ANALYSIS AND VARIATION OF THE MAIAC AEROSOL OPTICAL DEPTH IN UNDEREXPLORED URBANIZED AREA OF NATIONAL CAPITAL REGION, INDIA

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ABSTRACT

Aerosol monitoring is the emerging application field of satellite remote sensing. As a satellite-based indicator of aerosol concentration, aerosol optical depth (AOD) can aid in assessing the crucial effects of aerosols on the global environment. Among various satellite-based aerosol product, Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 (C6), Multiangle Implementation of Atmospheric Correction (MAIAC) aerosol product (1 km resolution) has still untapped potential in Indian regions. Considering the importance of regional validation of such high-resolution aerosol product, the present study attempts to fill this gap by validating MAIAC aerosol estimates (AOD_{MAIAC}) in highly polluted districts (Faridabad, Ghaziabad, Gautam Budh Nagar, Gurugram) of National Capital Region (NCR) with heavy aerosol loading using limited AErosol RObotic NETwork (AERONET) observations obtained from AERONET sites at Amity University (AU) and Gual Pahari (GP). Such evaluation of satellite-retrieved aerosol product with ground data confirms its practicality based on retrieval errors (Expected Error (EE) values (EE = 0.05 + 15 %*AOD) (EE: 78.85 % at AU, 73.58 % at GP), root mean square error (RMSE) values (RMSE: 0.15 at AU, 0.24 at GP), and correlation coefficient (R) values (R: 0.86 at AU, 0.73 at GP). The seasonal variation in AOD over the study area from 2010-2019 reveals increasing trend of AOD in the monsoon and post-monsoon season due to natural and anthropogenic factors. In addition to contributing to a holistic assessment of MAIAC aerosol estimates as a recent, high-resolution aerosol product, present results provide a basis for further research into NCR aerosols.

Keywords: MODIS, MAIAC, AOD, AERONET, NCR

INTRODUCTION

Production of aerosols containing solid and liquid particles is the result of a range of natural and manmade processes. A variety of geographic characteristics and strengths, as well as meteorological factors, contribute to the discrepancy in physical, chemical and especially the optical properties of aerosol (Altaratz *et al*., 2013; Banerjee *et al*., 2015; Ramanathan & Ramana, 2005; Singh *et al*., 2017a; Yang *et. al*. 2022). The Earth's environment is greatly affected by heterogeneous aerosols. For instance, aerosols affect our climate by altering the radiative flux, they serve as cloud seeds, increasing albedo and therefore changing the radiative forcing (Hansen & R., 1997; Seinfeld *et al*., 2016), the water cycle (Ramanathan *et al*., 2001), monsoonal patterns (Kumar *et al*., 2017; Lau & Kim, 2006), the crop yield (Banerjee *et al*., 2018; Burney & Ramanathan, 2014), reduced cloud cover due to cloud evaporation (Hansen & R., 1997). Furthermore, aerosols affect the mortality and morbidity rate by affecting the human health (Banerjee *et al*., 2017; Chowdhury *et al*., 2019b; Evans *et al*., 2013; Kaur & Pandey, 2021; Kumar *et al*., 2015; Rajput *et. al*. 2022). In addition, aerosol production could increase the number of accidents on the road because it reduces visibility level as well (Han *et al*., 2012).

Therefore, regular measurement of aerosol load and properties is the current research demand to create a resistant and resilient society towards air toxics. Ground-based equipment and remote sensing technology make such measurement of aerosol accurate and comprehensive at higher spatial and temporal scales (Li *et al*. 2022; Hoff & Christopher, 2009; Martin, 2008; Mhawish *et al*., 2018). Besides ground measurements through AErosol RObotic NETwork (AERONET), Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer (MISR), Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), POLarization and Directionality of the Earth's Reflectance (POLDER), Visible Infrared Imaging Radiometer Suite (VIIRS), and Ozone Monitoring Instrument (OMI) (Kahn & Gaitley, 2015; Kaufman *et al*., 2002; Remer *et al*., 2005; Torres *et al*., 2007; Winker & Pelon, 2003) are the major remote sensors which have been used for assessment of aerosols.

