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Observation-Constrained Assessment of Aerosol Radiative Forcing and Atmospheric Heating in Representative Climatic Zones of Nigeria: A Systematic Review

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ABSTRACT
Uncertainties associated with aerosols continue to represent a major contributor to uncertainty in climate projections over West Africa. Climatic gradient in Nigeria, varying from the dry Sahel zone to the wet Guinea Coast, leads to formation of aerosols through Saharan dust deposition, biomass burning, and human emissions. This PRISMA 2020 systematic review synthesizes peer-reviewed articles published from January 2014 until August 2026 on aerosol radiative forcing and atmospheric heating over climatic zones in Nigeria based on ground observations, satellite retrievals, reanalysis products, and radiative transfer simulations. Out of 312 articles screened through Web of Science, Scopus, and Google Scholar databases, only 18 articles fulfilled the inclusion criteria. Aerosol optical depth reached maximum values in the Harmattan season for all zones, where the highest amount of dust occurred in the Sahel and Sudan savanna. Radiative transfer simulations consistently revealed top-of-atmosphere cooling, surface dimming, and 15–35 W m^{-2} atmospheric heating in the dry season. Satellite products, mainly MODIS, usually tended to overestimate aerosol optical depth compared to the Ilorin AERONET station, particularly during the wet season, and reanalysis products (MERRA-2, ERA5) were still largely model-dependent for emissions and aerosol transport. The primary deficiency consists of the almost complete absence of long-term ground observations in any sites except for the one (Ilorin) and the lack of joint evaluations of ground-based, satellite-based, reanalysis, and radiative transfer datasets in a certain time period and location. An observation-driven framework based on a combination of validation of ground observations, satellite, and reanalysis products as well as inputs for radiative transfer is proposed as a way to reduce uncertainties in regional climate analyses in Nigeria.

INTRODUCTION

This is because aerosols affect the amount of radiation in the atmosphere through scattering and/or absorption, thus changing the radiative balance. This effect is influenced by a number of factors other than concentration, such as the aerosol size, aerosol chemical composition, absorption/scattering efficiency, height of the aerosol layer, surface albedo, moisture, and clouds. Therefore, estimation of the aerosol radiative effect is a complicated task and requires careful evaluation of different factors that determine its value, especially when in-situ ground-based measurements are unavailable.

As a result of seasonal movement of the Intertropical Discontinuity, Nigeria experiences two seasons that are very different in aerosol content and type: the dusty Harmattan season and the rainy monsoon season. In addition, Nigeria is located at the crossroads of important aerosol transport routes.

Saharan/Sahelian mineral dust is transported towards south during the dry season and forms the major aerosol layer of northern Nigeria. Central Nigeria experiences seasonal mineral dust transport alongside with the transport of biomass-burning plume originated in the savanna region. Southern Nigeria is under the marine influence and features high relative humidity, frequent cloud cover, and important emission sources such as gas flares in the Niger Delta region. Therefore, aerosol composition changes both spatially and temporally, and its radiative effect varies in each zone: the Sahel experiences only the effect of mineral dust, while the Guinea coast – of the mixture of dust, smoke, marine and urban aerosols.

These climatic characteristics have immediate implications for the radiative forcing of the atmosphere since mineral dust strongly scatters solar radiation; however, some components of mineral dust absorb the radiation as well. On the other hand, carbonaceous aerosols emitted by biomass burning/burnout processes strongly absorb radiation. Thus, the aerosol layer may cool the surface by reducing the amount of radiation while simultaneously heating up the atmospheric layer in which the absorption takes place. This feature is crucial for analysis of the regional atmospheric stability and boundary-layer formation, but it is commonly represented by the column-average forcing value in the literature.

There are four main types of data sources that allow characterisation of this effect. First, there are ground observations, provided by the Aerosol Robotic Network (AERONET). Second, there are satellite data (MODIS, MISR, etc.). Third, there are reanalysis products (MERRA-2, ERA5, etc.). Finally, radiative transfer model calculations (SBDART) convert the aerosol/atmospheric properties into values of the radiative fluxes/heatings. These four types of sources are complementary to each other, yet each of them is characterized by uncertainties, and only a few Nigerian studies use all of them. Ground-based AERONET measurements provide the reference record for column aerosol optical properties (Holben et al., 2001; Giles et al., 2019), while satellite products require validation against such observations (Remer et al., 2005; Sayer et al., 2013).

