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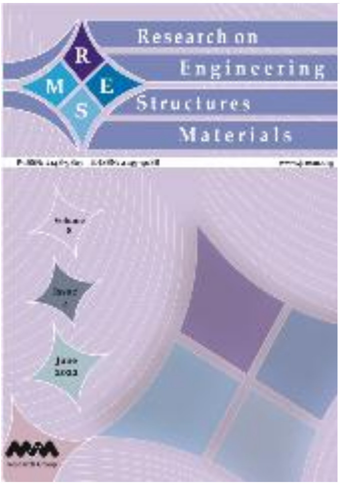

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Technical Note

Seasonal variation in aerosol optical depth and study of $PM_{2.5}$-AOD empirical relationship in Raipur, Chhattisgarh, India

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Abstract

Owing to urbanization and industrialization, $PM_{2.5}$ (particulate matter with a diameter of less than 2.5 m) pollution has developed into a severe environmental issue. The limited geographical precision and inadequate coverage of $PM_{2.5}$ measurement stations hinders research into the sources of contamination and the associated health hazards. The complex link between $PM_{2.5}$ and aerosol optical depth (AOD), which is again confounded by meteorological conditions, makes retrieving $PM_{2.5}$ from space difficult. AOD dataset was obtained from multiple satellite data retrieval tools including MERAA and OMI for the year 2020. Assessment of annual, seasonal and monthly AOD variation was carried out. The average aerosol optical depth obtained from OMI and MERRA is 1.60±0.56 and 1.33±0.12 respectively. Maximum AOD value was recorded in the summer, while the lowest value was recorded in the winter. Both the OMI and the MERRA AOD monthly change trends were similar, according to the comparative data. The months with the highest AOD values were July and October, and the months with the lowest AOD values were April and November. In the region, aerosol optical thickness (AOT) shows a significant seasonal change. Back-trajectory analysis indicated the contribution from local as well as distant sources. A significant association between $PM_{2.5}$-AOD was found with R-square =0.71 with validated model showing good model performance and can be used for predicting future ground-based $PM_{2.5}$ concentrations in the region. Substantial site-specific AOD-$PM_{2.5}$ associations enable OMI AOD to be used to monitor pollution levels.

1. Introduction

Pollution caused by $PM_{2.5}$ aerosols (particulate matter with a diameter less than 2.5 m) has long been a concern for the environment and for people's health [1,2]. The optical and microphysical properties of aerosols continue to be one of the largest sources of uncertainty when assessing the climatic forcing attributable to particles [2]. Aerosols can have significant impacts on the climate on local to global dimensions, but the magnitude and relevance of these effects are largely unknown [3]. Aerosols impact on the radiative equilibrium by scattering and absorbing radiation through solar energy [4]. Indirect effects on climate due to aerosols include aerosol-cloud interactions [5]. Aerosols' role in the atmosphere is determined by their physical, chemical, and optical properties, as well as complicated aerosol interactions changing greatly in both space and time [6]. Significant parameters controlling the radiative impacts include aerosol optical depth (AOD) or aerosol optical thickness (AOT), single scattering albedo (SSA) and Angstorm exponent (AE) [7]. The most important factors for determining the AOD are aerosol bulk load and aerosol extinction efficiency [8].

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The most important methods used and customized to study aerosol optical characteristics and the radiative impact that aerosols have on climatic conditions are satellite and ground-based multispectral data. Ground-based devices are the easiest to calibrate and, as a result, the least precise, and hence serve as the foundation for satellite algorithm calibration [9]. In China, the Pearson correlation coefficient of surface $PM_{2.5}$ and AOD indicates large inter-annual changes (27%) but no statistically significant trends. However, their application is limited to the area in which they operate [10]. Increasing AOD product geographic coverage is critical for mapping $PM_{2.5}$ variance, particularly in metropolitan regions [11]. Remote sensing technology, on either side, has become progressively popular in the recent decade for quantifying aerosols around the world [12]. Because of its fundamental virtue of giving full and comprehensive mapping of huge areas in single snap-shots, it is a new but strong technique for examining aerosol spatial distribution and attributes. Satellite data give global views of the Earth and enable for the retrieval of the spatiotemporal aerosol dispersion, which is caused by spatial heterogeneities and brief aerosol lifetimes [13]. As a result, aerosol spatial data from long-term operating satellites offers a once-in-a-lifetime opportunity to examine aerosol load and attributes globally and seasonally [14].

