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INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY EDUCATIONAL RESEARCH
ISSN:2277-7881(Print); IMPACT FACTOR :10.16(2026); IC VALUE:5.16; ISI VALUE:2.286
PEER REVIEWED AND REFEREED INTERNATIONAL JOURNAL
(Fulfilled Suggests Parameters of UGC by IJMER)
Volume:15, Issue:1(3), January 2026
Scopus Review ID: A2B96D3ACF3FEA2A
Article Received: Reviewed: Accepted
Publisher: Sucharitha Publication, India
Online Copy of Article Publication Available: www.ijmer.in

ATMOSPHERIC AEROSOL DYNAMICS OVER COASTAL EASTERN PENINSULAR INDIA AND MARINE ADVECTION OUTFLOW ACROSS THE BAY OF BENGAL: A COMPREHENSIVE SYNTHESIS

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Abstract

Atmospheric aerosols over South Asia exert a profound influence on regional radiation budgets, mesoscale weather patterns, and the South Asian monsoon. The eastern coastal margin of peninsular India—anchored by the industrialized urban hub of Visakhapatnam (17.72° N, 83.32° E)—serves as a primary outflow platform for continental pollution advecting into the Bay of Bengal (BoB). This review synthesizes findings from multi-year observational campaigns and radiative transfer modeling (incorporating JGR 2012, Annales Geophysicae 2011, JESS 2008, and Atmospheric Environment 2012). Co-located chemical, optical, and physical measurements confirm that non-sea-salt (NSS) sulfate (SO_4^{2-}) and Black Carbon (BC) dictate composite aerosol radiative forcing. NSS-sulfate accounts for >90% of total sulfate mass, proving the preeminence of fossil-fuel emissions over natural marine DMS. Net shortwave Top-of-Atmosphere (TOA) forcing is controlled by surface BC concentrations and aerosol mixing states, with internal core-shell configurations during dry winter months amplifying BC absorption via lensing effects. Intensive optical characterization reveals an annual mean Single Scattering Albedo (SSA) of 0.76 ± 0.13 (mode ~0.80) and an asymmetry parameter (g) of 0.65 ± 0.10, confirming a strongly absorbing atmosphere. Micro Pulse Lidar profiling details boundary layer trapping during winter (mixed layer contributing up to 100% of column AOD) versus convective venting during summer, where elevated Arabian dust layers (1.6–5.0 km) decouple surface loadings from column optics. Crucially, multi-year satellite and cruise observations (W-ICARB) demonstrate that daily advection pathways induce large short-period AOD perturbations—affecting 65% of BoB cases—with eastern BoB dominated by East Asian plumes (79%) and western BoB by Indian continental outflow (98%). Long-term trends (2005–2010) show a steady increase in AOD over western BoB, contrasting with stable conditions over southern BoB.

Keywords: Atmospheric Aerosols, Black Carbon, Non-Sea-Salt Sulfate, Single Scattering Albedo, Boundary Layer Trapping, Bay of Bengal Outflow, W-ICARB Advection, Regional Climate Forcing.

1. INTRODUCTION

Quantifying the climatic influence of atmospheric aerosols remains one of the most critical challenges in global and regional climate change assessments [IPCC, 2007]. Tropospheric aerosols directly alter the Earth-atmosphere radiation budget through the scattering and absorption of solar radiation (direct radiative forcing) and indirectly modify cloud microphysical properties, optical depth, and lifetimes (indirect radiative forcing). Over the South Asian subcontinent, accelerated urbanization, rapid industrialization, intense agricultural burning, and fossil fuel consumption generate an intricate aerosol environment where anthropogenic species—such as Black Carbon (BC), Organic Carbon (OC), sulfates, and nitrates—interact dynamically with natural marine sea-salt and wind-borne desert dust.

Peninsular India presents a unique geographic and meteorological setting for aerosol-climate investigations. Bounded by the Arabian Sea to the west and the Bay of Bengal (BoB) to the east, the peninsula undergoes dramatic seasonal shifts in synoptic airmass advection. During the winter and pre-monsoon months (November through May), prevailing north-easterly and north-westerly continental winds advect dense plumes of anthropogenic pollutants from the Indo-Gangetic Plains (IGP) and central/eastern India across the eastern coastline into the Bay of Bengal. The coastal urban-industrial city of Visakhapatnam (17.72° N, 83.32° E; ~230 m asl), situated directly on the eastern sea margin (<500 m from the coast), acts as an essential observational platform for capturing aerosol physical, chemical, and optical transformations at this critical land-ocean transition.

