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Meteorology of Air Quality in Kaduna State: Integrating Biomass Burning, Aerosol-Radiation Interactions, Ozone Formation and Public Health Risk (2015 – 2024)

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ABSTRACT

Air quality in northern Nigeria is shaped by dry-season smoke, harmattan dust and a humid wet season, yet ground observations are scarce and the links between pollution sources, atmospheric processes and health are rarely examined together. The aim was to determine whether meteorological conditions regulate biomass-burning-related pollution, aerosol–radiation interactions, ozone production and health risk in the Kaduna region (2015–2024), using evidence-graded synthesis of three companion reanalysis-based studies, whose results were re-derived from public repositories. Smoke-related tracers were 10–37% lower in April–October than in November–March. After removing the seasonal cycle, they were anti-correlated with 925 hPa wind speed in November–March (Spearman $\rho = -0.63$ to -0.85), whereas modelled dust was positively correlated ($\rho = +0.67$). Aerosol optical depth did not differ between seasons (0.39 vs 0.41) and showed no detectable effect on reanalysis surface solar radiation, a partly structural null result. A derived ozone-production index was 74% higher in April–October but is dominated by the CO/NO_2 ratio; including cloud attenuation of photolysis reduces the seasonal contrast. The results support ground-based monitoring, dry-season stagnation advisories, coordinated open-burning and household-fuel measures, enforcement of existing emission rules and dust-season health preparedness.

Keywords: Harmattan, biomass burning, aerosol optical depth, surface solar radiation, ozone production.

INTRODUCTION

Air pollution is a major and growing risk in sub-Saharan Africa, where ambient and household sources together impose substantial health and economic burdens while ground-based monitoring remains sparse. Combustion emissions across the continent are projected to grow rapidly, and fast-urbanising West African regions have become a focus of coordinated atmospheric research [1-3] use numbers for references in the text. Northern Nigeria adds a distinctive seasonal setting: a dry season (November–March, the Harmattan period) in which smoke from vegetation and agricultural

burning, mineral dust and weak ventilation coincide, followed by a humid monsoon season of cloud and rain.

Kaduna State combines a large urban and industrial centre with surrounding agricultural land. Three recent studies of the Kaduna region used the same reanalysis products to examine dry-season anomalies in smoke-related pollutants, an index of ozone production efficiency, and aerosol optical depth and surface solar radiation [4-6]. Each answers a bounded question. None asks how the components interact, which of the proposed links the data actually support, what this means for health, or what should be done. This paper addresses those four questions.

We treat "meteorological regulation" as a hypothesis to be tested link by link, not as an established result. The three source papers are cited as primary sources; they were accepted for publication but were unpublished at the time of writing. This manuscript does not reproduce their text, tables or figures. It shares their data sources and study domain, so its evidence is not independent of theirs; this overlap is disclosed in the Methods. What is new here is (i) re-derivation of key source results from repository data, (ii) new analyses of meteorological association, aerosol–composition relations and cloud sensitivity, (iii) an external, verified evidence base for the region, and (iv) a health and policy synthesis built only on findings.

Verified measurement evidence for Kaduna is limited. A source-apportionment study at industrial sites in Kaduna reported mean $PM_{2.5}$ of 135.7 µg m^{-3} at an agro-processing site and 37.2 µg m^{-3} at a refinery site, with positive matrix factorisation (PMF) attributing $PM_{2.5}$ to residual-oil combustion, soil, continental dust and motor vehicles [7]. These are means over that study's sampling campaign, not necessarily annual means, but both exceed the World Health Organization (WHO) annual guideline of 5 µg m^{-3} [8] Elsewhere in Nigeria, low-cost sensors in Ibadan recorded median outdoor $PM_{2.5}$ near 109 µg m^{-3} in January (Harmattan) against about 25 µg m^{-3} in May [9], an indication of the seasonal contrast in a different climatic zone. Regional campaigns such as Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa (DACCIWA) concentrated on southern West Africa [3]. Multi-year passive-sampler records of NO_2 and O_3 exist for African savanna and forest sites outside Nigeria, and the AMMA Sahelian dust transect showed that the seasonal cycle of dust there is governed mainly by transport from Saharan sources rather than by local wind alone [10, 11].. We found no verified long-term continuous $PM_{2.5}$, NO_2 or O_3 record for Kaduna itself, which is why reanalysis is used here and why every result below needs ground validation.

Nigeria's National Environmental (Air Quality Control) Regulations set ambient standards for gases and for PM_{10} [12] The ambient schedule has no $PM_{2.5}$ entry (PM_{10}: 60 µg m^{-3} annual and

150 µg m^{-3} 24-h; NO_2: 80 µg m^{-3} annual; O_3: 100 µg m^{-3} 8-h). The regulations also prohibit open burning of standing biomass except where authorised, require registration and emission testing of generating sets, and restrict two-stroke engines. WHO's 2021 guidelines are far stricter for the pollutants that matter most here: $PM_{2.5}$ 5 µg m^{-3} (annual) and 15 µg m^{-3} (24-h), PM_{10} 15 and 45 µg m^{-3}, NO_2 10 and 25 µg m^{-3}, and O_3 100 µg m^{-3} (8-h) and 60 µg m^{-3} (peak season) [13]. One Kaduna study cites a national $PM_{2.5}$ standard of 15 µg m^{-3} [7].

Table 1 summarises what verified literature says about source categories in agriculture-dominated rural areas and in urban or industrial areas, and how each relates to season. Two points matter for interpretation. First, the reanalysis grid used here (nominal resolution about 80 km) cannot separate urban from rural air, the rural–urban distinction below therefore comes from external evidence and cannot be tested with the Kaduna reanalysis. Second, most sources have a dry-season emphasis (burning, dust), but household fuel use and traffic operate year-round, so wet-season air is not automatically clean [13]

Table 1: Evidence on pollution sources by setting and season.