A range of satellite sensors (MERRA, OMI, MODIS) and methodologies have been applied for aerosol estimation and pollution load from local to global scales at varying spatial resolutions. The limited temporal resolution, the impacts of surface albedo, and the inclusion of clouds are all downsides of using satellite sensor systems. The aerosol mass concentration, mass extinction efficiency, hygroscopic growth factor, and effective scale height all play a role in the AOD- $PM_{2.5}$ association [15]. The vertical distribution of aerosols is a significant element in the AOD- $PM_{2.5}$ relationship [16]. Previous research indicated good correlation between AOD- $PM_{2.5}$ which will help to predict air quality through satellite data [17]. The relationship between AOD and $PM_{2.5}$ can be used for air quality monitoring, model verification, and data assimilation. The vertical distribution of aerosols is a significant element in the AOD- $PM_{2.5}$ relationship [16].

There are two types of methodologies for estimating near-surface $PM_{2.5}$ using space-borne AOD: observation-based and simulation-based methods [18]. Observation-based approaches rely heavily on statistical correlations among AOD and $PM_{2.5}$ measurements at the surface level [19]. $PM_{2.5}$ and AOD correlation is influenced by regional heterogeneity. Meteorological characteristics such as cloud cover, wind speed, boundary layer, and humidity were used to construct more advanced algorithms for estimating $PM_{2.5}$ from space improving correlation between $PM_{2.5}$ and AOD. If the association among AOD and PM concentration is proven (including $PM_{2.5}$ and PM_{10}), the satellite output can be used to determine the concentration of particulate matter (PM, including $PM_{2.5}$ and PM_{10}) over a vast area [20]. Recent investigations have been conducted across the globe, primarily over the Indo Gangetic Plains (IGP) [5, 21]. As far as we are aware, there are no specific investigations on the aerosol optical characteristics over the central research region. AOD and $PM_{2.5}$ frequently exhibit high connections when particles are in the boundary layer (since they are well mixed). Future research should focus on examining the AOD-PM connection with regard to the types of land uses, the sources of air pollution, and aerosol characterisation [22]. The nature and sources of aerosols and air pollution, as well as the intensity of the correlation between AOD and PM, vary widely, therefore the observed association between AOD and PM in one region cannot be extrapolated to other regions [22]. The present study investigates on annual, seasonal and monthly AOD variations and comparison between data retrieved through satellite sensors during 2020. A model was developed to identify the relationship between $PM_{2.5}$ and AOD with the inclusion of relative humidity in the study area using linear regression analysis approach.

2. Methodology

2.1. Study Area

Raipur, capital of state is a study area of about 1,760,411 people geographically located at the Chhattisgarh state of India Extends from latitude 21° 23″ to longitude 81° 65″. It is a developing city with an area of 226 square kilometers. The maximum temperature in Raipur district is 44.3° C, while the lowest temperature is 12.5° C. The district's total average rainfall is 1370 mm. The city has moderate temperature throughout the year. The area has experienced rapid industrial development and has emerged as a key industrial center in the state. Although the iron and steel industries help the city thrive economically, the city's industrial and vehicular activity lead to urbanization.

