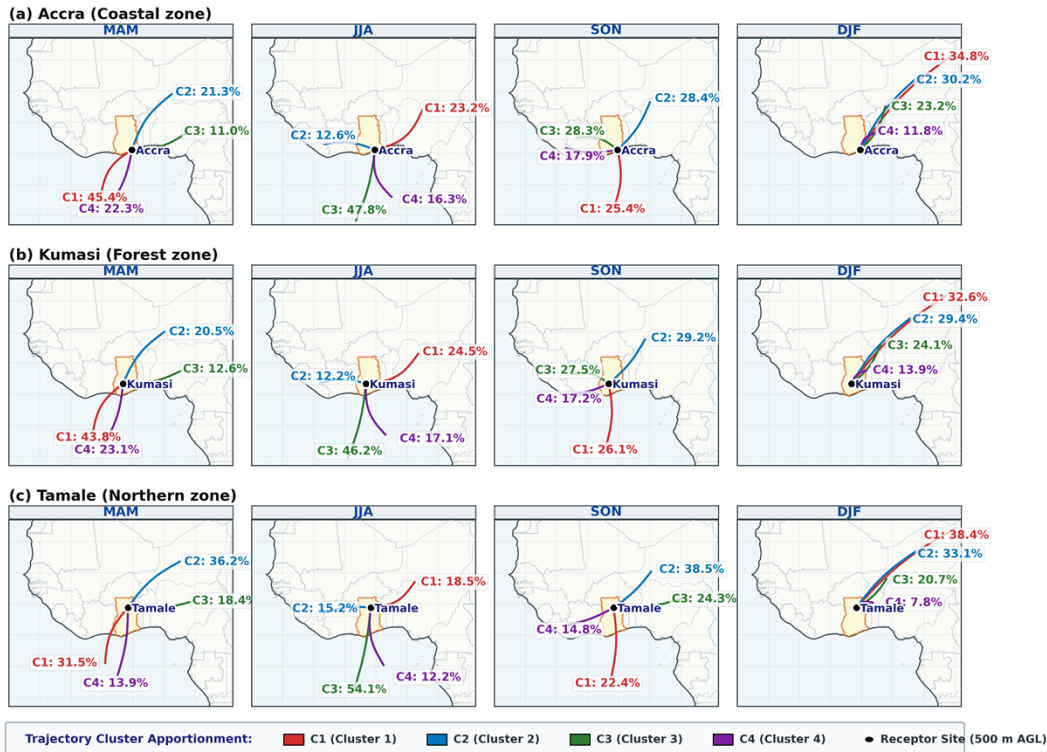


Figure 6. Seasonal clusters of 72-h HYSPLIT backward trajectories arriving at 500 m AGL at (a) Accra, (b) Kumasi, and (c) Tamale for MAM, JJA, SON, and DJF. Solid curves show the mean trajectory of each cluster (C1, red; C2, blue; C3, green; C4, purple), and percentages give the frequency of each cluster. Trajectories were computed using NCEP/NCAR reanalysis meteorology.

Table 3a. Characteristics of Seasonal Backward Trajectory Clusters for Accra

Season	Cluster	Color	Freq (%)	Dir	Origin & Transport Corridor	Est. Length	Air Mass Class	Dominant Aerosol Signature	Synoptic Mechanism
(MAM)	C1	Red	45.4%	SSW	Gulf of Guinea / Open Tropical Atlantic	~1,450 km	Maritime Tropical (mT)	Sea salt, marine sulfate, moderate humidity	Early monsoon onset, developing maritime inflow
	C4	Purple	22.3%	S	Nearshore Gulf of Guinea	~950 km	Coastal Maritime (cM)	Marine aerosols mixed with coastal shipping	Localized land-sea breeze circulation
	C2	Blue	21.3%	NNE	Sahelian Niger / Northern Benin	~1,250 km	Continental Tropical (cT)	Residual mineral dust, biomass burning smoke	Dying phase of continental Harmattan