Setting	**Source category**	**Verified evidence**	**Seasonal emphasis**	**Strength for Kaduna / N. Nigeria**
Rural, agricultural	Savanna and crop-residue burning	Africa accounts for the largest share of global burned area [14]; burning emits CO, black carbon (BC), organic carbon (OC), NO_x and VOCs with fuel-dependent emission factors [15].	Dry season	Regional; no local source apportionment
Rural (and urban low-income)	Household solid-fuel cooking	About 90% of rural vs 45% of urban households used solid fuels (NDHS 2013 [16] measured household $PM_{2.5}$ exceeded WHO guidelines there	Year-round; evening/morning peaks	National survey; northern Nigeria not separated
Rural and urban	Mineral and transported dust	Dust seasonality in the Sahel is controlled mainly by Saharan transport [11] Kaduna PMF resolved soil and continental dust [7].	Harmattan (dry)	Regional plus one local study
Urban, industrial	Industrial combustion and traffic	Kaduna industrial sites: $PM_{2.5}$ 37–136 µg m^{-3}; residual oil, soil, continental dust and vehicles (4%) resolved [7]; combustion emissions growing across Africa [2]	Year-round; dilution varies by season	Local, dated, site-specific
Urban	Generators, open waste burning	Regulated under national rules (generator registration and testing; burning prohibition) [12]; contribution to ambient air not measured in Kaduna	Year-round	Regulatory recognition only

Setting	Source category	Verified evidence	Seasonal emphasis	Strength for Kaduna / N. Nigeria
All	Wet-season removal and cloud	Measured $PM_{2.5}$ about 4–5 times lower in May than January in Ibadan [9]; Section 4 shows lower modelled smoke tracers in April–October	Wet season	Different region; model-based for Kaduna

The aim of this study was to determine whether meteorological conditions regulate biomass-burning-related pollution, aerosol–radiation interactions, ozone production and health risk in the Kaduna region (2015–2024), and to derive implementable, season- and setting-specific recommendations.

The specific objectives were: (1) to determine how seasonal and meteorological conditions regulate near-surface smoke-related pollutants and dust over the Kaduna region; (2) to determine whether aerosols measurably influence surface solar radiation, and whether solar radiation measurably influences ozone production; (3) to establish what the combined results, set against evidence from northern Nigeria and West Africa, imply for health risk in rural and urban settings and in the wet and dry seasons; and (4) to identify which actions are justified by the evidence, and what evidence is still missing.

MATERIALS AND METHODS

Design

This is an evidence-graded comparative synthesis with supplementary re-analysis. It is not a systematic review or meta-analysis. The steps were: (1) audit of the three source papers and their repositories; (2) re-derivation of key source results; (3) new analyses where the available data allowed; (4) a targeted, verified literature review for Northern Nigeria and West Africa; (5) link-by-link grading of the proposed causal chain; and (6) derivation of recommendations only from graded findings. Interpretations were graded as reported by literature,

Data and Domain

All three studies draw on the Copernicus Atmosphere Monitoring Service (CAMS) global reanalysis of atmospheric composition (EAC4) [13] and the ERA5 meteorological reanalysis [17] for a domain of 9.75–11.25°N, 6.75–8.25°E (about 150 km across; Kaduna city lies near 10.5°N, 7.4°E), monthly, 2015–2024. CAMS fields are on a 0.75° grid (nine points) and ERA5 fields on 0.25° (72 points). Gases were taken from the ozone repository at model level 60 (described in the

source paper as near-surface and, its lowest level in the EAC4 configuration, to be confirmed, and referred to below as the lowest model level); aerosol species, aerosol optical depth (AOD) at 550 nm, ERA5 925 hPa meteorology, surface solar radiation downwards (SSRD) and clear-sky SSRD (SSRDC) from the solar-radiation repository, and anomaly flags from the fire repository (public repositories listed under Data availability). The vertical level of the aerosol species fields is not stated in the source manuscript, so those fields are used only for relative changes and anomalies, never absolute concentrations. Seasons are defined as November–March (harmattan/dry) and April–October (transition and wet); April and October are transitional and one source paper uses a different definition. Because all three source papers use the same data system, agreement between them is consistency within one modelled system.

Verification and New Analyses

Reported results were re-derived from repository data where files allowed: the fire repository holds only a key-column dataset (450 observed plus synthetic rows, separated by a flag), the ozone repository holds raw and processed data, and the solar repository holds the monthly domain-mean dataset. New analyses were: (i) calendar-month climatologies of domain-mean fields; (ii) associations between deseasonalised monthly anomalies (calendar-month means removed) of seven responses and five meteorological predictors, using Spearman ρ with 95% moving-block bootstrap intervals (block length 6 months for all months, 3 for November–March; 70 tests, interpreted by interval exclusion of zero and consistency across variables, not by individual p-values); (iii) AOD associations with aerosol composition; (iv) trend checks on annual means (n = 10) and November–March seasonal means (n = 9) with Mann–Kendall and Theil–Sen estimators, as a conservative alternative to tests on smoothed series; (v) recomputation of the ozone-production index from its published formula, decomposition of its production terms, and a sensitivity test applying the monthly cloud transmissivity (SSRD/SSRDC) to the HCHO photolysis term; and (vi) classification of the $HCHO/NO_2$ ratio using the standard published thresholds [18].

RESULTS AND DISCUSSION

Verification of Source Results

Most headline numbers could be re-derived (Table 2). The anomaly count (86 of 450 dry-season cell-months, 19.1%), the carbonaceous aerosol mean, the ozone-production index and its seasonal contrast, the AOD seasonal means, the 38% seasonal drop in SSRD, and the raw and deseasonalised AOD–SSRD correlations were all reproduced. Three problems emerged. First, the $HCHO/NO_2$ regime labels in the ozone paper are reversed relative to the standard interpretation: ratios below 1

indicate NO_x-saturated (VOC-limited) conditions and ratios above 2 NO_x-limited conditions [18], whereas the source labelled ratios below 1 as NO_x-limited. Second, the very small p-values for AOD and SSRD trends in the solar paper come from tests on a smoothed trend component; tests on annual means are not significant (Table 2). Third, the wind-speed contrast between anomaly and normal months differs slightly from the published values (3.88 vs 5.64 m s^{-1} here against 3.68 vs 5.55 reported), with the same sign and similar magnitude;

Table 2: Re-derivation of key source results from repository data.

