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Long-term trend Analysis of aerosol optical characteristics in the Central Indo-Gangetic Plain

Prayagraj Singh* [(1)], Bakhtawar H. Abdullah [(1)], Aditya Vaishya [(2, 3)], Prabhunath Prasad [(1)] and Shantanu Rastogi [(1)]
(1) Department of Physics, Deen Dayal Upadhyaya Gorakhpur University, Gorakhpur, 273009, India
(2) School of Arts and Sciences, Ahmedabad University, Ahmedabad, 380 009, India
(3) Global Centre for Environment and Energy, Ahmedabad University, Ahmedabad, 380 009, India

Abstract

Long-term aerosol optical characteristics over Gorakhpur in the central Indo-Gangetic Plain (IGP) were assessed using satellite-derived aerosol data from 2003 to 2023. The temporal variation and trend analysis of aerosol optical depth (AOD), Ångström exponent (α), single scattering albedo (SSI), and absorption aerosol index (AAI) have been investigated for the same period. The temporal variation using daily values of aerosol optical parameters shows significant day-to-day variability, indicating diverse aerosol types in the study region. During the study period, annual mean values (higher percentage change) of AOD, α and AAI were observed to be 0.78 ± 0.39 (22.5%), 1.20 ± 0.36 (7.7%) and 1.36 ± 0.36 (8.4%), respectively. Seasonally, AOD and AAI showed a positive trend every year in all seasons, with the maximum increase observed in the PM season (53%) and PoM (31%), respectively. α shows a positive trend with a large increase in PM and W seasons (~13% to ~15%), suggesting an increase in aerosols during these seasons is mainly from diverse emission sources. SSA does not exhibit any considerable seasonal change during the study period.

1. Introduction

Atmospheric aerosols play a crucial role in regional and global climate change by scattering and absorbing solar and terrestrial radiation, and by modifying cloud properties and precipitation patterns [1-3]. Aerosols originate from both natural and anthropogenic sources and represent a significant source of uncertainty in climate change modeling [4, 5]. Their impact extends beyond climate to human health, reducing visibility and affecting air quality [6-9]. Due to their importance, extensive efforts have been made to monitor aerosols, including ground-based measurements, satellite remote sensing, and aerosol modeling. Satellite remote sensing provides crucial data for monitoring aerosol properties, focusing on parameters like aerosol optical depth (AOD), Ångström exponent (α), single scattering albedo (SSI), and absorption aerosol index (AAI), with advancements in spatial and temporal resolution enhancing monitoring capabilities over time [10-12]. Several investigations exhibited increased aerosol loading over the Indian subcontinent compared to other regions worldwide [13-15]. This increase was primarily attributed to escalating emissions of anthropogenic aerosols driven by rapid urbanization, industrialization, and population growth over recent decades [16-18].

The Indo-Gangetic Plain (IGP) is widely recognized for aerosol research due to significant aerosol loading [14, 19] influenced by diverse sources including anthropogenic (fossil fuel combustion, industrial emissions, crop residue burning, biofuel use) and natural emissions (mineral dust, sea salt) [5, 20]. Seasonal patterns show coarse-mode aerosols, primarily from dust and sea salt, dominating during pre-monsoon and monsoon seasons, transported from neighboring desert and oceanic regions [21-23]. In contrast, fine-mode aerosols increase during post-monsoon and winter due to activities like agricultural burning and heating, often trapped near the surface by inversion layers, limiting vertical dispersion [24].

This present study provides a long-term assessment of various aerosol parameters spanning from 2003 – 2023 using satellite measurements over Gorakhpur, a city in the central IGP. The primary objective is to analyze the changes and trends in aerosol characteristics over the study period. This in-depth analysis aims to provide valuable insights into the complex interplay between human activities and aerosol dynamics in the specified region.

2. Site Description, Data and Methodology

Gorakhpur (26.75° N; 83.38° E; 85 m amsl), situated in eastern Uttar Pradesh near the Shivalik Himalayas, is 270 km east of Lucknow, 220 km north of Varanasi and 100 km from the Nepal border. The main aerosol sources in this region are vehicular emissions, domestic heating, biomass burning, and dust transport. The climate of the region is very hot and dry in PM, hot and humid during M and PoM, and dry in W season. Western disturbances in the W season bring occasional rain and dense fog, while depressions from the northern Bay of Bengal during the M season led to moderate to heavy rainfall. Detailed information about the study region is discussed in [25, 26]