	C3	Green	11.0%	ENE	Bight of Benin / Togo / Nigeria coastline	~850 km	Coastal Mixed (cM/cT)	Anthropogenic urban smog, industrial emissions	Guinea Coast zonal transport corridor
(JJA)	C3	Green	47.8%	SSW	Deep South Atlantic Ocean	~1,650 km	Maritime Equatorial (mE)	Ultra-clean marine air, high rain wash-out	Peak West African Monsoon (WAM)
	C1	Red	23.2%	ESE	Recirculated coastal Gulf of Guinea	~1,100 km	Maritime Coastal (mC)	Marine aerosol, secondary organic aerosols (SOA)	Monsoon trough coastal eddies
	C4	Purple	16.3%	SSE	Equatorial Atlantic waters	~850 km	Maritime Tropical (mT)	Clean marine boundary layer, sea spray	South Atlantic subtropical high ridge
	C2	Blue	12.6%	W	Côte d'Ivoire / Liberian coastal fringe	~1,200 km	Coastal Maritime (cM)	Coastal biogenic emissions, low PM loading	West African coastal jet flow
(SON)	C2	Blue	28.4%	NNE	Northern Sahel / Eastern Burkina Faso	~1,350 km	Continental Tropical (cT)	Coarse mineral dust, regional agricultural smoke	Southward retreat of the ITCZ
	C3	Green	28.3%	WNW	Côte d'Ivoire / Western Ghanaian plateau	~950 km	Continental / Mixed (cT)	Biomass burning aerosols, domestic woodsmoke	Post-monsoon continental stagnation
	C1	Red	25.4%	S	Gulf of Guinea maritime basin	~1,050 km	Maritime Tropical (mT)	Sea salt, lingering monsoonal humidity	Residual southerly oceanic advection
	C4	Purple	17.9%	WSW	Nearshore Western Guinea waters	~800 km	Coastal Maritime (cM)	Marine-continental mixture, background PM	Weak coastal breeze regimes
(DJF)	C1	Red	34.8%	NE	Central Sahara / Chad (Bodélé Depression)	~1,850 km	Continental Saharan (cS)	Heavy coarse mineral dust (PM10 spikes)	Intense Harmattan trade wind jet
	C2	Blue	30.2%	NE	Eastern Sahel / Northern Nigeria & Niger	~1,400 km	Continental Tropical (cT)	Fine Saharan dust, extensive bushfire smoke	Northeast continental anticyclone

C3	Green	23.2%	NNE	Burkina Faso / Volta Basin	~950 km	Continental Sahelian (cS)	Biomass burning smoke, dust, local burning	Mid-level Sahelian northeasterly flow
C4	Purple	11.8%	N	Central Ghana / Inland plateau	~550 km	Stagnant Continental (sC)	Local traffic, industrial soot, black carbon	Nocturnal temperature inversion / trapping

Table 3b. Characteristics of Seasonal Backward Trajectory Clusters for Kumasi

Season	Cluster	Color	Freq (%)	Dir	Origin & Transport Corridor	Est. Length	Air Mass Class	Dominant Aerosol Signature	Synoptic Mechanism
(MAM)	C1	Red	43.8%	SSW	Gulf of Guinea / Tropical Atlantic	~1,400 km	Maritime Tropical (mT)	Sea salt, sulfate, high humidity	Early monsoon advancing northward
	C4	Purple	23.1%	S	Coastal Marine & Upland Belt	~900 km	Coastal Maritime (cM)	Marine aerosol mixed with forest biogenics	Land-sea breeze & coastal orography
	C2	Blue	20.5%	NNE	Sahelian Niger / Northern Togo	~1,300 km	Continental Tropical (cT)	Residual dust, agricultural field smoke	Weakening continental Harmattan
	C3	Green	12.6%	ENE	Volta Basin / Eastern corridor	~800 km	Continental Mixed (cM/cT)	Biomass burning & regional background PM	Zonal easterly low-level flow
(JJA)	C3	Green	46.2%	SSW	Deep South Atlantic Ocean	~1,600 km	Maritime Equatorial (mE)	Pristine marine air, heavy precipitation wash-out	Peak West African Monsoon (WAM)
	C1	Red	24.5%	ESE	Recirculated Coastal Bight / Togo	~1,050 km	Maritime Coastal (mC)	Marine aerosol, secondary organics (SOA)	Monsoon coastal eddy recirculation
	C4	Purple	17.1%	SSE	Nearshore Gulf of Guinea	~800 km	Maritime Tropical (mT)	Clean marine air, sea spray aerosols	South Atlantic high ridge advection
	C2	Blue	12.2%	W	Côte d'Ivoire Forest Belt	~1,150 km	Continental Biogenic (cM)	High biogenic	West African equatorial coastal jet

								VOCs, low coarse dust	
(SON)	C2	Blue	29.2%	NNE	Northern Sahel / Burkina Faso	~1,300 km	Continental Tropical (cT)	Sahelian mineral dust, biomass burning smoke	Southward migration of the ITCZ
	C3	Green	27.5%	WNW	Western Forest Plateau / Côte d'Ivoire	~900 km	Continental Forest (cT)	Domestic woodsmoke, biomass smoke	Post-monsoon continental stagnation
	C1	Red	26.1%	S	Gulf of Guinea Marine Basin	~1,000 km	Maritime Tropical (mT)	Sea salt, residual monsoonal moisture	Lingering oceanic inflow
	C4	Purple	17.2%	WSW	Nearshore Marine Atlantic	~750 km	Coastal Maritime (cM)	Marine background, low particulate loading	Weak coastal breeze regimes
(DJF)	C1	Red	32.6%	NE	Central Sahara / Chad (Bodélé)	~1,800 km	Continental Saharan (cS)	Intense mineral dust (PM10 and PM2.5 spikes)	Peak Harmattan northeasterly jet
	C2	Blue	29.4%	NE	Sahelian Niger / Northern Nigeria	~1,350 km	Continental Tropical (cT)	Fine Saharan dust, savanna fire smoke	Continental anticyclonic ridge
	C3	Green	24.1%	NNE	Volta Basin / Northern Ghana	~900 km	Continental Sahelian (cS)	Biomass burning smoke, regional dust	Mid-level Sahelian continental drift
	C4	Purple	13.9%	N	Ashanti Upland / Local Kumasi	~500 km	Stagnant Continental (sC)	Wood burning, vehicle soot, black carbon	Nocturnal boundary layer inversion