Quantity	**References**	**Reported**	**Re-derived here**	**Status**
Anomalous dry-season cell-months	[4]	86 / 450 (19.1%)	86 / 450 (19.1%); by month Nov 19, Dec 17, Jan 18, Feb 19, Mar 13	Reproduced
Mean carbonaceous aerosol (BC+OC, 925 hPa)	[4]	55.5 µg m^{-3}	55.5 µg m^{-3}	Reproduced (a species-mean entry in A's table appears inconsistent with this total)
925 hPa wind speed, anomaly vs normal months	[4]	3.68 vs 5.55 m s^{-1}	3.88 vs 5.64 m s^{-1}; difference −1.75 (95% CI −2.28 to −1.24)	Same direction; small numerical gap unresolved
Ozone-production index, mean; Nov–Mar vs Apr–Oct	[5]	5.26; 3.68 vs 6.39	5.25; 3.68 vs 6.39	Reproduced
HCHO/NO_2 regime labels	[5]	Ratio <1 "NO_x-limited"	Ratio <1 is NO_x-saturated; cells: 8 transitional, 1 NO_x-saturated	Labels reversed in source; standard reading used here
AOD, Nov–Mar vs Apr–Oct	[5, 6]	0.39 vs 0.41	0.393 vs 0.406	Reproduced
SSRD seasonal drop (March peak to August minimum)	[6]	38%	38.4%	Reproduced
AOD–SSRD correlation, raw; deseasonalised	[6]	0.454; 0.032	0.454; 0.032 (block-bootstrap interval −0.15 to 0.17)	Reproduced

Quantity	References	Reported	Re-derived here	Status
AOD and SSRD trends	[6]	−0.098 per decade; +9.9 W m^{-2} per decade ($p < 0.001$, smoothed series)	Annual means: AOD τ = −0.42, p = 0.11; SSRD τ = 0.33, p = 0.22	Significance not robust
November–March NO_2 trend	[4]	τ = 0.556, p = 0.048 (925 hPa)	τ = 0.556, p = 0.045 (lowest model level); CO, BC+OC, HCHO not significant	Borderline; one of several tests

Seasonal Structure

Near-surface smoke-related tracers peaked in the late wet-season-to-dry-season transition and early dry season (Figure 1): BC+OC and NO_2 in November, CO in October at the lowest model level, and HCHO in March. Table 3 shows that all four were lower in April–October than in November–March (CO −19%, NO_2 −37%, BC+OC −34%, HCHO −10%). The CO peak in October at the lowest model level differs from the late dry-season rise at 925 hPa described in the biomass-burning paper [4] this vertical or definitional difference is unresolved. Modelled dust peaked in February and was 70% lower in April–October. AOD at 550 nm behaved differently: it peaked in March–April, was lowest in November and was essentially the same in the two seasons (+3%). Surface solar radiation was 15% lower in April–October, with cloud transmissivity falling from 0.975 to 0.754 and 925 hPa relative humidity rising from 24% to 71%, Modelled near-surface ozone was 25% higher in November–March.

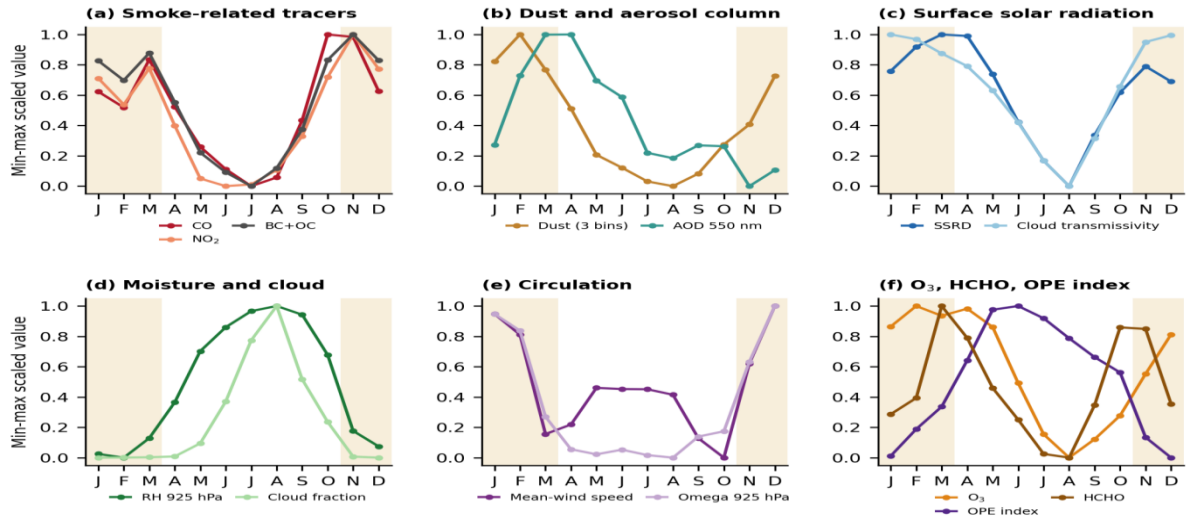

Figure 1: Calendar-month climatologies of domain-mean fields, each scaled to its own minimum (0) and maximum (1) to compare timing, not magnitude. Shading marks November–March. Source: CAMS EAC4 and ERA5 data from the authors' repositories. Mean-wind speed is the magnitude of the monthly-mean 925 hPa wind vector.

Table 3: Seasonal means of domain-mean fields (2015–2024) and calendar month of maximum. Composition fields are modelled; relative change is shown because absolute levels are model- and level-dependent.