Such remote assessment of aerosol depends on Aerosol Optical Depth (AOD) which is the important variable to determine aerosol load in the atmosphere. AOD products from MODIS sensor has been used more compared to other sensors to determine aerosol loading worldwide because of its frequent measurements (Bilal & Nichol, n.d.; Levy *et al*., 2013; Mhawish *et al*., 2017a; Remer *et al*., 2013). Initially, MODIS provides Dark Target (DT) and Deep Blue (DB) algorithms for achieving AOD at the spatial resolution of 10km and 3 km: DT algorithm used over land (Levy *et al*., 2013), DB algorithm used over ocean (Tanré *et al*., 1997). Constant improvement in retrieval algorithms leads to, Multiangle Implementation of Atmospheric Correction (MAIAC) algorithm, at a spatial resolution of 1 km (Alexei *et al*., 2011; Hsu *et al*., 2013; Hsu *et al*., 2004) which is the current preference of the researchers for determining AOD, as it addresses the limitation of low retrieval accuracy and coarse resolution of previous MODIS algorithms (Gupta *et al*., 2018; Mhawish *et al*., 2017; Sharma *et al*., 2021).

Aside from a global validation, an area-specific validation of such new retrieval algorithm is required before implementing it for determination of AOD in that region, since the accuracy of satellite based AOD can vary with size, climatic setting, and topography of a study region. Moreover, there is insufficient information available about the spatial variation of AOD at the district and city levels when depictions are made at the national or world levels. MAIAC AOD has been validated regionally across various study areas with different climatic setting and urbanization level in numerous time periods (Chen *et al*., 2021; Falah *et al*., 2021; Li *et al*., 2018; Mhawish *et al*., 2019; Qin *et al*., 2021). In several sites in

North Africa, California, and Germany MAIAC AOD exhibits better retrieval accuracy for forest areas compared to desert regions (Falah *et al.*, 2021). Further, in the arid region, MAIAC was reported to be less effective than DB/DT on urban sites, whereas MAIAC AOD was more effective than DB/DT in semiarid regions (Mhawish *et al.*, 2021; Sever *et al.*, 2017). However, compared to other parts of the world, relatively few studies have examined MAIAC AOD in the Indian scenario (Mhawish *et al*., 2018, 2017; Pal *et al*., 2018; Sayer *et al*., 2014; Sen *et al*., 2017; Singh *et al*., 2017b, 2017a).

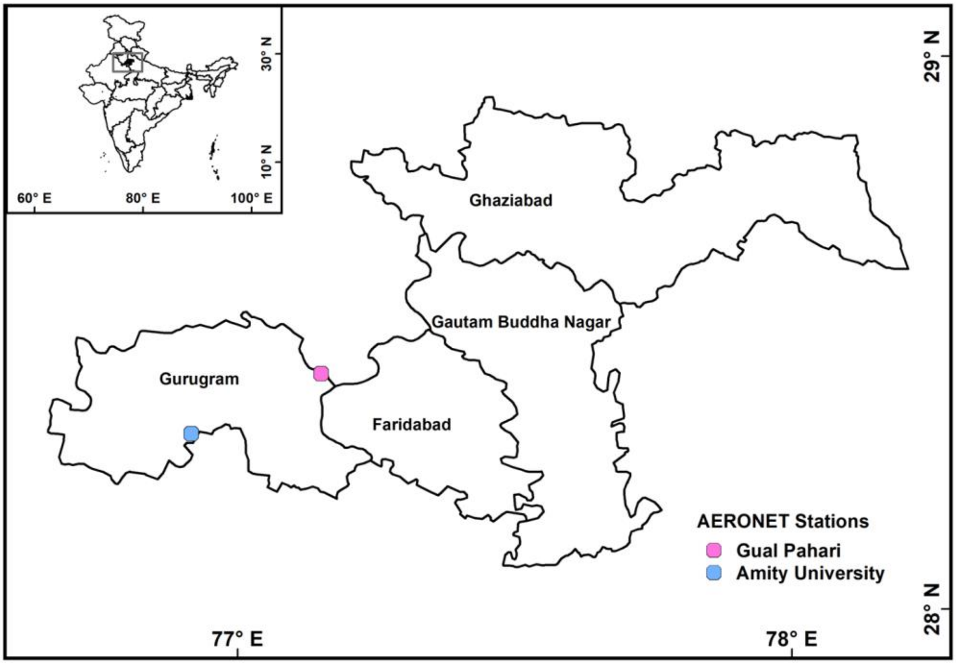
More specifically, there is insufficient literature on aerosol monitoring in the highly urbanized and significantly polluted National Capital Region (NCR) of India, due to the lack of AERONET surface stations in the region and the use of MAIAC AOD in only a few studies to understand the influence of aerosols on climate (Sharma *et al*., 2022; Shastri *et al*., 2020; Chowdhury *et al*., 2019a; Dey *et al*., 2020). In such a region with limited data, it is necessary to estimate the uncertainty associated with new retrieval algorithm. We started our study with the hypothesis that improved resolution of satellite based AOD might not be the sole criterion that will determine whether it will perform well in micro studies compared to other AODs with coarse resolution. Retrieval uncertainties are region specific and varying with climatic and topographic variables and anthropogenic activities as well. Therefore, in the present study MAIAC retrieved AOD observations (AOD_{MAIAC}) is validated with the ground based AERONET data ($AOD_{AERONET}$) over parts of the less explored data-scarce area of NCR which can contribute to air quality research.