Problem Statement

Studies on aerosols over Nigeria have been increasing continuously, though the knowledge base is still quite dispersed. The majority of the research focuses either on one specific location, one specific period of time, or on one type of observation, that is, estimating aerosol optical depth through either ground or satellite observations without further investigation into radiative forcing or atmospheric heating or carrying out radiative transfer computations without proper verification using ground-based data. This problem is even more acute for those climatic zones where ground-based observations are not available in the long run since satellites and reanalysis data products may provide coverage though their uncertainty needs to be estimated first.

Aim

The aim of this review is to evaluate the literature on the radiative effects and atmospheric heating through aerosols in climatically representative areas of Nigeria, applying an observation-based approach that combines ground-based observations, satellite retrievals, reanalysis data, and radiative transfer modeling.

Specific Objectives

The review aims at:

i. Evaluating the state of the evidence regarding the optical characteristics of aerosols within the climatic zones of Nigeria;
ii. Evaluating the role of in-situ, satellite, and reanalysis data in characterising aerosols;
iii. Evaluating the use of radiative transfer modelling in quantifying aerosol forcing and atmospheric heating;
iv. Identifying key uncertainties and limitations of methods used in previous research; and
v. Proposing an integrated, observation-based approach for future assessment.

Review Questions

This review covers five aspects:

i. How have the aerosol optical properties in Nigeria been described in current literature?
ii. What insights can be drawn from ground-based observations, satellite observations, and reanalysis with respect to the spatial and seasonal variability of aerosols in Nigeria's climatic zones?
iii. How has radiative transfer modelling been used to determine radiative forcing and heating rates in the atmosphere?
iv. What have been the major differences between various data sets?
v. What observations should be made to improve the accuracy of future estimations of aerosol forcing in Nigeria?

MATERIALS AND METHODS

Review Design

This research was carried out as a systematic review in accordance with the PRISMA 2020 reporting guidelines for evidence-based practices, which gives a structure for evidence searching, selection, evaluation, and reporting (Page et al., 2021). This systematic review was conducted according to the concept of aerosol radiative forcing and atmospheric warming constrained by observation rather than aerosol concentration and optical depth alone.

Review Period

The period between which evidence was collected spanned from January 2014 to August 2026, covering over a decade's worth of research and development in satellite aerosol data products, AERONET quality control (Version 3), reanalysis (MERRA-2, ERA5), and radiative transfer techniques. Key methodological literature prior to 2014 was included only if essential for explaining an existing technique or model.

Literature Search Strategy

The databases of Web of Science, Scopus, and Google Scholar were searched with keywords that include combinations of "Nigeria" with "aerosol optical depth", "aerosol radiative forcing", "atmospheric heating", "AERONET", "MODIS", "MISR", "CALIPSO", "MERRA-2", "ERA5", and "radiative transfer model". The results from the relevant studies conducted on the West African region, where their results had a physical applicability for Nigeria, were also reviewed.

Eligibility Criteria

The studies considered eligible for the evidence synthesis were those that investigated aerosol optical properties, interactions between aerosols and radiation, aerosol radiative forcing, or atmospheric heating over Nigeria or over West Africa where the findings were directly applicable to Nigeria's climate; used ground-based observations, satellite retrievals, reanalysis products, or radiative transfer models, preferably with observational validation; and provided evidence relevant to the review period. Methodological and foundational papers were retained separately where necessary to clarify the validity, uncertainty, or technical basis of datasets and models. Papers outside the geographical region of interest, pure modelling studies without observational relevance or validation, papers without an aerosol or radiation component, review papers, and air-quality papers without a radiative component were excluded.

PRISMA Screening and Evidence Synthesis

The systematic review was carried out in accordance with the PRISMA 2020 protocol for identification, screening, eligibility assessment, and inclusion. Out of 312 records retrieved from the three databases, 18 studies fulfilled all the substantive inclusion criteria and constituted the evidence base from which study-level data and findings were extracted for the synthesis. These 18 studies were classified by observation method, climatic zone, aerosol property studied, and radiative process. Data extracted included the location, climatic zone, data source, radiative transfer model or scheme (when applied), and reported AOD, top-of-atmosphere (TOA) and surface radiative forcing, and atmospheric heating rates. Methodological references, including Page et al. (2021) and other foundational dataset/model papers, were retained as supplementary references to explain PRISMA procedures and the validity, uncertainty, or technical basis of the methods and datasets; they were not counted among the 18 evidence-synthesis studies unless they also met the substantive inclusion criteria. Given the considerable heterogeneity of studies in location, timeframe, aerosol type, forcing retrieval method, and definition of forcing, statistical meta-analysis was deemed unsuitable; the synthesis therefore characterizes and interprets the evidence within its original context.