In this study, daily mean AOD at 550 nm was obtained from 2003 - 2023 from the Moderate Resolution Imaging

Spectroradiometer (MODIS) Level 3 combined Dark Target-Deep Blue (DB-DT) retrievals from the Terra (MOD08_D3) and Aqua (MYD08_D3) at 1° x 1° spatial resolution. Similarly for the same period, hourly α at 470–870 nm was sourced from the Modern-Era Retrospective Analysis for Research and Applications, Version-2 (MERRA-2) reanalysis (M2T1NXAER_V5.12.4) at a resolution of 0.5° x 0.65°, and daily averages were computed for analysis. Additionally, Ozone Monitoring Instrument (OMI) Level 3 (OMTO3d_003) gridded daily SSA at 500 nm and AAI observations at 1° x 1° resolution were used for the period from October 2014 to December 2023. Some of the aerosol data during the M and W seasons were heavily cloud-contaminated, which could introduce uncertainties. Therefore, these data were excluded from the analysis. The detailed description of the abovementioned satellite sensors was discussed in several studies [27-29]. A long-term trend analysis was conducted using daily mean data of aerosol optical parameters, following the methodology described by [30].

4. Results and Discussion

Figure 1 illustrates the temporal variation and trends of AOD, α, SSA and AAI using the daily mean values for the study period. The respective figures also indicate statistical parameters of decadal trends of each aerosol parameter including trend/day, percentage change (%) and number of available days (N) at the study region.

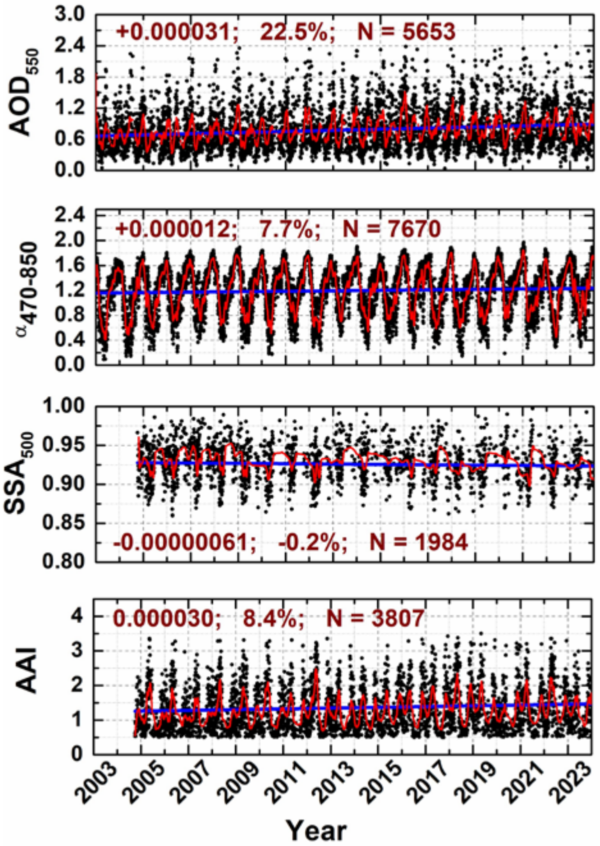

Figure 1: Inter-annual variability and trend of AOD_{500}, $\alpha_{470\text{-}850}$, SSA_{500}, and AAI using daily values (indicated by black circles) and monthly moving running average (indicated by a red line) over Gorakhpur during the study period. The slope of the regression analysis along with the % variation and the number of available days during the study period (N) are given in the parenthesis.

The temporal variation using daily values of aerosol optical parameters shows significant day-to-day variability throughout the study period, indicating diverse aerosol types over Gorakhpur in the central IGP. It also suggests that the study region is strongly influenced by the local emission and meteorological conditions of the region. During the study period, AOD, α, SSA and AAI values range from 0.03 to 2.39, 0.09 to 1.97, 0.85 to 0.99 and 0.5 to 3.5, with a mean value of 0.78 ± 0.39, 1.20 ± 0.36, 0.93 ± 0.03 and 1.36 ± 0.36, respectively. The observed annual mean values of AOD and α are comparable with earlier reported values for Gorakhpur [25] and other locations of the central IGP like Varanasi [31] and Kanpur [32]. The yearly trend in the above aerosol optical parameters has been also studied which exhibits a significant positive trend in AOD (22.5%) and a moderate increasing trend of 7.7% and 8.4% in α and AAI, respectively. In contrast, SSA has shown an insignificant decrease during the study period.