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Over the past two decades, multi-year observational campaigns employing high-volume air samplers, multi-wavelength Aethalometers, integrating 3-color Nephelometers, Quartz Crystal Microbalance (QCM) impactors, ground-based Sun photometers, and Micro Pulse Lidars (MPL) have produced a wealth of observational data over this site [Niranjan et al., 2008, 2011, 2012; Spandana et al., 2012]. Furthermore, ship-borne cruises during the Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB in 2006 and Winter-ICARB in 2008–2009) have extended ground observations into the marine boundary layer across the entire Bay of Bengal.

This review paper provides an in-depth synthesis of these four foundational research publications, structuring the findings into a cohesive, physically rigorous framework. Specifically, this review addresses: (1) chemical speciation and the controlling role of BC and sulfate mass loadings on net composite radiative forcing; (2) seasonal and diurnal characteristics of intensive optical properties (Single Scattering Albedo and asymmetry parameter); (3) boundary layer trapping, mixing layer AOD contributions, and elevated long-range transport layers; and (4) advection-induced short-period optical depth perturbations, offshore spatial gradients, and multi-year trend dynamics across the Bay of Bengal.

2. AEROSOL CHEMICAL SPECIATION AND RADIATIVE FORCING CONTROLS

2.1 Chemical Composition and Non-Sea-Salt (NSS) Sulfate Dominance

Accurately partitioning light extinction among distinct chemical species requires detailed speciation of ambient aerosol mass. High-volume air sampler (HVS) measurements of Total Suspended Particulates (TSP) over Visakhapatnam yielded a multi-year mean TSP mass loading of 115 ± 37 μg m^{-3}, with total water-soluble ionic species (NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-}) contributing 30 ± 12 μg m^{-3} [Niranjan et al., 2012]. Sulfate (SO_4^{2-}) emerged as the single most abundant water-soluble ion across all seasons.

Because coastal urban atmospheres receive inputs from both natural ocean biological activity (dimethylsulfide, DMS) and anthropogenic fossil-fuel combustion (SO_2), separating total sulfate into sea-salt (SS) and non-sea-salt (NSS) components is essential. Using Sodium (Na^+) as a marine tracer, the mass of NSS-sulfate is derived via:

$$M\_nss(SO_4^{2-}) = M\_total(SO_4^{2-}) - (M\_SO_4^{2-} / M\_Na^+)\_sw \times M\_Na^+$$

where $(M\_SO_4^{2-} / M\_Na^+)\_sw$ represents the standard mass ratio in seawater (0.25). Chemical analysis demonstrates that non-sea-salt sulfate accounts for more than 90% of total sulfate mass across all seasons (Winter NSS-sulfate ~11.9 μg m^{-3} vs SS-sulfate ~0.7 μg m^{-3}; Summer NSS-sulfate ~9.2 μg m^{-3} vs SS-sulfate ~0.9 μg m^{-3}) [Niranjan et al., 2012]. This overwhelming dominance confirms that industrial emissions and fossil fuel combustion overwhelmingly surpass natural marine sources at this coastal interface.

2.2 Black Carbon (BC) and Sulfate Co-Variability

Near-surface Black Carbon mass concentrations, measured via 7-wavelength Aethalometer, show a strong positive linear correlation with anthropogenic NSS-sulfate mass ($R^2 > 0.75$) [Niranjan et al., 2012]. Because BC (a primary product of incomplete combustion) and NSS-sulfate (a secondary product of SO_2 oxidation) share industrial combustion origins, their daily mass loadings co-vary across the year. Winter months record peak BC concentrations (5–10 μg m^{-3}) due to shallow boundary layer compression and continental advection from northeastern India. Conversely, pre-monsoon and summer periods record lower BC concentrations (1–3 μg m^{-3}) driven by deeper convective boundary layer mixing [Niranjan et al., 2011, 2012]. Size-segregated Quartz Crystal Microbalance (QCM) measurements confirm that BC consistently constitutes 10–11% of total fine-mode ($Dp < 1.0$ μm) particle mass across all seasons, establishing that BC is thoroughly incorporated within the ambient fine aerosol matrix.