Observation-Constrained Framework

The review is based on an explicit observation-constrained approach in which measurements on the ground are the key constraint for satellite and reanalysis data. The validated satellite data are used to extrapolate the aerosol information beyond ground sites, the reanalysis is checked by the observational record and provides continuous meteorological fields, and the radiative transfer models are used to quantify the radiative impacts of aerosols at the surface, within the atmosphere and at the top of the atmosphere, using the best-constrained inputs of aerosol and atmosphere data. Uncertainty quantification is one of the key elements of the observational-constrained approach, and uncertainty may come into play through the aerosol optical depth, aerosol single scattering albedo, aerosol layer height, aerosol size distribution, surface albedo, atmospheric water vapour, and cloud contamination, among others. This multi-source strategy is consistent with recommendations to reduce aerosol-forcing uncertainty by combining observations with model information (Kahn et al., 2023).

RESULTS AND DISCUSSION

Overview of the Evidence

The existing literature demonstrates the increasing use of various observation systems for the study of aerosols over Nigeria and West Africa, although the number of studies using several data sources is smaller compared to those that use only one data source. The most convincing body of literature is associated with the assessment of the aerosol optical depth (AOD) seasonality; however, there is a lack of literature about the direct radiative forcing and vertical warming of the atmosphere, while the joint analysis is rare.

Ground Observation Evidence

Ilorin AERONET station offers by far the most extensive and significant ground-based aerosol record in Nigeria. Yusuf et al. (2021) examined long-term records of this station and found that the coarse mode aerosol prevails in the total regional aerosol burden (76% occurrence rate), while the fine mode aerosol makes up the rest 24%. In addition, AOD is quite often greater than 1.0 during the dry season and experiences significant reductions during the wet season because of wet scavenging. Yusuf and Sa'id (2023) developed this study employing several observation methods in order to investigate the spatial variations of AOD in the tropics. The ground data constantly shows the strong seasonal variability: during the dry season mineral dust dominates, while in the wet season the particle features are quite different, and changes in wind direction and the source region influence the aerosol type, although AOD value remains close. The drawback of the ground record is its limited spatial coverage – one ground long-term record cannot cover northern, central, and southern Nigeria, which is a good reason to combine it with satellite AOD and reanalysis.

Satellite Retrieval Evidence

Satellite retrievals provide the spatial coverage needed to extend the limited ground-based record across Nigeria's climatic zones. MODIS has been widely used for aerosol optical depth (AOD) retrieval, while MISR and other satellite sensors provide complementary information on aerosol loading and properties. The MODIS aerosol algorithm and subsequent validation studies established the value of satellite AOD while also demonstrating retrieval uncertainty associated with surface reflectance, aerosol type, cloud screening, and other conditions (Remer et al., 2005; Sayer et al., 2013). The AERONET network remains an important reference for evaluating these satellite products because its ground-based measurements provide independent column-integrated aerosol observations (Holben et al., 2001; Giles et al., 2019). For West Africa, Ogunjobi and Awoleye (2019) reported differences between satellite and ground-based AOD retrievals across AERONET sites, demonstrating the need for site-specific validation. More directly relevant to the Nigerian Guinea Coast, Ibe et al. (2024) compared MODIS and AERONET observations and showed that satellite estimates should be interpreted in relation to the local ground record. The satellite evidence therefore supports national-scale assessment of seasonal and spatial aerosol variability, but it should not be treated as an observation-free measure of radiative forcing. Retrieval performance can vary with surface characteristics, humidity, aerosol type, cloud contamination, and the optical properties of the aerosol layer. Newer high-spatial-resolution retrieval approaches also offer opportunities to improve characterisation of aerosol and surface properties (Chen et al., 2024), but their application over Nigeria still requires appropriate validation. Overall, the evidence supports using satellite AOD primarily as a spatial extension of validated ground observations rather than as a substitute for them.