STUDY REGION

Four highly urbanized districts of NCR suffer from data-scarcity have been selected: Faridabad at 28.40°N, 77.31°E, Ghaziabad at 28.66°N, 77.45°E, Gurugram at 28.45°N, 77.02°E, and Gautam Buddha Nagar at 28.33°N latitude, 77.60°E longitude respectively (Figure 1). There are 46 million people living in this urban-rural region (Census of India, 2011), which is 62.6 % urbanized (Census of India, 2011). Present study area, emerged from polycentric urbanization suffers from heavy industrial pollution, vehicle emissions, fossil fuel burning etc (Kumar *et al*., 2022; Ranjan *et al*., 2022). Gurugram ranked 6th for the most polluted city, Ghaziabad at 2nd position, Faridabad 4th most polluted city, and Gautam Buddha Nagar also equally polluted in the region of South Asia (Dahiya *et al*., 2017; *IQAir AirVisual 2018 World Air Quality Report*, 2018).

Figure 1 represents the study area region with AERONET sites. These districts feature four distinct seasons: winter, pre-monsoon, monsoon, and post-monsoon, with the winter season lasting from December to February, pre-monsoon lasting from March to May, monsoon lasts from June to September and post-monsoon is from October to November. Temperatures vary between 25 °C and 49 °C in the summer and 22 °C and 2 °C in the winter. Weather patterns in the study area are significantly affected by Rajasthan’s dust storms and snowfalls of Kumaon and Garhwal. This region experiences a tropical climate with hot summers and cold winters. A semi-arid environment is there in the present area (Gogikar & Tyagi, 2016). Validation observations have been collected from AERONET sites in Gurugram, Amity University (28.317°N, 76.916°E), and Gual Pahari (28.426°N, 77.150°E). These areas are still underexplored as far as aerosol characteristics are concerned, despite extreme urbanization and high air pollution levels.

Fig. 1: Location of the study area



DETAILS OF THE DATA

AOD Data from January 2010 to December 2019 was used in the present analysis through use of MODIS combined-Terra-Aqua collection 6 (C6) (MCD19A2) AOD observations (AOD_{MAIAC}) and the ground-based AERONET data ($AOD_{AERONET}$). In the present study, AOD_{MAIAC} (550 nm) with spatial resolution of 1 km from 2010 to 2019 were considered. An overview of the AOD_{MAIAC} and $AOD_{AERONET}$ aerosol products used in this study is presented in Table 1. This study's general concept is about the processing of images to get AOD and analyzing the series of images with time. Assuming that the surface is spatially heterogeneous and stable, the algorithm of MAIAC separates aerosol contributions from surface contributions based on the time series data. Using background aerosol models and SHARM scalar codes, a look-up table can be created by incorporating the bidirectional reflectance effects in the MAIAC algorithm (Zhang *et al.*, 2019). For more information on the MAIAC algorithm, please review (Alexei *et al.*, 2011a, 2011b; Lyapustin *et al.*, 2018, 2012). In MAIAC, aerosol models can be based on geographically prescribed parameters, which are derived from AERONET. Since MAIAC C6 aerosol models are static, seasonal variations of aerosol properties are not included in the current model. For this study, AODs were selected that were of the highest quality at 0.55 μm. As a measure of the MAIAC AOD's accuracy, the error envelope used is ±(0.05 + 15 %*AOD) (Alexei *et al.*, 2011b; Bilal *et al.*, 2018; Remer *et al.*, 2013).

The Aeronet network, a collection of ground-based sunphotometers, provides AOD at 5–15-minute intervals and sky radiance every 30 minutes in a time- and space-resolution. From 2010 to 2019, AOD_{MODIS} data for two sites in Gurugram, namely Gual Pahari and Amity University, were compared with the cloud-screened AOD at Level 2.0 quality-controlled data with large amount of data gap. The data are summarized in Table 1. Figure 1 illustrates where these AERONET sites are located. We interpolated $AOD_{AERONET}$ from 500 to 550 nm using Angstrom Exponent (*) of the 440 nm and 675 nm wavelength pair (Cesnulyte *et al.*, 2014) for comparison between the two datasets (AOD_{MAIAC} is available at 550 nm and $AOD_{AERONET}$ at 500 nm).