2.2. Data Collection

The set of data used in this research consists of one year of observations made during 2020. The data was collected from January 2020 to December 2020 derived from Ozone monitoring instrument (OMI) and Modern-Era Retrospective analysis for Research and Applications (MERRA) satellite data. OMI is a mission to the Earth Observing System (EOS) Aura project from the Netherlands Agency for Aerospace Programs (NIVR) in partnership with the Finnish Meteorological Institute (FMI). The OMI gadget delivers daily global coverage over a 2600-kilometer swath. The AOD data used here was generated using the UV method (OMAERUV) [16, 23, 24]. MERRA was based on a 2008-frozen version of the GEOS-5 atmospheric data assimilation system. MERRA data was created on a 0.5° 0.66° grid with 72 layers [25]. $PM_{2.5}$ data was obtained through online data collection from air quality index data [26].

3. Results and Discussions

3 .1. Annual, Seasonal and Monthly AOD Variations

Based on the seasonal changes identified from OMI and MERRA data, the highest AOD value occurred in summer and lowest value occurred in winter. Figure 1. shows the comparison of seasonal AOD variation during Jan 2020 to Dec 2020 from OMI and MERRA satellite data. Table 1 and 2 shows the descriptive statistics of AOD obtained from OMI and MERRA respectively. The comparison results show that both the OMI and MERRA AOD monthly change trends were similar and were compatible with $PM_{2.5}$ seasonal trends. OMI and MERRA show that during summer the concentrations values were maximum which remains constant during spring when observed from MERRA results. The mean AOD values were less during spring as observed through OMI data. The intricacy of the Earth's surface and atmosphere makes it difficult to retrieve AOD from satellites, and it also leads to inconsistencies between the various sensors that are employed [27, 28]. The trend change was similar during autumn and winter using both OMI and MERRA satellite retrieval. In terms of maximum aerosol optical depth, OMI and MERRA reanalysis produce quite similar results. High AOD occurred in summer and is often associated with dusty weather conditions occurring in this season. Low AOD values in winter is attributed to reduced winter wind and dust activity. The downward trend increases from summer to winter during 2020 and is reflected from the perspective that atmospheric conditions would have been more severe in summer than in autumn and winter and the air quality is relatively poor. Typically, places with high $PM_{2.5}$ concentrations also have elevated AOD loads in China and the presence of dust storms results in high PM_{10} and AOD concentrations indicating comparable variation [19].

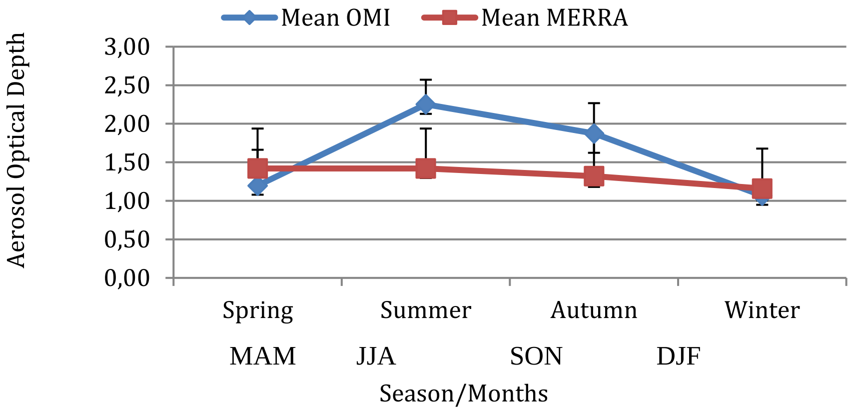

Fig. 1 Seasonal AOD variation during 2020 retrieved from OMI and Merra satellite data

Table 1. Seasonal AOD concentrations during 2020 retrieved from OMI

Season	Mean	Min	Max	Std dev	Std error
Spring	1.20	0.60	1.91	0.47	0.12
Summer	2.25	1.86	2.72	0.32	0.12
Autumn	1.87	1.24	2.32	0.39	0.25
Winter	1.07	0.80	1.38	0.19	0.06