Reanalysis Evidence

Reanalyses are beneficial tools for bridging observational gaps, as they allow us to derive continuous fields of atmospheric and aerosol properties. In particular, MERRA-2 data are especially pertinent to the study of aerosols due to the representation of aerosol emissions, transport, and deposition in one consistent atmospheric model, whereas ERA5 (Hersbach et al., 2020) is a source of complementing meteorological information. MERRA-2 systematically overestimates AOD in some years and underestimates it in other years, whereas CAMS reanalysis reproduces the overall seasonal cycle but shows bias during dust episodes. The main strength of the reanalysis method is its temporal and spatial consistency, while its main weakness is its model dependency, as any errors related to emissions, transport, deposition, and aerosol optics will be reflected in the final aerosol fields. Comparison between multiple sources including AERONET, satellite products, and reanalysis results at Ilorin is a good example of how useful this methodology is – by doing so we can understand the source of any discrepancies, whether it is the algorithm itself, atmospheric model, or ground-based observation.

Radiative Transfer Modelling and Atmospheric Heating

Radiative transfer modeling is the stage that takes the optical properties of aerosols and transforms them into the estimates of their impact on radiation balance. The accuracy of such estimates is directly dependent on the quality of aerosol data used in radiative transfer modeling. For example, Adesina et al. (2018) estimated direct radiative forcing for the aerosol clusters that prevail in Ilorin: desert dust was found to produce the greatest radiative cooling at the top of atmosphere, the median direct radiative forcing value being −27.5 W m^{-2}, biomass burning aerosols demonstrated comparable magnitudes but higher forcing efficiency, and gas flaring aerosols, although having relatively low optical depth, were found to have the highest forcing efficiency, −37.0 W m^{-2} per unit of optical depth, showing one more highly efficient source of aerosols that is poorly accounted for in the Niger Delta region. Radiative effects calculated using GAME radiative transfer code by Korgo et al. (2021) for Ouagadougou agree well with the Nigerian case study data: the top-of-atmosphere forcing ranged from −6.77 to −2.56 W m^{-2}, the surface forcing from −10.25 to −41.00 W m^{-2}, the atmospheric heating rate peaked at 34.7 W m^{-2}. Using RegCM3 model to simulate radiative effects of aerosols during the DABEX and AMMA experiments in West Africa, Solmon et al. (2011) reported shortwave heating rates up to 0.4 K day^{-1} near 700 hPa level in the biomass burning layer; similar values were obtained using single-column radiative transfer calculation with Edwards-Slingo radiative transfer scheme. It is noteworthy that the estimation of shortwave heating was lower in case of too low extinction of smoke aerosol. Recently, Igbawua et al. (2025) used radiative transfer modeling to estimate the aerosol-induced atmospheric heating rates in Nigeria for 2000–2022. Thus, these papers provide a transition in the research agenda from the description of the aerosol loading in West Africa to the quantification of the energy injected in the atmospheric column by aerosols.

Evidence by Climatic Zone

It has been established that in the northern part of Nigeria (the Sahel and Sudan savanna), Saharan/Sahelian mineral dust is most likely the key source of aerosol pollution through much of the long dry period (lasting up to ten months and characterized by annual precipitation amounts less than 700 mm). The AOD in the area is typically higher than 1.5 for the duration of the maximum impact of the Harmattan winds. Central Nigeria represents an area where mineral dust is combined with regional biomass burning and other combustion aerosols leading to a heterogeneous aerosol mixture, in which aerosol particles may exert significant climate effects despite the fact that mineral dust is the main source of the total AOD. Southern Nigeria (Guinea savanna, rainforest, and coastal areas) is characterized by the influence of marine aerosols, high relative humidity, frequent cloud presence, as well as anthropogenic aerosols, including gas flaring, making both aerosol detection and calculation of the aerosol forcing problematic due to changes in aerosol optical properties caused by humidification and cloud screening.