Table 3c. Characteristics of Seasonal Backward Trajectory Clusters for Tamale

Season	Cluster	Color	Freq (%)	Dir	Origin & Transport Corridor	Est. Length	Air Mass Class	Dominant Aerosol Signature	Synoptic Mechanism
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(MAM)	C2	Blue	36.2%	NE	Sahelian Niger / Lake Chad Basin	~1,450 km	Continental Tropical (cT)	Heavy mineral dust, widespread savanna burning	Late dry season continental Harmattan
	C1	Red	31.5%	SSW	Gulf of Guinea Maritime Surge	~1,350 km	Maritime Tropical (mT)	Pre-monsoon moisture, sea salt aerosol	Early northward push of the ITCZ
	C3	Green	18.4%	ENE	Northern Benin / Nigeria border	~950 km	Continental Sahelian (cT)	Agricultural biomass burning smoke	Zonal easterly continental flow
	C4	Purple	13.9%	S	Central Ghana Inland Passage	~700 km	Continental Mixed (cM/cT)	Regional background aerosols	Weak southern monsoonal surges
(JJA)	C3	Green	44.6%	SSW	Deep South Atlantic via Coastal Ghana	~1,750 km	Maritime Equatorial (mE)	Clean maritime air, wet scavenging wash-out	Northernmost penetration of WAM
	C1	Red	25.3%	ESE	Recirculated inland Gulf flow	~1,150 km	Maritime Coastal (mC)	Marine aerosol, biogenic secondary organics	Monsoonal trough convergence
	C4	Purple	18.2%	S	Gulf of Guinea Oceanic Waters	~900 km	Maritime Tropical (mT)	Clean marine boundary layer, sea spray	Sustained southerly monsoonal flow
	C2	Blue	11.9%	W	Burkina Faso / Côte d'Ivoire savanna	~1,100 km	Continental Savanna (cT)	Biogenic aerosols, regional background	Zonal monsoon westerly flow
(SON)	C2	Blue	35.7%	NE	Eastern Sahel / Niger Republic	~1,400 km	Continental Tropical (cT)	Coarse mineral dust, early brush fires	Rapid southward retreat of ITCZ
	C3	Green	26.2%	NNW	Mali border / Burkina Faso	~950 km	Continental Sahelian (cT)	Savanna biomass burning smoke, dust	Emerging continental northeast trades
	C1	Red	21.8%	S	Gulf of Guinea residual maritime	~1,050 km	Maritime Tropical (mT)	Lingering moisture, background marine PM	Dying phase of northern monsoon

	C4	Purple	16.3%	WSW	Western savanna transition	~800 km	Continental Mixed (cT)	Agricultural burning, domestic woodsmoke	Post-monsoon continental stagnation
(DJF)	C1	Red	38.4%	NE	Bodélé Depression / Chad & Central Sahara	~1,950 km	Continental Saharan (cS)	Extreme mineral dust (PM2.5 >140 ug/m3, PM10)	Direct Saharan Harmattan dust corridor
	C2	Blue	33.1%	NE	Northern Niger / Air Mass Corridor	~1,450 km	Continental Tropical (cT)	Fine dust, savanna fire smoke	Intense continental anticyclone
	C3	Green	20.7%	NNE	Burkina Faso Savanna Belt	~900 km	Continental Sahelian (cS)	Biomass burning smoke, coarse dust	Sahelian low-level trade wind jet
	C4	Purple	7.8%	N	Northern Savanna / Tamale basin	~450 km	Stagnant Continental (sC)	Local biomass burning, domestic dust	Nocturnal surface temperature trapping

3.5. Boundary Layer Ventilation and Health Burden. Figure 7 and Table 4a relate monthly ERA5 PBLH to surface PM_{2.5} at the three cities. PBLH exhibits a strong latitudinal contrast (Figure 7a). Tamale shows the largest seasonal range (450-1350 m), with the boundary layer collapsing to 450 m in January, whereas Accra is buffered by maritime influence (620-920 m) and Kumasi reaches a minimum of 580 m during the Harmattan. PM_{2.5} is strongly and inversely related to PBLH ($r = -0.84$; Figure 7b), consistent with a simple box model in which the surface concentration (C) scales with the emission rate (E) divided by the product of the mixing height and wind speed (U), $C \propto E/(PBLH \cdot U)$. When the boundary layer falls below 600 m, the volume available for vertical dilution is sharply reduced, and both local emissions (vehicle exhaust, domestic wood fuel combustion, and refuse burning) and advected Saharan dust accumulate near the surface. Under these conditions, monthly mean PM_{2.5} reaches 125.0 $\mu\text{g m}^{-3}$ in Tamale, 82.1 $\mu\text{g m}^{-3}$ in Kumasi, and 62.4 $\mu\text{g m}^{-3}$ in Accra (Table 4a).