Table 2. Seasonal AOD concentrations during 2020 retrieved from MERRA

Season	Mean	Min	Max	Std dev	Std error
Spring	1.42	0.43	1.84	0.67	0.11
Summer	1.42	0.64	1.92	0.45	0.14
Autumn	1.32	0.61	2.01	0.51	0.21
Winter	1.16	0.50	1.38	0.30	0.01

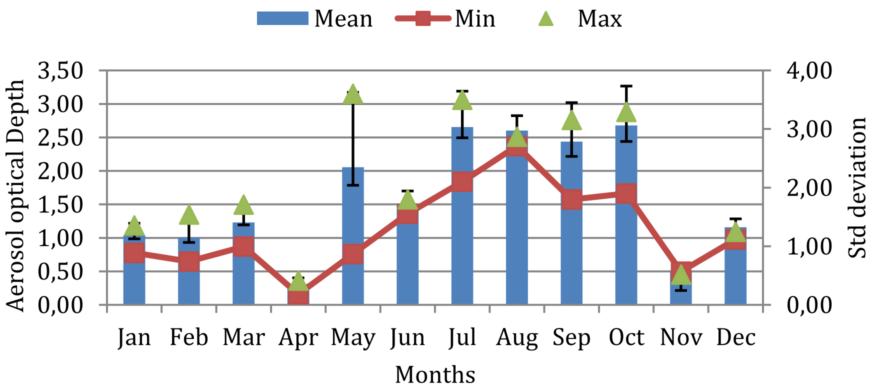

Fig. 2 Monthly AOD variation during 2020 retrieved from OMI satellite data

Figure 2. shows the AOD Data from OMI (-Aura_L2-OMAERUV_2020m0501t0758-o84012_v003-2020m0503t164542.SUB.he5). As monsoon approaches after June, peak values of AOD can be seen arising due to higher wind speeds which may be due to advection of dust particles and increase in columnar water vapour. The high AOD values were observed mainly during July & October and low AOD values during April & November. Excluding the monsoon months, from June to September, October month observed highest OMI mean value over the region which may be attributed from regional crop residue and biomass burning activities. During May, Jun and July transported dust might be the significant contributors to high AODs.

3.2 Seasonal Classification of Aerosols

Figure 3. shows the seasonal AOD variation during summer, monsoon and winter. AOT shows a distinct seasonal variation in the region. The averages of AOT were higher in summer (1.58) than in winter (1.38) and found minimum in monsoon (1.14) season during 2019 to 2020. This indicates that precipitation levels and humidity accumulate the particles and settle them down minimizing their concentration in the air. AOT mainly comprises of fine particles. This signifies that even during summer, the concentration of fine particulates in the region is higher from a stable source. Also, dust aerosol concentrations rise during summer as compared to winter season. Similar seasonal trends are observed in Raipur city with minimum AOD values in winter (0.44±0.15) and maximum values during spring and summer (0.98±0.21) from 2019 to 2021 showing the presence of scattering aerosols in summer and absorbing aerosols in winter season [29]. By utilizing a sunphotometer and the AERONET network, seasonal and yearly fluctuations in the optical characteristics of aerosols in Kanpur, Karachi, and Ahemdabad were tracked [30]. When compared to other sites, the AOD and angstrom exponent were found to be greater in Kanpur. AOD was investigated in Bhubaneshwar utilizing satellite and ground-based assessment methods [31]. They discovered that AOD ranged from 0.39 to 0.96, with the highest concentration in February and the lowest in July. In 2013 and 2014, the optical characteristics of Lumbini, Nepal, a UNESCO World Heritage Site were measured [32]. They discovered an average AOD (0.64) with a greater AOD (0.72) post-monsoon. The pre-monsoon month's high AOD suggest that natural desert dust aerosols with a preference for coarse mode particulate have been loaded into the atmosphere in Jodhpur [33].