Variable	Nov – Mar	Apr – Oct	Change, Apr – Oct vs Nov – Mar	Peak month
CO (lowest model level)	—	—	−19%	October
NO_2 (lowest model level)	—	—	−37%	November
HCHO (lowest model level)	—	—	−10%	March
O_3 (lowest model level)	—	—	−20%	February
BC + OC	—	—	−34%	November
Dust (three bins)	—	—	−70%	February
AOD at 550 nm	0.393	0.406	+3%	April
SSRD (W m^{-2})	263.8	224.5	−15%	March
Cloud transmissivity (SSRD/SSRDC)	0.975	0.754	−23%	January
RH at 925 hPa (%)	23.8	71.2	+199%	August
Mean-wind speed, 925 hPa (m s^{-1})	5.36	2.95	−45%	December
Ozone-production index	3.68	6.39	+74%	June

Meteorological Association with Smoke Tracers and Dust

After removing the calendar-month means, anomalies of smoke-related tracers were strongly and consistently anti-correlated with 925 hPa wind speed (Figure 2). In November–March, CO (ρ = −0.85, 95% interval −0.92 to −0.73), BC+OC (−0.82), HCHO (−0.80) and NO_2 (−0.63) all had intervals excluding zero; the relationship persisted across all months (ρ = −0.58 to −0.72). Anomalies in temperature were positively associated with the same tracers (ρ = 0.68–0.82 in November–March) and anomalies in vertical motion were negatively associated (ρ = −0.61 to −0.85), but wind speed, temperature and vertical motion are themselves strongly inter-related, so the evidence supports regulation by a bundle of calm, warm anomalies rather than by any single variable. Dust had the opposite sign: positively associated with wind speed (ρ = +0.67 in November–March, +0.33 across all months). Ozone and AOD showed no association with these predictors in November–March (intervals include zero). These associations are drawn from model fields whose dust and composition respond to modelled meteorology by construction, so they show consistency with the hypothesis, not independent observational proof.

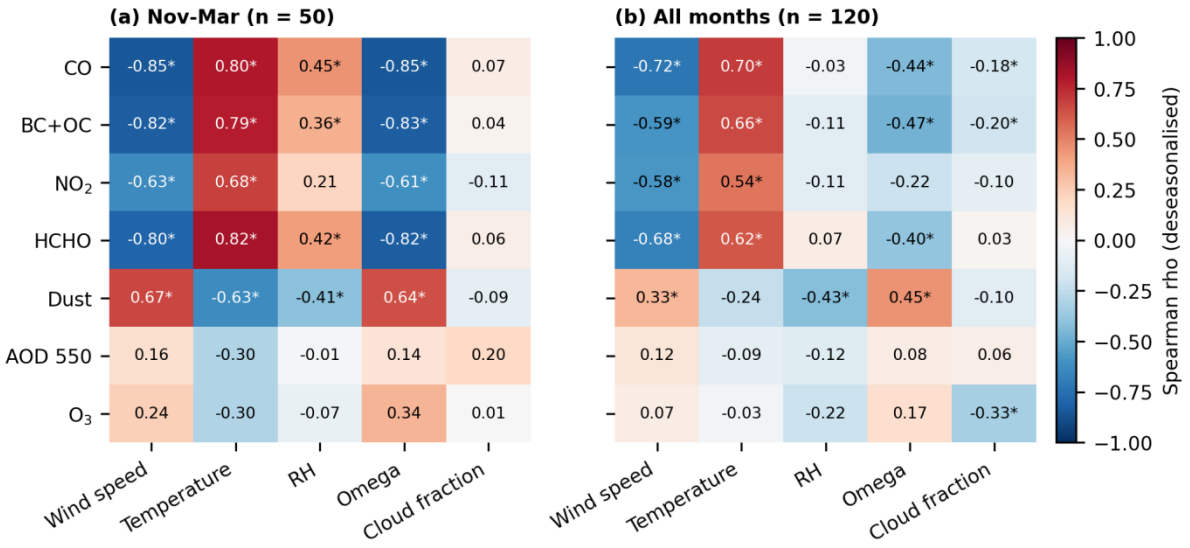

Figure 2: Spearman correlations between deseasonalised monthly anomalies of reanalysis composition fields (rows) and meteorological predictors (columns), (a) November–March and (b) all months. Asterisks mark 95% moving-block bootstrap intervals that exclude zero. Predictors are strongly inter-correlated; see text.

Aerosol Column and Surface Solar Radiation

AOD anomalies were closely tied to dust (deseasonalised ρ = 0.76, 95% interval 0.67–0.83) and unrelated to carbonaceous aerosol (ρ = 0.07, interval −0.15 to 0.31) or CO (ρ = −0.12); the association with NO_2 was weakly negative (−0.26). Nothing in these monthly fields supports the idea that smoke-related pollution raises AOD at monthly scale. In the SSRD record, cloud transmissivity and humidity dominate: the raw AOD–SSRD correlation (0.454) vanishes after deseasonalisation (0.032, interval −0.15 to 0.17). This null result must be read with care. If, as ECMWF documentation for earlier versions of its forecasting system indicates, the ERA5 radiation scheme uses a fixed aerosol climatology rather than the time-varying CAMS AOD (to be confirmed for ERA5 itself), ERA5 SSRD cannot respond to aerosol variability and the null result tests nothing about the real atmosphere. The only cloud variable in the source analysis is the 925 hPa cloud fraction (mean 0.017), which cannot represent total cloud cover. Aerosol–radiation interaction in Kaduna is therefore unresolved, not shown to be weak.

Ozone-Production Index and Regime

The ozone-production index in the source study equals the ratio of HOx production from CO oxidation and HCHO photolysis to NO_2 loss by reaction with OH. Because OH appears in both numerator (CO term) and denominator, the index reduces largely to a CO/NO_2 ratio: its Spearman correlation with molar CO/NO_2 is 0.96, and the CO term supplies 75% of production in November–

March and 58% in April–October (Figure 3b). The index is a derived, modelled quantity, not a measurement of ozone produced per NO_x oxidised. Its seasonal pattern (lowest in December, highest in June; 74% higher in April–October) therefore reflects mainly the seasonal behaviour of CO and NO_2 and of HCHO.