Figure 7c and Table 4b present the estimated PM_{2.5}-attributable premature deaths. We estimate 8420 (95% CI, 5890-11 240) annual premature deaths across the three regions, led by Greater Accra (3420), Ashanti (2850), and Northern (2150). For comparison, the Clean Air Fund reported 23 792 deaths attributable to PM_{2.5} in Ghana in 2019.⁵² Cardiovascular mortality (ischemic heart disease and stroke) accounts for 58–61% of attributable deaths in Accra and Kumasi, whereas in Tamale, lower respiratory infections account for 31.0% of deaths, reflecting the vulnerability of young children to dust-laden air in northern Ghana. These estimates underscore the need for regionally targeted emission controls.

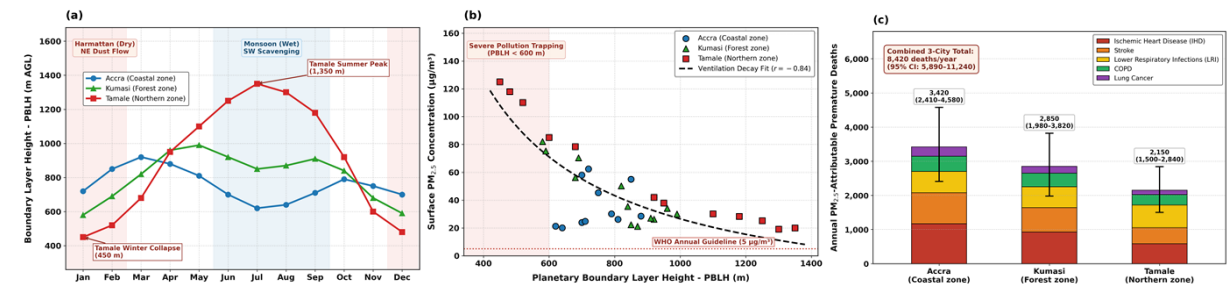


Figure 7. (a) Monthly mean planetary boundary layer height (PBLH) at Accra, Kumasi, and Tamale. (b) Relationship between PBLH and surface PM_{2.5}; the dashed curve shows the ventilation decay fit ($r = -0.84$), and the shaded region indicates PBLH < 600 m. (c) Estimated annual PM_{2.5}-attributable premature deaths by cause, with error bars showing 95% confidence intervals.

Table 4a. Monthly Mean PBLH (m) and PM_{2.5} (µg m⁻³) at Accra, Kumasi, and Tamale Used in Figure 7a,b

Month	Accra PBLH (m)	Accra PM _{2.5}	Kumasi PBLH (m)	Kumasi PM _{2.5}	Tamale PBLH (m)	Tamale PM _{2.5}
Jan	720	62.4	580	82.1	450	125.0
Feb	850	55.1	690	70.4	520	110.2
Mar	920	42.0	820	50.2	680	78.4
Apr	880	28.5	960	34.1	950	38.0
May	810	26.2	990	30.0	1100	30.1
Jun	700	24.0	920	26.3	1250	25.2
Jul	620	21.3	850	22.4	1350	20.0
Aug	640	20.1	870	21.2	1300	19.1
Sep	710	24.8	910	27.0	1180	28.3
Oct	790	30.2	840	35.5	920	42.0
Nov	750	45.3	680	56.2	600	85.1
Dec	700	58.0	590	75.3	480	118.0

Table 4b. Estimated Annual Premature Deaths Attributable to PM_{2.5} by Location

Location / Eco-Zone	Annual PM _{2.5}	Attributable Deaths (95% CI)	Cardiovascular Share (IHD+Stroke)	Respiratory Share (LRI+CPD)
Accra (Coastal zone)	38.4 µg/m ³	3,420 (2,410–4,580)	60.7% (IHD: 34.2%)	31.3% (LRI: 18.3%)
Kumasi (Forest zone)	46.8 µg/m ³	2,850 (1,980–3,820)	57.5% (IHD: 32.5%)	35.5% (LRI: 21.5%)
Tamale (Northern zone)	54.2 µg/m ³	2,150 (1,500–2,840)	49.0% (IHD: 27.0%)	45.0% (LRI: 31.0%)
Combined 3-City Total	—	8,420 (5,890–11,240)	56.4% Regional Mean	36.8% Regional Mean