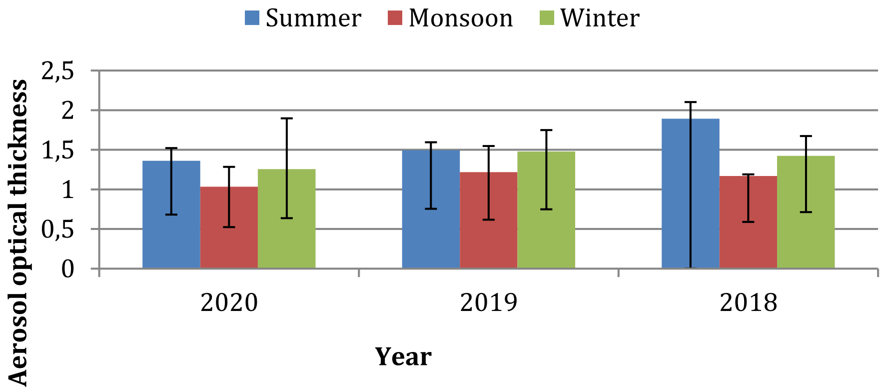

Fig. 3 Monthly mean of aerosol optical thickness at 550 nm during 2018-2020 retrieved from GIOVANNI

3.3 Back Trajectory Analysis

Back trajectory analysis was performed to find the significance of local sources contributing to high aerosol concentrations using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by National Oceanic and Atmospheric Administration. The trajectories were calculated at 500 m, 1000 m and 2000 m above ground level at latitude 21.25 N and longitude 81.62 E during periods of higher concentrations (GDAS 1 degree, global, 2006-present). Maximum concentrations were observed on 14th May 2020 and 15th May 2020. Local air masses inside the boundary layer enhanced by anthropogenic aerosols are related with the UI type, resulting in high AOD550 and FM values (0.54 and 0.98, respectively) [14]. Figure 4 shows the back trajectories during periods of maximum concentrations. Contribution from local along with distant sources is observed during the period indicating that aerosol in the region is contributed from both natural i.e., windblown mineral dust as well as anthropogenic sources like industrial emissions, vehicular pollution and anthropogenic activities at urban areas.

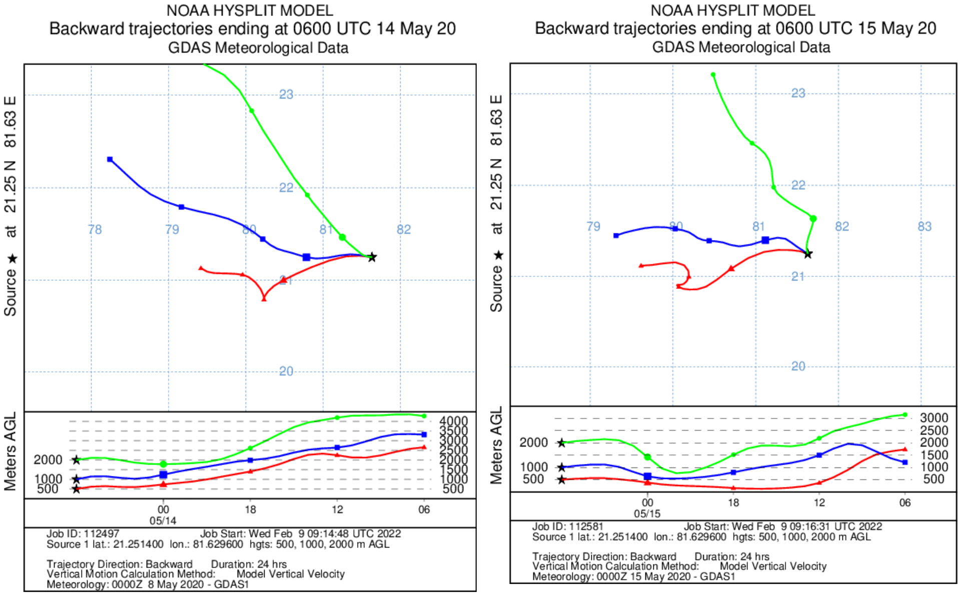

Fig. 4 Back trajectories during periods of maximum concentrations using HYSPLIT model