Table 1: Statistical parameters for the regression analysis of yearly trends on both seasonal and annual basis during the study period for Gorakhpur. The statistically significant trends at the 95% confidence level ($p < 0.05$) are indicated in bold italic.

Parameters	Mean ± SD	Trend/yr	p	%
		PM		
AOD_{550}	***0.71±0.36***	***0.0081***	***<0.0001***	***22.5***
$AE_{470\text{-}850}$	***0.81±0.29***	***0.0063***	***<0.0001***	***15.6***
SSA_{500}	0.93±0.03	0.0003	0.07	0.7
AAI	1.60±0.65	0.0043	0.17	5.2
		M		
AOD_{550}	***0.67±0.37***	***0.0081***	***0.005***	***24.2***
$AE_{470\text{-}850}$	1.19±0.25	-0.0047	0.15	-7.9
SSA_{500}	0.95±0.02	0.0002	0.94	0.4
AAI	***0.76±0.27***	***0.0074***	***0.0007***	***18.5***
		PoM		
AOD_{550}	***0.77±0.38***	***0.0112***	***<0.0001***	***29.1***
$AE_{470\text{-}850}$	***1.47±0.18***	***-0.0033***	***0.044***	***-4.9***
SSA_{500}	***0.92±0.02***	***-0.0008***	***0.007***	***-1.7***
AAI	***1.36±0.60***	***0.0228***	***<0.0001***	***30.9***
		W		
AOD_{550}	***0.92±0.55***	***0.0243***	***0.0005***	***52.8***
$AE_{470\text{-}850}$	1.44±0.27	0.0094	0.12	13.1
SSA_{500}	***0.92±0.02***	***-0.0011***	***0.003***	***-2.3***
AAI	***1.22±0.50***	***0.0143***	***<0.0001***	***22.6***
		Annual		
AOD_{550}	***0.78±0.39***	***0.0102***	***<0.0001***	***26.2***
$AE_{470\text{-}850}$	***1.20±0.36***	***0.0022***	***<0.0001***	***3.7***
SSA_{500}	0.93±0.03	-0.0003	0.94	0.6
AAI	***1.36±0.63***	***0.015***	***<0.0001***	***20.4***

The trend analysis on a yearly mean basis is also attempted for AOD, α, SSA and AAI during different seasons and is mentioned in Table 1. AOD trend showed a significant increase over the study region, with a maximum increase of 53% observed in the W season, and also characterized by seasonal high AOD, indicating an increase in aerosol buildup and turbid atmosphere during this season. Whereas other seasons showed an increase in AOD trend in the range of 23% to 29%. α shows a positive trend with a large increase in PM and W seasons (~13% to ~15%), suggesting an increase in aerosol loading during PM and W seasons, possibly due to the emission of coarse and fine mode aerosol from diverse sources, respectively. M and PoM seasons exhibit a negative trend in α of ~5% to ~8% during the study period. SSA does not exhibit any considerable seasonal change throughout the study period, with a positive trend of ~0.5% during PM and M seasons and a negative trend of ~2 in PoM and W seasons. The AAI shows a positive trend in all seasons with a relatively high contribution observed in the PoM season (31%) followed by W (23%) and M season (18%), respectively. During the PoM and W seasons, columnar aerosol loading in terms of AOD, α, and AAI is higher compared to other seasons. This suggests that fine-mode absorbing aerosols dominate the study region. It also exhibits that these seasons have nearly identical emission sources, which are dominated by biomass burning such as agricultural residue burning, forest fires, and domestic heating. In addition, shallow boundary layer height and stable meteorological conditions during these seasons also play an important role.

5. Conclusions

The present work examined the long-term variation and trends in aerosol optical properties like AOD, α, SSA and AAI at Gorakhpur in the central IGP, utilizing satellite data for the period from 2003 to 2023. Linear regression analysis along with statistical significance tests were applied to examine the robustness of the trends on a daily and yearly basis. The study also indicates the significant temporal variation in the values of aerosol parameters, with a relatively higher positive trend observed in AOD (22.5%), followed by α (7.7%) and AAI (8.4%), respectively. While SSA has no considerable change during the study period. On a seasonal basis, the yearly trend of AOD, α and AAI are found to be more pronounced during the W season (53%), PM (15.6%), and PoM (31%), respectively. The findings also suggest the higher columnar aerosol loading with higher AOD, α and AAI, and lower SSA during PoM and W season, indicates prevalent fine mode absorbing aerosols over the study region, Gorakhpur, in the central IGP.

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