2.3 Radiative Forcing Controls and the Role of Aerosol Mixing State

To evaluate how individual chemical constituents govern net atmospheric energetics, optical properties reconstructed using the OPAC (Optical Properties of Aerosols and Clouds) model were coupled with the SBDART (Santa Barbara DISORT

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Atmospheric Radiative Transfer) model [Niranjan et al., 2012]. Under clear-sky conditions, top-of-atmosphere (TOA) composite shortwave radiative forcing generally tracks surface BC mass loadings. However, specific clear-sky anomalous episodes reveal that net composite forcing is heavily modulated by the aerosol mixing state (external vs. internal core-shell configurations) and ambient relative humidity (RH):

• Winter Internal Mixing Episode (18 January 2006): On January 18, surface sulfate mass loading doubled to 26 μg m^{-3} (dominated by ammonium sulfate, $(NH_4)_2SO_4$) [Niranjan et al., 2012]. Standard clear-sky radiative transfer models assuming external mixing predict a large negative (cooling) shift at TOA. However, radiative simulations revealed a twofold increase in positive BC TOA forcing. Under dry winter conditions, extended aerosol atmospheric lifetimes allow BC aggregates to become coated by a shell of non-absorbing sulfate. This core-shell internal mixture acts as a refractive lens, focusing incoming solar flux onto the absorbing BC core, thereby amplifying light absorption and counteracting sulfate cooling.

• Summer Hygroscopic Growth Episode (26 April 2006): On April 26, elevated sulfate mass (22 μg m^{-3}) was accompanied by strong marine winds and high ambient relative humidity [Niranjan et al., 2012]. Composite TOA forcing shifted toward net cooling. Because sulfate is strongly hygroscopic, high RH drives liquid water uptake, enlarging particle size and boosting light scattering cross-sections. Conversely, BC mass extinction efficiency is independent of RH. Lower ambient BC loadings in summer also reduce the probability of internal core-shell formation, allowing negative forcing from sulfate scattering to dominate.

• Elevated Dust Transport Episode (24 August 2006): On August 24, composite TOA negative forcing increased sharply without any change in surface BC or sulfate concentrations [Niranjan et al., 2012]. CALIOP/CALIPSO space-borne lidar profiles and HYSPLIT trajectory models confirmed an elevated layer of coarse mineral dust advecting from the Arabian desert at altitudes of 3–5 km. Optical depth spectra showed low Ångström exponent values ($\alpha = 1.225$), proving that elevated dust layers can completely decouple column radiative transfer from ground-level chemical loadings.

3. AEROSOL INTENSIVE OPTICAL PROPERTIES: SSA AND ASYMMETRY PARAMETER

3.1 Single Scattering Albedo (SSA) Characteristics

Integrating 3-color Nephelometers (measuring total scattering σ_sp) and multi-wavelength Aethalometers (measuring absorption σ_abs) allow direct determination of surface Single Scattering Albedo at 550 nm ($\omega = \sigma\_sp / (\sigma\_sp + \sigma\_abs)$) [Niranjan et al., 2011]. Over Visakhapatnam, surface SSA ranges between 0.65 and 0.90, with an annual mean of 0.76 ± 0.13 and a primary mode at 0.80. SSA values below 0.85 denote net atmospheric light absorption, implying that the aerosol layer induces localized radiative warming over the eastern coast.

Seasonal mean SSA values are: Winter (0.78 ± 0.05), Summer (0.75 ± 0.04), Monsoon (0.75 ± 0.06), and Post-Monsoon (0.76 ± 0.05) [Niranjan et al., 2011]. During winter and post-monsoon months, SSA exhibits a steep inverse relationship with surface BC mass loading and BC fine-mode mass fraction. When surface BC rises to ~9.4 μg m^{-3}, SSA drops to 0.65; as BC falls to ~1.5 μg m^{-3}, SSA rises to 0.90. In summer, SSA is modulated by mesoscale sea-breeze dynamics. Morning sea-breeze incursions bring humid marine air that promotes gas-to-particle conversion from local industrial precursor gases (SO_2, NOx), forming new nucleation-mode particles. Simultaneous sea-salt advection boosts total scattering, elevating SSA despite ambient BC loadings.

3.2 Asymmetry Parameter (g) and Particle Size Correlations

The asymmetry parameter (g), representing the cosine-weighted average of the angular scattering phase function, was derived from Nephelometer hemispheric backscatter fraction ($b = \sigma\_bsp / \sigma\_sp$) using the Henyey-Greenstein parameterization [Niranjan et al., 2011]:

$$g = -7.143889\, b^3 + 7.464439\, b^2 - 3.96356\, b + 0.9893$$

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The annual mean asymmetry parameter at 550 nm over Visakhapatnam is 0.65 ± 0.10. Radiative transfer sensitivity studies indicate that a 10% decrease in g corresponds to a 19% reduction in TOA forcing and a 13% reduction in surface forcing [Andrews et al., 2006; Niranjan et al., 2011].