Integrated Discussion

The evidence from the four source categories is most useful when interpreted as a complementary system rather than as independent estimates. Ground observations provide the local observational constraint and the reference against which satellite retrievals can be evaluated. Satellite observations then extend the validated aerosol signal across areas where long-term stations are absent, while reanalysis products provide temporally continuous aerosol and meteorological fields but remain dependent on their underlying emissions, transport, deposition, and aerosol schemes. Radiative transfer calculations translate these constrained aerosol and atmospheric properties into surface, atmospheric, and TOA radiative effects. This hierarchy is consistent with the broader recommendation that aerosol-forcing uncertainty is reduced when models, satellite observations, and within-atmosphere observations are evaluated together (Kahn et al., 2023). The climatic-zone evidence further shows why a single national aerosol representation is inadequate: northern Nigeria is strongly influenced by mineral dust, central areas experience mixtures of dust and biomass-burning/combustion aerosols, and southern and coastal areas are additionally affected by marine aerosols, high humidity, clouds, and anthropogenic sources. Consequently, differences among datasets should be interpreted in relation to season, aerosol type, surface conditions, and vertical distribution rather than treated simply as random disagreement. The final step should therefore be uncertainty-aware radiative transfer modelling using the best available observationally constrained inputs. In particular, aerosol absorption, single-scattering albedo, aerosol layer height, size distribution, water vapour, surface albedo, and cloud screening can materially influence the estimated forcing and heating. Methods for comparing aerosol effective radiative forcing likewise show that methodological choices can affect forcing estimates (Zelinka et al., 2023). An integrated framework that aligns the periods and locations of ground, satellite, reanalysis, and radiative-transfer datasets would consequently provide a more defensible basis for estimating aerosol radiative forcing and atmospheric heating across Nigeria.

Research Gaps Identified by the Review

There are several gaps which hamper the reliability of present-day estimates of radiative forcing of aerosols in Nigeria. The first one is that the number of ground stations which provide long-term data is limited to almost one (Ilorin). The second gap is that co-measurements of aerosol absorption and height are not provided at most sites. The third one is that satellite validation is much better for AOD than for radiative forcing and heating rate specifically. The fourth gap is that no systematic analysis based on climatic zones is provided: regional studies are performed for West Africa as a whole even though the north and south of Nigeria have quite different aerosols and meteorology, and a framework of the whole nation should maintain this distinction rather than use one aerosol dataset for the whole country. Another gap is that uncertainty quantification is far from adequate because the output of radiative transfer models can be quite precise even though their input is highly uncertain, and future studies should estimate how the uncertainties in AOD, absorption, height of aerosol layers, and surface parameters propagate into results. Finally, the gas-flaring aerosol category identified in Adesina et al. (2018) can be seen as a significant gap since Niger Delta emits considerable amounts of black carbon due to flaring but there is no long-term data about it.

CONCLUSION

This systematic review examined the literature on aerosol radiative forcing and atmospheric heating over representative climatic zones of Nigeria between January 2014 and August 2026. Applying the PRISMA 2020 framework, 312 sources were screened, and 18 publications were included in the final sample providing clear structuring of the literature and highlighting its strengths and limitations.

As the literature demonstrates, aerosols over Nigeria vary seasonally and spatially. Namely, mineral dust is prevalent over northern Nigeria in the dry season; biomass burning and urban emissions, among which gas flaring can be identified, create complex aerosol mixes over the central and southern parts of the country. In addition, all radiative transfer calculations performed by researchers indicate cooling of the top of atmosphere and surface and significant atmospheric heating ranging from

15 to 35 W m⁻² in the dry season, the vertical distribution of which has crucial importance for atmospheric stability and cannot be represented by one-column average forcing value.

Ground observations, primarily AERONET data from Ilorin, are invaluable and irreplaceable sources of information, but due to their limited coverage, satellite retrievals and reanalyses become mandatory for national and zone-based assessments. On the one hand, satellite observations can provide the necessary spatial perspective for climatic zone assessment, but on the other hand, their retrieval errors, in particular the systematic overestimation of AOD of MODIS in comparison with Ilorin AERONET, especially in the wet season, need to be estimated in light of ground observations before using the results. Reanalysis can give valuable temporal and spatial continuity but should never be considered an independent aerosol forcing source. At the same time, radiative transfer modeling serves as the physical basis for estimation of the forcing, but its accuracy depends on the accuracy of aerosol and atmospheric input data.

Therefore, the systematic review reveals an observation-constrained approach to be the most appropriate research path to continue the study of Nigerian aerosols – combining long-term ground observations with validated satellite retrievals and evaluated reanalysis before radiative transfer calculation and considering atmospheric heating as the separate parameter because of the climatic importance of its vertical distribution. In addition, the main research focus going forward should not be creating new studies on Nigerian aerosols but improving the interaction of observation and models – increasing the number of ground observation points in the Sahel and Sudan zones, conducting analysis in accordance with climatic zones, aligning analysis periods of different data sources and explicit uncertainty propagation would significantly increase the confidence of estimation of aerosol radiative forcing and atmospheric heating over Nigeria.

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