$$AOD_{550nm} = AOD_{500nm} * \left(\frac{550}{500}\right)^{-\alpha} \qquad \text{…………………………..(1)}$$

Table 1: Summary of data used in the present study

Data	Scientific Data Sets (SDS)	Description	Resolution	Location	Time Period	Source
AERONET	Aerosol Optical Depth (V2)	Version 2 Direct Sun Algorithm	500nm	Amity University	2010,2016,2017,2018	http://aeronet.gsfc.nasa.gov/
				Gual Pahari	2017,2018,2019	
MCD19_A2	Optical_Depth_055	MAIAC AOD at 550nm over land	1km	Gurugram, Faridabad, Ghaziabad, Gautam Buddha Nagar	2010-2019	https://ladsweb.modaps.eosdis.nasa.gov/

METHODOLOGY

Based on the hypothesis mentioned in the introduction, AOD_{MAIAC} is validated with $AOD_{AERONET}$ received from two AERONET stations available in the study area. Specifically, three steps were taken to conduct the study: 1.) Preprocessing of MAIAC data, 2.) Validation of AOD_{MAIAC} against $AOD_{AERONET}$, and 3.) Trend analysis. After the detailed validation, accuracy of AOD_{MAIAC} has been compared with the accuracy of traditional algorithms which has been applied in the same study area in our previous research (Sharma *et al.* 2021).

It was necessary to use the parameter "Optical_Depth_055" that has a quality assurance flag of the highest quality to prevent data from contamination by clouds and other associated errors from occurring during the pre-processing of AOD_{MAIAC}. In the preprocessing of the AERONET data, $AOD_{AERONET}$ was interpolated to 550nm. In order to convert $AOD_{AERONET}$ from UTC to Indian standard time, UTC (Coordinated Universal Time) is extended by 5.5 hours for regional analysis. $AOD_{AERONET}$ is averaged during the satellite passing time window of 10:00 am-2:00 pm at the site of AERONET (Habib *et al.*, 2019; Jiang *et al.*, 2007; Zhang *et al.*, 2016). Using yearly and seasonal AOD_{MAIAC} averages for 2010-2019, we analyzed the spatial distribution of AOD retrieved from satellite and seasonal variations. We have examined the trends in AOD as a function of space and seasonal variation of the products. To assess AOD_{MAIAC}'s spatial distribution over the current study area, a multi-year average of AOD has been calculated from 2010 through 2019.The validation analysis has examined both the point-based collocation and the buffer-based collocation centered on each AERONET site. MODIS provides spatial measurements of AOD during the passing time of satellite, while AERONET provides measurements with high temporal resolution (Terra: 10:30 AM, Aqua: 2:30 PM), twice a day. AOD_{MAIAC}'s pixel value cannot be directly compared to $AOD_{AERONET}$'s point-based measurement. For a correct match between $AOD_{AERONET}$ and AOD_{MODIS}, we averaged (a) the $AOD_{AERONET}$ during satellite passing time,

(b) and AOD_{MAIAC} based on a 3 by 3 spatial window of pixels centered around each AERONET site, to compensate for different types of landmasses and types of aerosol as well (Xie *et al*., 2011). After validation of findings, the average of AOD_{MAIAC} was estimated for 10-years from 2010-2019 to find out the daily averaged median value. Median values minimize the effects of outliers on the trend. Each grid point is fitted with a linear fit in order to determine the slope of the linear trend. A statistically significant linear trend is determined by applying Student's t-tests at the 95 % significant level. Stippling has been used for statistically significant regions in each season, as shown in Figure 7. Using the following formula of Student's t-test, the confidence intervals for trends were calculated as follows:

$$t = r_{xy}\sqrt{\frac{n-2}{1-r_{xy}^2}} \quad \ldots\ldots(2)$$

where r_{xy} = denotes coefficient of correlation for the original and linear time series
n = matchups