During winter, g displays a strong negative correlation with columnar Ångström exponent α (R = -0.652 ± 0.022) and a positive correlation with accumulation-mode mass concentration (R = +0.246 ± 0.028) [Niranjan et al., 2011]. Furthermore, SSA shows a robust linear increase when plotted against particle geometric mean radius (R = +0.694). Larger accumulation- and coarse-mode particles scatter light primarily in the forward direction, increasing g and boosting SSA.

Table 1: Seasonal Summary of Aerosol Physical, Chemical, and Optical Parameters over Visakhapatnam

Parameter / Variable	Winter Season	Summer / Pre-Monsoon	Monsoon / Post-Monsoon	Annual Mean / Baseline
Total Suspended Particulate (TSP)	135 ± 28 μg m^{-3}	110 ± 32 μg m^{-3}	85 ± 22 μg m^{-3}	115 ± 37 μg m^{-3}
NSS-Sulfate Mass Loading	~11.9 μg m^{-3} (>94%)	~9.2 μg m^{-3} (>91%)	~7.8 μg m^{-3} (>88%)	~9.8 μg m^{-3}
Black Carbon (BC) Mass Loading	5.0–10.0 μg m^{-3}	1.0–3.0 μg m^{-3}	1.5–3.5 μg m^{-3}	~11% fine mass
Single Scattering Albedo (SSA @ 550nm)	0.78 ± 0.05	0.75 ± 0.04	0.75–0.76	0.76 ± 0.13 (Mode: 0.80)
Asymmetry Parameter (g @ 550nm)	0.62–0.70	0.64–0.68	0.63–0.67	0.65 ± 0.10
Aerosol Optical Depth (AOD @ 500nm)	0.45–0.55	0.58–0.75	0.32–0.50	~0.55
Mixed Layer AOD Contribution	35% to >90%	< 35%	< 30%	Variable by boundary height

4. BOUNDARY LAYER DYNAMICS AND ELEVATED LONG-RANGE TRANSPORT

4.1 Boundary Layer Trapping vs. Convective Venting

Continuous Micro Pulse Lidar (MPL) observations reveal strong seasonal shifts in vertical aerosol distribution [Niranjan et al., 2006, 2007, 2011]. In winter, lower surface temperatures and nighttime radiative cooling produce a shallow nocturnal boundary layer capped by strong inversions. Aerosols are trapped near the ground. Consequently, the atmospheric mixed layer accounts for 35% to nearly 100% of total column AOD. Under these boundary layer trap conditions, surface measurements of SSA, particle size, and BC mass correlate tightly with column-integrated optical depths.

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In contrast, intense summer solar heating drives strong vertical convection and high ventilation coefficients (product of mixing height and horizontal wind speed) [Niranjan et al., 2011]. Surface pollutants are diluted and vented into the upper troposphere. As a result, the mixed layer accounts for less than 35% of column AOD during summer.

4.2 Elevated Dust Layers

MPL backscatter profiles regularly show elevated aerosol layers between 1.6 km and 5.0 km altitude during summer [Niranjan et al., 2007, 2011]. Seven-day HYSPLIT back-trajectories confirm that ~60% of these elevated layers originate over the Arabian peninsula and desert regions, carrying coarse mineral dust across the Arabian Sea and peninsular India. On these days, low columnar Ångström exponent values ($\alpha \approx 0.5–0.8$) contrast with fine-mode-dominated surface size distributions, completely decoupling ground-level measurements from integrated column properties.

5. MARINE ADVECTION OUTFLOW AND LONG-TERM TRENDS OVER BAY OF BENGAL

5.1 ICARB Land-Ocean Synchronization & Offshore Spatial Gradients

During the ISRO-GBP Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB; March–May 2006), land-based monitoring at Visakhapatnam was synchronized with research vessel observations across the Bay of Bengal [Niranjan et al., 2008]. Ground-based Microtops sun photometers at Visakhapatnam recorded an average 500 nm AOD of ~0.55, with episodic spikes exceeding 0.70–1.10 during early and late April. These optical spikes coincided with high surface aerosol mass loadings (140–175 $\mu g\ m^{-3}$) and elevated BC mass concentrations (4.5–5.3 $\mu g\ m^{-3}$).

Plotting land-based AOD at Visakhapatnam against offshore MODIS satellite-derived AOD (0.55 µm) along the BoB cruise track demonstrates strong temporal co-variability [Niranjan et al., 2008]. Spikes in continental outflow at the coastline correlate directly with elevated AOD across adjacent marine boundary layer waters, confirming that continental advection from eastern peninsular India strongly dictates marine atmospheric optical properties.