The source calculation of photolysis uses solar geometry and a small aerosol correction but no cloud term. Applying the monthly cloud transmissivity (0.975 in November–March, 0.754 in April–October) to the HCHO photolysis term lowered the April–October mean index from 6.38 to 5.63, left November–March almost unchanged (3.66 to 3.63), shifted the seasonal maximum from June to May, and reduced the seasonal contrast from 74% to 55% (paired test across years, $p < 10^{-6}$ in both cases; Figure 3). The seasonal contrast therefore survives but is smaller; this is a sensitivity analysis, not a corrected estimate, because OH and other photochemical terms were not re-derived. Under the standard HCHO/NO_2 thresholds [18], eight of nine grid cells have time-mean ratios in the transitional range (1.05–1.86) and one is NO_x-saturated (0.92); by grid-month, 52% of November–March months are transitional and 46% NO_x-saturated, while 72% of April–October months are transitional and 21% NO_x-limited. These thresholds were derived for satellite columns and may not transfer to model mixing ratios, so they are indicative only; the key point is that a single, fixed regime cannot be assigned to the Kaduna region and that conditions may change with season.

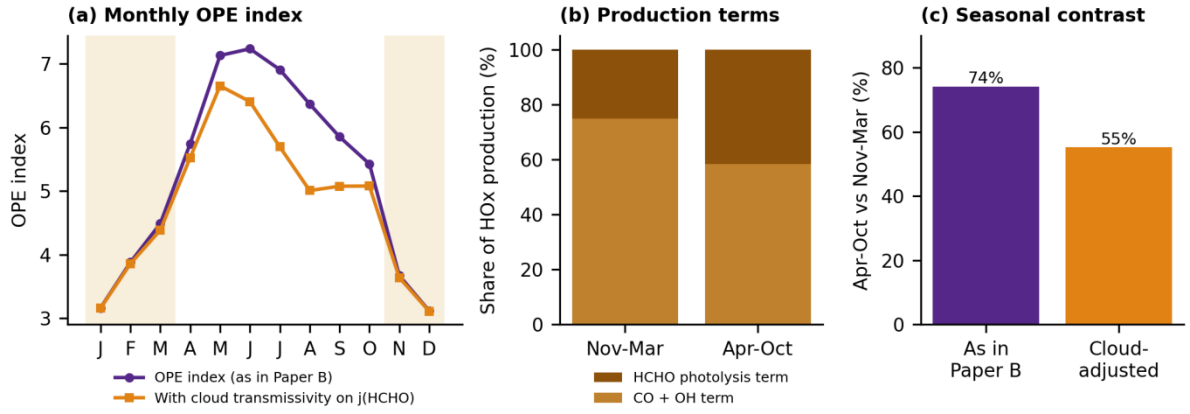

Figure 3: (a) Monthly ozone-production index as computed in the ozone paper and with cloud transmissivity applied to the HCHO photolysis term; (b) share of HOx production from the CO + OH and HCHO photolysis terms by season; (c) seasonal contrast (April–October relative to November–March). Sensitivity analysis only.

Trends

At annual resolution, no trend reached significance: AOD $\tau = -0.42$ ($p = 0.11$), SSRD $\tau = 0.33$ ($p = 0.22$), CO $\tau = 0.42$ ($p = 0.11$) and NO_2 $\tau = 0.29$ ($p = 0.29$). In November–March seasonal means ($n = 9$), only NO_2 showed a borderline increase ($\tau = 0.56$, $p = 0.045$; Theil–Sen +2.4% of the mean per season), alongside non-significant changes in CO, BC+OC, HCHO, AOD and wind speed. With ten years, reanalysis inhomogeneity (changes in assimilated observations are one possibility) and several parallel tests, these results do not support statements that air quality in the Kaduna region is improving or worsening.

Figure 4 sets out the proposed interactions, and Table 4 grades each link against the evidence. The best-supported statement is about ventilation: in the dry season, months with weaker, warmer, calmer flow have markedly higher near-surface CO, BC+OC, HCHO and NO_2 in the reanalysis. This agrees with the biomass-burning paper's finding that anomalous months have weaker winds [4] and with the physical expectation that dilution limits accumulation of emitted pollutants. It does not identify the source: the co-variation of CO, BC+OC and NO_2 is consistent with combustion, and CAMS fire emissions are satellite-derived, but without local source apportionment attribution to burning rather than household or urban combustion is an interpretation. The second robust statement is seasonal: smoke tracers and dust are lower, cloud transmissivity lower and humidity higher in the wet season.

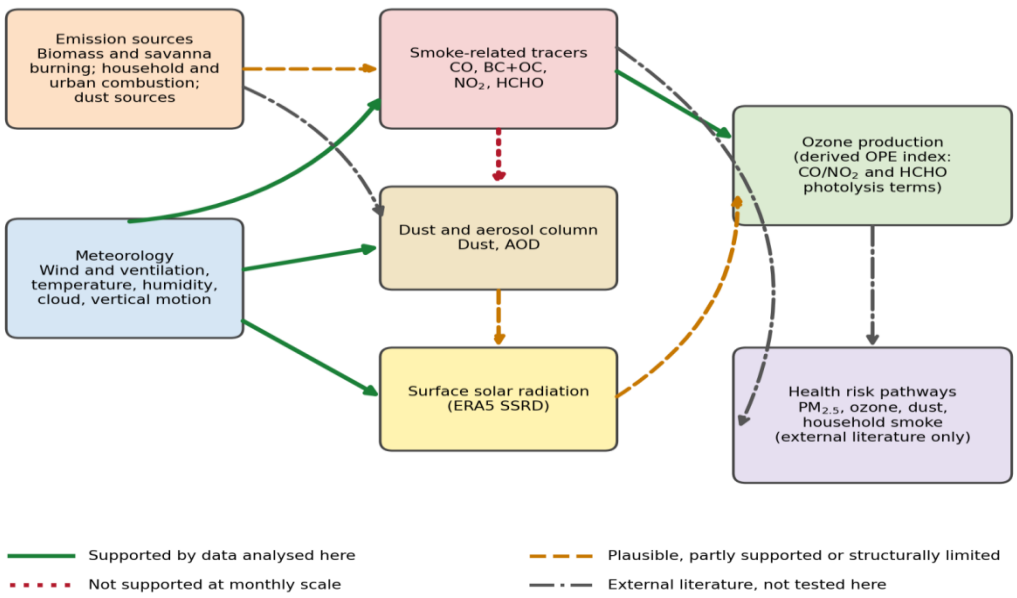

Figure 4: Conceptual framework of the interactions proposed in the source studies, with link styles showing the evidence grade assigned in this paper. This is a conceptual diagram of hypotheses and evidence, not a measured result.