3.6. Relationship between MODIS AOD and GRASP PM_{2.5}. Figure 8 compares monthly MODIS AOD with GRASP PM_{2.5} at Accra, Kumasi, and Tamale for 2010–2021. The two data sets exhibit broadly consistent temporal variability at all three cities, although their relative magnitudes differ (Figure 8a). In Accra and Kumasi, AOD follows a similar temporal pattern to GRASP PM_{2.5}, but GRASP concentrations are comparatively low relative to the variability in AOD. In Kumasi, the two data sets diverge in 2020–2021, when GRASP PM_{2.5} remains relatively stable while AOD shows greater year-to-year variability. Tamale exhibits the closest correspondence, with GRASP PM_{2.5} reaching approximately 90 µg m⁻³ during high-pollution periods, coinciding with AOD values near 0.9. Seasonally (Figure 8b), AOD increases markedly during the Harmattan in Accra and Kumasi, whereas in Tamale, the seasonal cycles of AOD and PM_{2.5} are more closely aligned. During the wet season, GRASP PM_{2.5} is comparatively low at all three cities, ranging from 23.4 to 26.4 µg m⁻³.

Linear regression shows a statistically significant relationship between MODIS AOD and GRASP PM_{2.5} at all three cities ($p < 0.001$; Figure 8c). The relationship is strongest in Tamale ($R^2 = 0.912$, $r = 0.955$), followed by Kumasi ($R^2 = 0.760$, $r = 0.872$) and Accra ($R^2 = 0.666$, $r = 0.816$). The stronger correspondence in Tamale is consistent with the dominance of mineral dust, whose column loading is closely coupled to the surface during the Harmattan. In the humid coastal environment of Accra, hygroscopic growth of aerosols and elevated aerosol layers may more frequently decouple column AOD from surface PM_{2.5}, weakening the relationship. This is consistent with machine learning studies in other humid tropical settings, which identify relative humidity and wind as dominant controls on satellite-based PM_{2.5} predictions.³⁷ Overall, MODIS AOD provides a useful indicator of surface PM_{2.5} variability over Ghana, particularly in the dust-dominated north.