3.4 Particulate Matter and AOD Correlation

Aerosol particles with a large aerodynamic diameter are responsible for the region's high AOD. Globally, MODIS AOD has a geographic pattern analogous to that of $PM_{2.5}$. This suggests that areas with high AOD are also likely to have elevated $PM_{2.5}$ levels [19]. Also, aerosol particle hygroscopic expansion was discovered to be widespread, which necessarily results in uncertainty of variable degrees when obtaining AOD from satellite data [34]. Hence, regression analysis was conducted to find out the relation between $PM_{2.5}$, AOD and RH. Statistical analysis was performed between the parameters to check the significance of the parameters on the $PM_{2.5}$ values. The p-value was found to be significant for AOD (<0.05), however it is observed to be insignificant for RH. Correlation analysis was conducted and correlation co-efficient between AOD and $PM_{2.5}$ was observed to be 0.83 making it significant parameter, whereas for RH it is -0.03 considering the parameter as insignificant. Through statistical analysis, F-value was found to be greater than F-critical indicating the R^2 value is significant and t-test was performed and observed that t-critical is less than t-value, hence the R^2 value was significant. The R^2 value between $PM_{2.5}$ and AOD was observed as 0.70 ($p<0.05$). Figure shows the relation between predicted and observed $PM_{2.5}$ values with $R^2 = 0.71$($p<0.05$). Sensitivity analysis was conducted and AOD was observed as an influencing parameter with $R^2 = 0.81$ ($p<0.05$). Equation 1 represents the developed model. Satellite AOD was utilized in order to obtain $PM_{2.5}$ data from a total of 15 sites in India [35]. They came to the conclusion that the co-efficient was 77%, and the diurnal scale co-efficient ranged from 0.45 to 0.75. AOD-$PM_{2.5}$ correlation studies have yielded conflicting results depending on the study area's size, geographic location, and spatial resolution [21]. On days where there is no discernible relationship between AOD and $PM_{2.5}$, this variability is likely due to a number of different causes. Numerous factors, such as local aerosol origins and weather patterns, greatly affect $PM_{2.5}$ levels. $PM_{2.5}$ fluctuation can be caused by a variety of reasons. Few factors influencing urban PM concentrations include local origins of primary PM, topographic boundaries between locations, intermittent generation episodes, meteorological processes, changes in the behaviour of semi volatile constituents, and measurement imprecision [36]. A strong linear association (coefficient = 0.96) between the daily mean satellite AOD and ground-based PM2.5 measurements for a total of 26 cities around the world has been observed [37]. In Finland, correlation values involving AOD and $PM_{2.5}$ were ranged from 0.57 to 0.91 [38]. The paucity of a substantial AOD-$PM_{2.5}$ association during certain days in the region could be attributed to the fact that AOD is a marker of light attenuation by particles in a vertical column, whereas terrestrial $PM_{2.5}$ is a marker of aerosol content (less than 2.5 m) on the surface. AOD is susceptible to the vertical atmospheric pattern, which is primarily determined by the structure of the aerosol cover and the elevation of the layer's higher or lower boundary [39]. In the research area, however, a region-specific steady and persistent seasonal AOD-PM2.5 association is observed.