Table 4: Link-by-link evidence assessment (grades: reported by a source paper; re-derived or new analysis here; external literature; integrated interpretation; plausible but unconfirmed; unsupported).

Proposed link	**Evidence**	**Grade**	**Main caveat**
Calm, warm anomalies → accumulation of smoke tracers	Weaker winds in anomalous months [4]; ρ −0.63 to −0.85 in Nov–Mar (this study)	Re-derived / new; interpretation	Correlated meteorological bundle; model-based; monthly resolution
Burning and other combustion → smoke tracers	Co-variation of CO, BC+OC, NO_2, HCHO; emission characteristics [15]	Interpretation; plausible	No local source apportionment; shared model emission inputs
Stronger winds → dust	ρ +0.67 (Nov–Mar); Sahelian dust governed by transport [11]	New; mechanism unconfirmed	Model dust responds to modelled wind; transport not separated
Smoke tracers → AOD	AOD equal in both seasons; AOD tracks dust (ρ 0.76), not BC+OC (0.07)	Unsupported at monthly scale	Column vs near-surface; assimilated AOD; monthly means
Cloud and humidity → surface solar radiation	Transmissivity 0.975 → 0.754; SSRD −38% March to August [6]	Reported; re-derived	925 hPa cloud variable weak; reanalysis, no ground validation
Aerosol → surface solar radiation	Anomaly r = 0.03 [6]	Cannot be tested here	ERA5 may not use time-varying aerosol (to be confirmed)
Cloud / solar radiation → photolysis → ozone production	Cloud-adjusted index lowers seasonal contrast 74% → 55%	Plausible; sensitivity only	OH and other terms not re-derived
Precursors → ozone-production index	Index ≈ CO/NO_2 (ρ 0.96); CO term 58–75% of production	Re-derived	Derived index, not measured ozone production
Burning → ozone	Modelled O_3 25% higher in Nov–Mar, but index 74% lower; no source tagging	Plausible but unconfirmed	Transport, titration and precursor effects not separated
$PM_{2.5}$, ozone, dust, household smoke → ill health	WHO guidelines [8]; regional burden [8]; meningitis–dust [19, 20]	External literature	No Kaduna exposure or health data analysed

Aerosols, Radiation and Ozone

The proposed chain from burning to aerosol to reduced sunlight to suppressed ozone formation is not supported at monthly resolution. AOD follows dust rather than smoke tracers, its seasonal mean is flat, and the apparent absence of an aerosol effect on SSRD may be an artefact of how ERA5 treats aerosol. By contrast, cloud is clearly the first-order control on surface sunlight, and the cloud-sensitivity result suggests that ignoring cloud overstates the wet-season rise in the ozone-production index. Because that index is mostly a CO/NO_2 ratio, it should be read as a descriptor of precursor balance, not as evidence that the wet season produces more ozone. Modelled ozone itself is higher in the dry season, which is compatible with burning precursors, regional transport or other causes; the data analysed cannot separate them. Passive-sampler records of NO_2 and O_3 at African savanna sites [10] illustrate the kind of continuous surface observation needed to test the reanalysis.

Rural and Urban Settings and Seasons

The evidence supports different emphasis by setting. In agriculture-dominated rural areas, dry-season burning and household solid-fuel use are the credible dominant sources [14-16] while in urban and industrial Kaduna the only local source apportionment found residual-oil combustion, soil and dust and vehicles [7], with regulated but unquantified contributions from generators and open burning [12]Dust affects both settings in the dry season. In the wet season, higher humidity and cloud and lower modelled smoke tracers imply less accumulation of combustion pollutants, but sources such as household cooking continue, and the index-based argument that ozone production is greater is weak. and from domain-wide reanalysis; the Kaduna data cannot quantify rural versus urban contributions, and the north-east cell sometimes labelled urban in a source paper does not contain Kaduna city, which lies nearer the domain centre.

Table 5: Synthesis by setting and season. Sources and exposure statements come from external literature; atmospheric statements are reanalysis results from this study. Strength of evidence for Kaduna is limited throughout.

Setting and season	Credible dominant sources	Atmospheric regulation (this study)	Exposure and health relevance	Priority actions
Rural, dry (Nov–Mar)	Burning of savanna and crop residues; household solid fuels; dust [14-16]	Calm, warm anomalies raise smoke tracers (ρ up to −0.85); RH about 24%; cloud transmissivity 0.975; dust rises with wind	Largest combined load: household plus ambient smoke plus dust; seasonal dust–meningitis link in Niger (20)	Burn calendar and community fire management; clean cooking; dust and stagnation advisories; ground monitors
Rural, wet (Apr–Oct)	Household solid fuels continue; burning and dust much reduced	Modelled smoke tracers 10–37% lower and dust 70% lower; RH about 71%; transmissivity 0.754	Household smoke likely remains the main source of exposure	Sustain clean-fuel access; measure kitchen and ambient $PM_{2.5}$ in both seasons
Urban and industrial, dry	Industrial combustion, traffic, road and soil dust [7]; generators and open burning (regulated, unquantified) [12]; transported smoke (unconfirmed)	Same stagnation association; reanalysis cannot resolve the urban scale	People near sources and roads; industrial workers; sensitive groups during dust and smoke	Enforcement of generator, vehicle and stack rules; fence-line monitoring; stagnation advisories
Urban and industrial, wet	Same local sources persist	More dilution and removal likely (seasonal contrast measured in Ibadan (9); ozone-index interpretation unresolved	Local source exposure persists; ozone burden unmeasured	Continued enforcement; start surface ozone, NO_2 and VOC measurements

Season-by-Season Interaction Pathways

Taken together, the evidence supports the following interpretation, which remains a set of graded hypotheses. In the dry season, weak, warm and calm flow, low humidity (about 24%) and near-clear skies (cloud transmissivity 0.975) coincide with the highest near-surface smoke tracers and dust and with the largest modelled ozone. Meteorology here acts first on accumulation and transport: emitted CO, carbonaceous aerosol and NO_2 are poorly diluted, while stronger winds raise modelled dust. AOD, a column quantity, does not rise in step because it follows dust and is influenced by factors that near-surface tracers do not capture. In the wet season, high humidity (about 71%) and cloud (transmissivity 0.754) coincide with lower smoke tracers and dust, 15% less surface sunlight, and a higher ozone-production index that is mostly a precursor ratio and falls by a quarter of its seasonal contrast when cloud attenuation is included. The seasons therefore differ in what regulates exposure: ventilation and transport in the dry season, removal, cloud and humidity in the wet season. Sources that do not depend on season, notably household cooking and traffic, mean that low wet-season tracers in the reanalysis should not be read as low exposure everywhere.