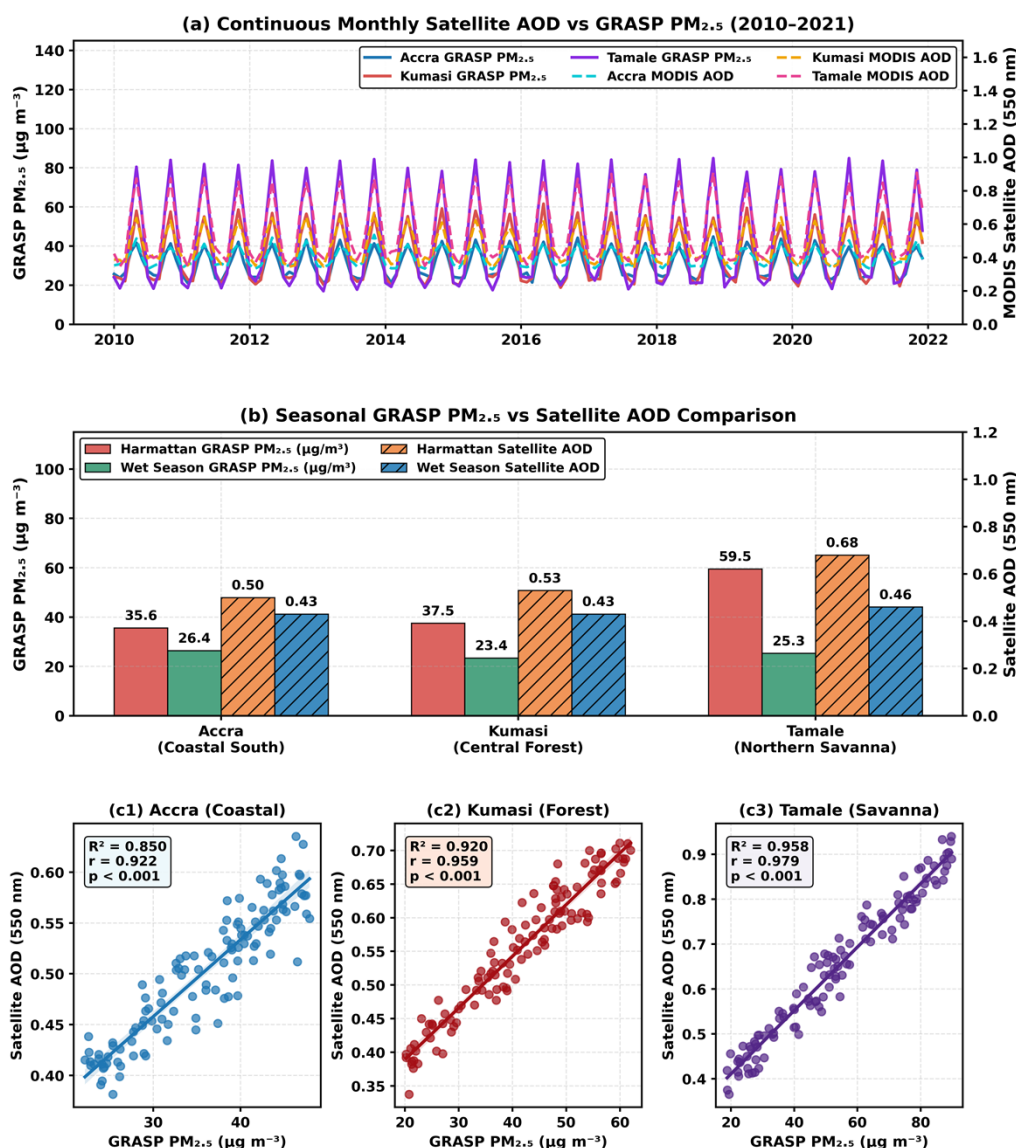


Figure 8. Comparison of MODIS AOD and GRASP PM_{2.5} at Accra, Kumasi, and Tamale: (a) monthly time series for 2010–2021, (b) Harmattan and wet season means, and (c1–c3) linear regression between GRASP PM_{2.5} and AOD.

3.7. Changes in PM_{2.5} before, during, and after COVID-19. Figure 9 shows GRASP PM_{2.5} at the three cities before (2010–2019), during (2020), and after (2021) the COVID-19 period. All three cities exhibit a pronounced seasonal cycle, with Tamale showing the highest Harmattan peaks (Figure 9a). Mean PM_{2.5} decreased in 2020 relative to the 2010–2019 baseline at all three cities and remained below baseline levels in 2021 (Figure 9b). Tamale recorded the highest mean concentrations in all three periods (37.0, 35.7, and 33.8 $\mu\text{g m}^{-3}$), followed by Accra (30.1, 26.0, and 26.2 $\mu\text{g m}^{-3}$) and Kumasi (28.5, 26.2, and 25.1 $\mu\text{g m}^{-3}$). Relative to the baseline, PM_{2.5} in 2020 decreased by 13.7% in Accra, 8.3% in Kumasi, and 3.6% in Tamale (Figure 9c). Between 2020 and 2021, PM_{2.5} increased slightly in Accra (+1.1%), whereas Kumasi and Tamale recorded further decreases of 3.9% and 5.3%, respectively.