$$PM_{2.5} = 91.32 + 52.85 * \mathrm{AOD} \tag{1}$$

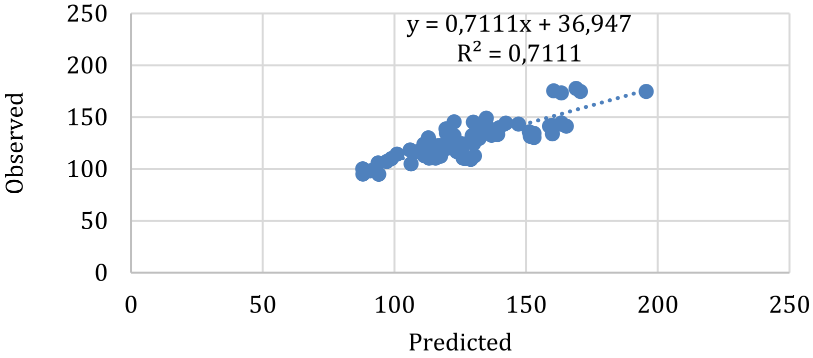

Fig. 5 Scatterplots and relationship between observed and predicted $PM_{2.5}$ values

3.5 Model Validation

The 25% dataset was used for model validation with R^2 value as 0.81. Statistical testing was conducted to check the statistical acceptance of the data and it was found that the model is statistically acceptable. Also, error analysis was carried out and mean absolute percentage error was found as 0.07 which is acceptable. Hence the developed model was statistically significant. Figure 6. shows the association between actual and predicted $PM_{2.5}$ values estimated using the developed model.

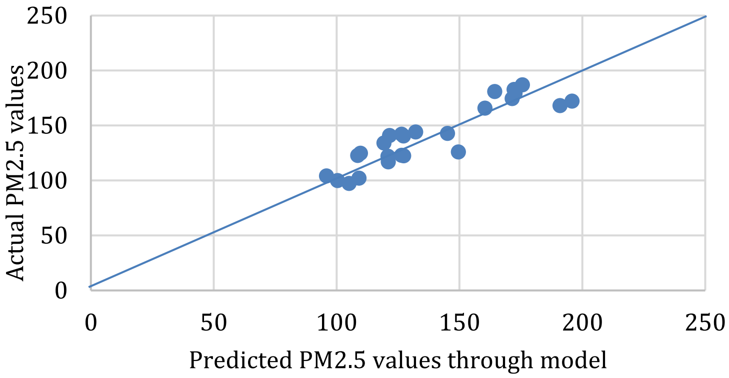

Fig. 6 $PM_{2.5}$-AOD model validation

4. Conclusion

This study highlights the importance of monitoring aerosol concentrations in regions with high anthropogenic activities, to mitigate their negative impact on human health and the environment. The findings provide valuable insights into the temporal and spatial variability of aerosols and their impact on the Earth's radiation balance. It is worth noting that aerosol concentrations are not only affected by natural sources but also by anthropogenic activities. The average AOD concentrations obtained from OMI and MERRA is 1.60±0.56 and 1.33±0.12 respectively over 2020 indicating variability in aerosols in the region. AOD levels were high over the summer, which is generally associated with dusty weather conditions. Winter wind and dust activities are reduced, resulting in lower AOD readings. AOT averages were greater in the summer (1.58) than in the winter (1.38) and were lowest during the monsoon (1.14) season from 2019 to 2020 indicating high amounts of precipitation and humidity collecting the particles and settling them down, reducing their concentration in the air. The results obtained through back-trajectory analysis indicate that both wind-blown mineral dust and anthropogenic activities are significant contributors to aerosol concentrations in the study region. High correlations were observed between annual $PM_{2.5}$ and AOD concentrations during the study period. AOD is found as an influencing parameter to $PM_{2.5}$ with $R^2 = 0.71$ ($p<0.05$). The mean absolute percentage error is less than 10% indicating good prediction accuracy. The validated model demonstrated good prediction accuracy and is suitable for making accurate projections about possible potential ground-based $PM_{2.5}$ concentrations in the region. Therefore, it can assist policymakers and environmentalists in making informed decisions about air quality management and the development of effective mitigation measures. OMI AOD can be used to assess possible levels of pollution as there are substantial site-specific connections between AOD and $PM_{2.5}$. Further research is needed to improve our understanding of the sources and transport of aerosols to develop more effective mitigation measures.

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