Contradictions and Corrections

Three source interpretations are not carried forward. The reversed HCHO/NO_2 labels would turn an apparently NO_x-limited urban cell into a NO_x-saturated one, which reverses the policy implication; policy based on that regime classification is therefore dropped. The claim that biomass burning raises AOD is not supported by flat seasonal AOD and by AOD tracking dust. The significance of AOD and SSRD trends does not survive annual-mean testing. These differences should be resolved with the authors of the source papers before publication, including whether corrections to the source papers are required.

Health Implications

Health implications are therefore inferred from three lines of evidence: measured concentrations in Kaduna and comparable Nigerian settings, intervention and exposure studies, and the seasonal timing of the atmospheric drivers found here.

Fine particles: Measured $PM_{2.5}$ at Kaduna industrial sites and in Ibadan during Harmattan exceeded WHO guideline values by wide margins [7-9]. Africa-wide assessments attribute substantial disease and economic burden to air pollution [1]. Our results indicate that the atmospheric conditions favouring accumulation of combustion pollutants (calm, warm flow) are concentrated in November–March, so exposure risk is likely seasonal, with higher risk when ventilation is weakest; direct measurement is needed to confirm and quantify this.

Household air pollution: In a Nigerian suburban community, household air pollution was associated with respiratory symptoms in women and children [16], and national survey suggest solid-fuel cooking is far more common in rural than urban households [16]. Household sources are not captured by the reanalysis but probably contribute to exposure irrespective of season, and may be the largest contributor to personal exposure in rural homes. Intervention trials show that liquefied petroleum gas (LPG) stoves reduced $PM_{2.5}$ and black carbon exposure in pregnant women [21], but in the same multi-country trial, the intervention did not improve fetal growth outcomes [22]. Exposure reduction is therefore a necessary target but should not be promised to deliver specific health gains over short periods.

Dust and meningitis:. In Niger and across the African meningitis belt, dust and aerosols have been identified as strong predictors of the seasonality of meningitis [19,20]. Our results show that modelled dust in Kaduna peaks in February, in the middle of the dry season, and increases with stronger winds. The relevance to Kaduna is by analogy with Niger, an adjacent Sahelian country, not demonstrated here.

Ozone: Modelled ozone is higher in the dry season. Because the ozone-production index is not a measure of ozone burden and surface ozone was not measured, the health implication is limited to the need for surface measurements against WHO peak-season and 8-hour guideline values [8] Combined exposure to particles and ozone is plausible in the dry season but cannot be quantified here.

Timing and evidence gaps: The seasonal contrasts found here imply that surveillance and preparedness should concentrate on November–March for particles and dust, with year-round attention to household and workplace sources. The main evidence gaps are measured personal and ambient exposure in Kaduna, health-service data linked to air pollution episodes, and surface ozone; without them, burden estimates for Kaduna would be speculative and none is offered.

Who is most exposed? The available evidence as presented in Table 5 and the preceding paragraphs of this section points to women and young children in households that cook with solid fuels, people working near industrial sources and roads, and populations exposed to dust and smoke in the dry season.

Solutions, Policy and Recommendations

Where evidence is limited, the recommendation is to measure first. Targets are process or monitoring indicators; no pollution-reduction percentages are predicted because no relevant effectiveness evidence for Kaduna was found. Three principles follow from the results. First, validate before regulating: every atmospheric result here is modelled. Second, differentiate by season: the dry season (November–March) needs operational actions on ventilation-linked accumulation, burning and dust, while the wet season needs source controls that work independently of dilution (household fuels, traffic and industry). Third, differentiate by setting: rural interventions centre on fire management and household energy, urban and industrial interventions on enforcement and monitoring. Policy based on a NO_x-versus-VOC regime has been dropped, because the regime cannot be assigned from the present data.

Sequencing, Review and Decision Triggers

Actions can be phased by what the evidence already supports. Table 6 separates immediate operational steps from medium- and long-term measures and states what result would change each decision. Review should follow each dry season, when stations, advisories and burning indicators can be assessed together. Evidence that would change recommendations includes: ground data showing weak seasonality of $PM_{2.5}$ (reducing emphasis on dry-season advisories), source apportionment showing urban combustion rather than burning as the main dry-season source (shifting emphasis toward urban enforcement), and surface ozone and precursor measurements establishing a regime (permitting precursor-specific targets).

Table 6: Sequencing of actions and evidence triggers for review.

Horizon	**Actions**	**Evidence that would trigger revision**
Immediate (before the next dry season)	Agree stagnation-advisory protocol; begin monitor deployment and collocation; enforce existing burning, generator and vehicle rules; confirm $PM_{2.5}$ standard status	Early station data contradicting the modelled seasonal pattern
Medium term (1–3 years)	Scale the monitoring network; pilot burn calendar and community fire management; expand clean-fuel access with exposure tracking; link dust forecasts to health preparedness	Pilot results; source apportionment; household exposure measurements
Longer term	Adopt $PM_{2.5}$ standard and interim targets; design ozone policy only after one or more years of surface observations; combine reanalysis with ground data for forecasting	Established ozone-production regime; multi-year ground trends

Table 7**:** Policy and implementation matrix. Responsible bodies are proposed, not assigned and need confirmation by the institutions concerned.