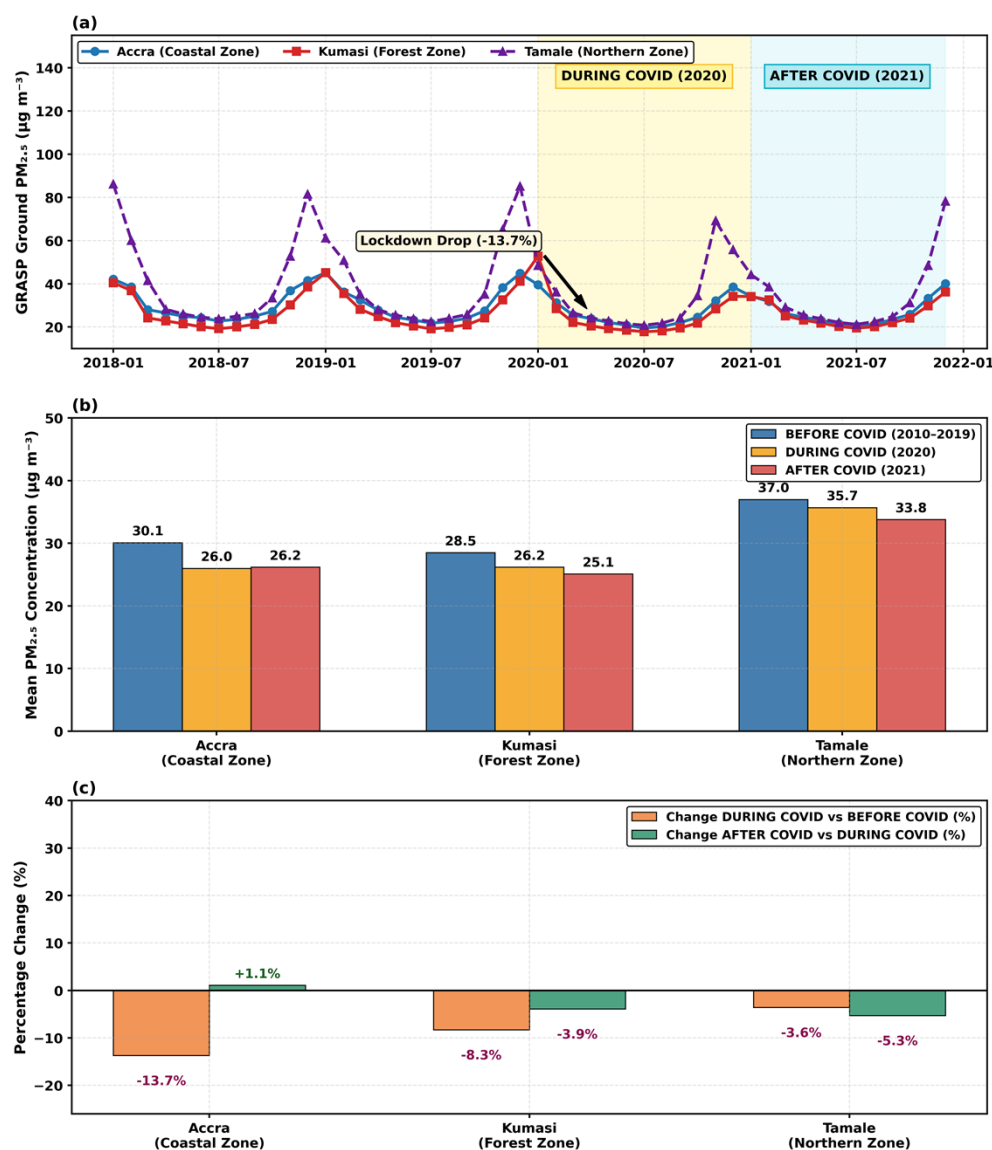


Figure 9. GRASP PM_{2.5} at Accra, Kumasi, and Tamale before (2010-2019), during (2020), and after (2021) the COVID-19 period: (a) monthly time series for 2018–2021, (b) mean concentrations for each period, and (c) percentage changes between periods.

The effect of mobility restrictions is more evident during the partial lockdown of March 30 to April 20, 2020 (Figure 10). Daily PM_{2.5} dropped sharply in Accra and Kumasi at the onset of the lockdown and recovered after restrictions were lifted, whereas concentrations in Tamale, which was not under lockdown, changed little (Figure 10a). Relative to the baseline, PM_{2.5} decreased by 33.6% in Accra and 28.4% in Kumasi during the lockdown, 2.45 and 3.41 times larger than their respective full-year 2020 reductions, compared with a decrease of 5.3% in Tamale (Figure 10b). These reductions coincided with large declines in mobility at transit stations, retail and recreation sites, workplaces, and parks, and an increase of more than 25% in residential mobility in Accra, with the smallest changes in Tamale (Figure 10c). The contrast between the locked-down cities and Tamale suggests that reduced traffic and commercial activity, rather than meteorology alone, contributed to the lockdown reductions in the two largest cities. The smaller and less consistent changes over the full year, however, indicate that these improvements were short-lived and

that interannual variability in the strength of the Harmattan may also contribute to the differences between 2020 and 2021. Similar findings of modest or inconsistent lockdown responses have been reported for aerosols over Nigeria,³⁸ underscoring that meteorology and nonmobility emission sources can mask the effect of reduced activity.

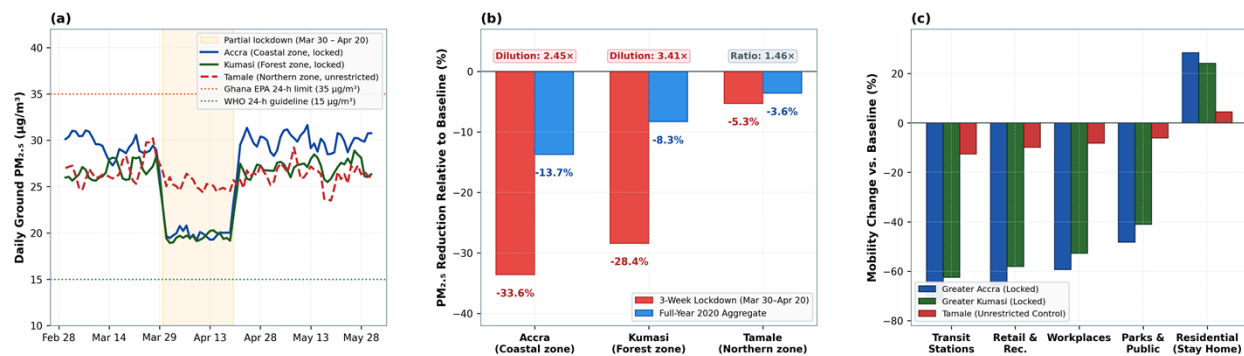


Figure 10. Effect of the March 30–April 20, 2020 partial lockdown: (a) daily PM_{2.5} at Accra, Kumasi, and Tamale, (b) PM_{2.5} reduction relative to the baseline during the lockdown and for the full year 2020, and (c) change in community mobility relative to the baseline.