To evaluate how far continental aerosols extend over the ocean, spatial AOD gradients (ΔAOD / ΔDegree Latitude) were calculated taking Visakhapatnam as the origin point for continental outflow [Niranjan et al., 2008]:

• Near-Coastal Zone (< 6° Latitude Distance): Offshore AOD gradients remain low (~0.02–0.04 per degree latitude). Marine atmospheric columns near the coast sustain high, uniform aerosol loadings directly supplied by continental advection.

• Far-Coastal Zone (> 8° Latitude Distance): Offshore AOD gradients steepen sharply (~0.07–0.10 per degree latitude). Gravitational settling of coarse particles, wet scavenging, and atmospheric dilution weaken continental signatures, transitioning the atmosphere back to clean maritime conditions.

5.2 W-ICARB Advection Perturbations and Source Apportionment

Crucially, cruise observations alone can lead to misinterpretations if short-period temporal spikes are mistaken for permanent spatial structures. To resolve this, Spandana et al. [2012] conducted an extensive statistical analysis combining Winter-ICARB (W-ICARB; Dec 2008–Jan 2009) cruise data with multi-year MODIS satellite records. By analyzing 7-day HYSPLIT trajectory clusters across 30 cruise locations, they proved that advection pathways induce large short-period AOD anomalies in 65% of all oceanic cases.

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Table 2: Regional Advection Origin Statistics Causing High AOD Perturbations over Bay of Bengal [Spandana et al., 2012]

BoB Sub-Region	Indian Landmass Origin	East Asian / Eastern Origin	Total Analyzed Cases
Eastern Bay of Bengal (E BoB)	7 cases (20.6%)	27 cases (79.4%)	34 cases
Western Bay of Bengal (W BoB)	43 cases (97.7%)	1 case (2.3%)	44 cases
Southern Bay of Bengal (S BoB)	12 cases (15.6%)	65 cases (84.4%)	77 cases

As detailed in Table 2, the western Bay of Bengal is almost exclusively influenced by airmass advection from the Indian subcontinent (97.7% of cases), carrying heavy Indo-Gangetic outflow. In contrast, the eastern BoB (79.4%) and southern BoB (84.4%) are predominantly governed by long-range trans-boundary advection originating from East Asia and Southeast Asia [Spandana et al., 2012].

5.3 Multi-Year Trend Analysis (2005–2010)

A long-term assessment using MODIS Level-3 AOD data from 2005 to 2010 across representative marine nodes revealed distinct spatial trend dynamics [Spandana et al., 2012]:

• Western BoB Outflow Zone: AOD at northern/western outflow points (e.g., 18.65° N, 85.22° E) showed a steady upward trend from 2005 (annual mean 0.38) to 2009–2010 (annual mean 0.51), reflecting expanding industrialization and combustion emissions in the Indo-Gangetic Basin.

• Southern and Central BoB: AOD over southern oceanic nodes (e.g., 9.00° N, 87.50° E) remained highly stable across the 6-year period (annual mean 0.24–0.26), indicating a pristine marine background buffer resilient to localized inter-annual fluctuations.

6. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This review synthesizes multi-year empirical datasets and radiative transfer simulations across coastal eastern peninsular India and the Bay of Bengal. The core scientific conclusions are:

1. Chemical Dominance of Anthropogenic Sulfate & BC: Water-soluble aerosols over coastal eastern India are overwhelmingly dominated by NSS-sulfate (>90%), arising from fossil-fuel combustion. Surface BC co-varies linearly with NSS-sulfate, governing clear-sky shortwave radiative forcing.

2. Radiative Heating via Low SSA: An annual mean SSA of 0.76 ± 0.13 (mode ~0.80) and asymmetry parameter g = 0.65 ± 0.10 confirm a strongly absorbing troposphere. Dry winter conditions promote internal core-shell mixing, amplifying BC light absorption and driving localized atmospheric warming.

3. Boundary Layer Trapping & Elevated Layers: Winter atmospheric subsidence traps aerosols within the lower boundary layer (mixed layer contributing up to 100% of column AOD). Summer convection and Arabian desert dust advection create elevated layers (1.6–5 km) that decouple ground loading from column optics.

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4. Advection Perturbations & Long-Term Trends: Airmass advection induces short-period AOD anomalies in 65% of BoB cases. Western BoB is dominated by Indian continental advection (98%) and shows a steady 6-year increasing AOD trend (2005–2010), whereas eastern and southern BoB are governed by East Asian transport.

Future research must prioritize continuous high-resolution vertical profiling using Raman/Depolarization Lidars, state-of-the-art aerosol mass spectrometry (AMS) for organic carbon speciation, and dynamic chemistry-climate modeling (e.g., WRF-Chem) to assess aerosol impacts on the South Asian monsoon.

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