Problem and evidence	**Intervention**	**Target (place, season)**	**Lead and partners**	**Implementation and indicator**	**Uncertainty**
No verified continuous ground data; all results modelled; $PM_{2.5}$ not in national schedule [12]	Establish a small, collocation-calibrated network: $PM_{2.5}$, PM_{10}, CO, NO_2, O_3 at Kaduna city, an industrial site and 2–3 rural or peri-urban sites; publish data	Year-round; dry-season focus	Federal Ministry of Environment, National Environmental Standards and Regulations Enforcement Agency (NESREA), state environmental authority; universities	Phased deployment; indicator: share of valid hourly data and public release; validation of reanalysis against stations	Cost, maintenance; sensor accuracy must be shown by collocation
Smoke tracers rise with calm, warm anomalies (ρ −0.63 to −0.85)	Dry-season stagnation advisories from weather and composition forecasts; link to temporary burning restrictions and health advice	Kaduna region, Nov–Mar	NiMet, state environmental authority, Ministry of Health	Advisory protocol agreed before season; indicator: advisories issued and verified against station data	Derived from monthly anomalies; daily skill untested
Dry-season burning is a credible source; open burning is regulated [12,14]	Coordinated burn calendar and community fire management; assess residue alternatives locally before scaling	Agricultural areas, Oct–Mar	State Ministry of Agriculture, local governments, community leaders, NESREA	Indicator: satellite burned area and fire counts in the domain each season	No local apportionment; effectiveness of alternatives not assessed here

Problem and evidence	**Intervention**	**Target (place, season)**	**Lead and partners**	**Implementation and indicator**	**Uncertainty**
Solid-fuel cooking dominant in rural homes [16]; exposure falls with LPG [21], health benefit not shown in trial [22]	Expand clean-fuel access with financing and safe supply; monitor stove stacking; track exposure and health, not stove sales alone	Rural and low-income urban households, year-round	Federal and state energy and health ministries; development partners	Indicator: share of households primarily using clean fuel; kitchen $PM_{2.5}$ in a sample	Northern data absent; affordability; continued use of solid fuels
Industrial and traffic sources in Kaduna [7] generator and vehicle rules exist [12]	Enforce generator registration and emission testing, vehicle inspection and industrial stack monitoring; fence-line and road-dust measurements	Industrial zones and corridors, year-round	NESREA, state environmental authority, industry operators	Indicator: inspections, compliance rates, fence-line PM	Current compliance data unavailable; shares are site-specific and dated
Dust peaks in the dry season; dust is a recognised meningitis predictor in Niger [20]	Use dust forecasts to inform health-system preparedness and outdoor-activity advisories	Whole region, Nov–Mar	State Ministry of Health, disease-control and meteorological agencies	Indicator: lead time of alerts; surveillance link to incidence	Evidence from Niger, not shown for Kaduna
Ozone-production regime cannot be assigned; modelled O_3 higher in dry season	Do not set NO_x- or VOC-specific targets now; measure surface O_3, NO_2 and HCHO or VOC for at least one year	Kaduna city and downwind rural site, year-round	NESREA, universities	Indicator: days above WHO 8-h guideline (WHO, 2021)	Needs observations before policy design
National schedule lacks $PM_{2.5}$; WHO guidelines stricter [8,12]	Confirm legal status; adopt a $PM_{2.5}$ standard with interim targets	National, with Kaduna pilot reporting	Federal Ministry of Environment, NESREA	Indicator: published standard; stations reporting against it	Statutory text to be confirmed by legal review

RECOMMENDATIONS FOR DECISION-MAKERS

i. In the dry season (November–March), when winds are weak and warm, smoke-related pollutants in the Kaduna region build up; in the wet season they are lower.

ii. Dust is highest in the dry season.

iii. Sunlight at the surface is controlled mainly by cloud and humidity; we could not show that smoke or dust change it.

iv. The data used are computer reanalysis, not measurements, so ground monitoring is the first priority.

v. Smoke from cooking fires in homes and from burning of vegetation, together with industry and traffic, are the sources most relevant to action; the evidence supports advisories, fire and household-fuel measures, enforcement of existing rules and dust-season health preparedness, not ozone-precursor targets.

LIMITATIONS AND UNCERTAINTY

All atmospheric results come from reanalysis (CAMS EAC4 and ERA5) with nominal 80 km resolution, no ground validation, monthly resolution and ten years of record. CAMS composition fields respond to modelled meteorology and to assimilated observations whose streams may change, so associations may partly reflect model physics. Anomalies are domain means; correlated predictors preclude attributing effects to single meteorological variables; and the moving-block bootstrap only partly accounts for dependence. The designation of model level 60 as the lowest level should be confirmed against EAC4 documentation. The treatment of aerosol in ERA5 radiation has been indicated by ECMWF sources for earlier model versions but not confirmed for ERA5, and the vertical level of the aerosol fields was not documented. The ozone-production index is a derived diagnostic, and the standard $HCHO/NO_2$ thresholds were developed for satellite columns. No source apportionment, land-use data, exposure data or health outcomes for Kaduna were analysed; all health and rural–urban statements rest on external literature, which for northern Nigeria is sparse, and part of the cited evidence comes from other Nigerian regions or from Niger. The literature search was targeted, not systematic. Machine-learning results in the source papers were not used. Two unresolved numerical differences with the source papers (the wind-speed contrast and the vertical difference in CO seasonality) require access to the original files.

CONCLUSION

In the Kaduna region, the strongest evidence for meteorological regulation is the dry-season dependence of near-surface smoke-related pollutants on calm, warm flow, with dust behaving oppositely; this is consistent across variables but rests on reanalysis. The proposed links from smoke to aerosol optical depth to surface sunlight to ozone production are not supported at monthly scale, partly for structural reasons: AOD follows dust, ERA5 solar radiation is governed by cloud and humidity and may not respond to aerosol, and the ozone-production index mainly reflects CO and NO_2. Health risk is therefore best framed as seasonal and source-specific: highest in the dry season when ventilation is weakest and smoke and dust are present, and persistent in households and workplaces with direct sources. The evidence justifies prioritising ground-based monitoring and validation, dry-season stagnation advisories, coordinated open-burning and household-fuel measures, enforcement of existing emission rules, and dust-season health preparedness, while withholding ozone-precursor targets until surface observations exist.

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