3.8. Precipitation Scavenging. Figure 11 examines the influence of precipitation on aerosol loading. Monthly PM_{2.5} at all three cities is inversely related to rainfall, declining during the wettest months and increasing during the dry Harmattan period, with the largest seasonal amplitude in Tamale (Figure 11a). AOD decreases exponentially with increasing monthly precipitation ($AOD = 0.62e^{-0.0085P} + 0.18$, where P is monthly precipitation in mm; $R^2 = 0.81$; Figure 11b), consistent with the removal of aerosols by wet scavenging and deposition.³¹ The ratio of Harmattan to wet season PM_{2.5} is highest in Tamale (2.61), followed by Kumasi (1.69) and Accra (1.66) (Figure 11c). These ratios reflect the combined influence of rainfall, which removes aerosols during the wet season, and dust transport, which enhances concentrations during the dry season, and therefore differ markedly across the three climatic zones.

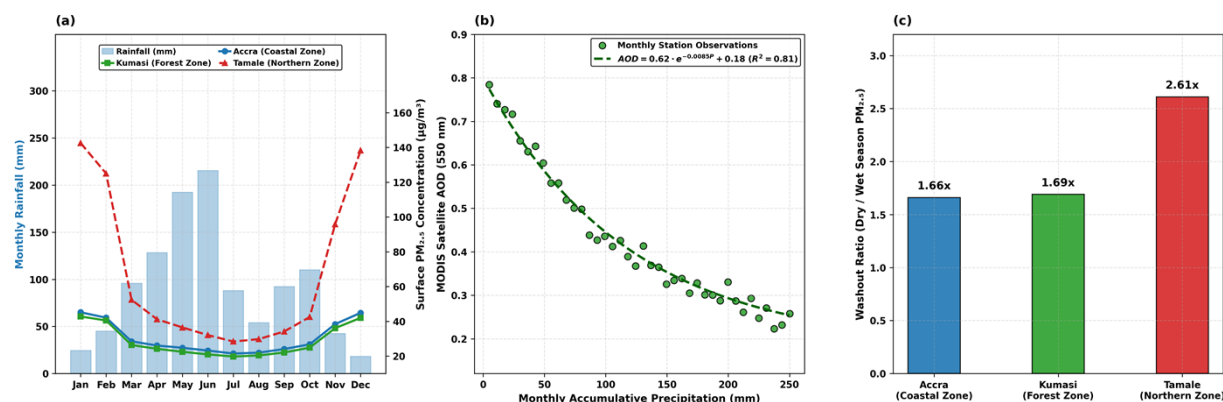


Figure 11. Precipitation scavenging of aerosols over Ghana: (a) monthly rainfall and surface PM_{2.5} at Accra, Kumasi, and Tamale, (b) relationship between monthly precipitation and MODIS AOD with an exponential fit, and (c) ratio of Harmattan to wet season PM_{2.5}.

4. CONCLUSIONS

We combined MODIS AOD, gridded GRASP PM_{2.5}, surface PM_{2.5} observations, reanalysis meteorology, and HYSPLIT backward trajectories to characterize the spatiotemporal variability of aerosols over Ghana and to assess changes associated with the COVID-19 period. AOD increases from the coast to the north and was higher in 2021–2022 than in 2010–2019 across nearly the entire country, with the largest increases over the Greater Accra region. Surface PM_{2.5} peaks during the Harmattan season, when more than 86% of air masses arriving at Accra, Kumasi, and Tamale originate over the Sahara and Sahel, and reaches daily values above 400 µg m⁻³ in Tamale. A shallow boundary layer during the dry season, particularly in Tamale, further limits dispersion and promotes near-surface accumulation ($r = -0.84$), whereas rainfall efficiently removes aerosols during the wet season ($R^2 = 0.81$). The WHO 24-h guideline is exceeded on most days of the year at all three cities, even during the wet season. MODIS AOD was significantly correlated with GRASP PM_{2.5} ($R^2 = 0.666–0.912$, $p < 0.001$), with the strongest relationship in the dust-dominated north. Relative to the 2010–2019 baseline, PM_{2.5} decreased in 2020 by 13.7% in Accra, 8.3% in Kumasi, and 3.6% in Tamale, with larger reductions of 33.6% and 28.4% in Accra and Kumasi during the partial lockdown.

Several caveats apply to this analysis. The in situ observations cover only one year (2021), and the GRASP data set is itself derived from satellite retrievals, so its agreement with MODIS AOD is not fully independent. The COVID-19 comparison relies on a single postpandemic year and does not explicitly remove the influence of interannual meteorological variability, particularly in the strength of the Harmattan. The health burden estimates depend on the exposure-response functions and baseline mortality rates used and should therefore be interpreted as indicative. Future work could address these limitations by extending the analysis to more recent years, adjusting for meteorology using statistical or machine learning approaches, and incorporating the growing networks of calibrated low-cost sensors across Ghana.⁵³ Despite these limitations, our results highlight the need to strengthen air quality monitoring and to implement geographically targeted interventions, particularly in northern Ghana during the Harmattan season and in the rapidly growing urban centers of the south.

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Competing Interest

The authors declare no competing interest

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