Several statistical techniques were employed to evaluate the accuracy of the MODIS MAIAC algorithm retrieval. These include root mean square error (RMSE), mean absolute error (MAE), relative mean bias (RMB), and expected error (EE) etc. Due to poor availability of in-situ data and stations (AERONET) data, the validation was only possible for 2010, 2016, 2017, 2018, and 2019. In order to perform a statistical validation, Number of collocated points (N), Coefficient of Correlation (R), Mean Absolute Error (MAE), Relative mean bias (RMB), Mean Bias (MB), Root Mean Square Error (RMSE), and Expected Error (EE) (Remer *et al*., 2013) have been computed. The equations used is provided as Eq. 3-8. Using the slope of linear regression (Levy *et al*., 2010), the uncertainties associated with surface reflectance can be seen. Based on the expected error envelopes ± (0.05 + 15 %*$AOD_{AERONET}$) derived from MAIAC, the algorithm's performance was evaluated.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|AOD_{(MODIS)i} - AOD_{(AERONET)i}\right| \ldots\ldots(3)$$

$$MB = 1/N\sum_{i=1}^{N}\left(AOD_{(MODIS)i} - AOD_{(AERONET)i}\right) \ldots\ldots(4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(AOD_{(MODIS)i} - AOD_{(AERONET)i}\right)^2} \ldots\ldots(5)$$

$$EE_{MAIAC} = \pm(0.05 + 0.15AOD_{AERONET}) \ldots\ldots(6)$$

RESULTS

AOD_{MAIAC} product's validation

Based on the evaluation of the AOD_{MAIAC} product for the AERONET sites, high correlation between the AOD_{MAIAC} and the $AOD_{AERONET}$ has been observed. The $AOD_{AERONET}$ - AOD_{MAIAC} R value for Amity University is 0.86, while the correlation for Gual Pahari is 0.73. For point-based validation at the AERONET sites (Amity University and Gual Pahari), about 79 % and 74 % of AOD_{MAIAC} retrievals are within the EE envelope, respectively. There has been seen a prominent underestimation (approx. >21 %) for few AOD_{MAIAC} retrievals which has been depicted by the negative bias for the study period

2010-2019 while no overestimation has been observed. Such underestimation in AOD_{MAIAC} might be due to overestimation of aerosol single scattering albedo (SSA).

In the present research, 52 and 53 matchups points of AOD_{MAIAC} with $AOD_{AERONET}$ measurements for the AERONET locations of Amity University and Gual Pahari respectively, have been considered for point-based validations in the present research. Both the stations in Gurugram have a cumulative value of R as 0.81 and RMSE as 0.16, with the total match-up points for both stations being 105 (Figure 2-4, Table 2-3). The value of slope for both sites regression line is greater than 1. In the analysis of correlation between AOD_{MAIAC} and $AOD_{AERONET}$, the slope represents systematic uncertainties, which can be certain model assumptions for aerosol and intercept estimate surface reflectance that deviates from reality (Choudhry *et al*., 2012; Sayer *et al*., 2013). An increasing bias is also observed with increasing AOD when it exceeds 0.5. Therefore, it can be concluded that as the AOD increases the uncertainty of the MAIAC algorithm escalates as well. Similar observations have been found for global studies also where the uncertainty of algorithm of MAIAC increases with level of AOD loading increases (Qin *et al*., 2021) (Fig. 3, Fig. 4, Table 2, Table 3).

Fig. 2: Validation of AOD_{MAIAC} against $AOD_{AERONET}$ over Amity University and Gual Pahari, Gurugram with bins of <0.5, 0.5-1.0 and >1.0. The green line represents a regression line, and the solid black line is 1:1 line.

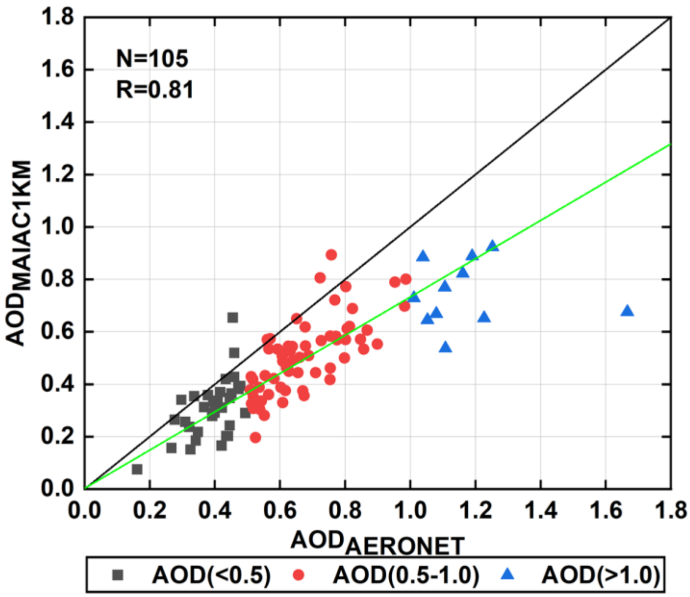


Fig. 3: Buffer validation of AODMAIAC against AODAERONET over Amity University and Gual Pahari, Gurugram. The red line represents a regression line, and the solid black line is 1:1 line.

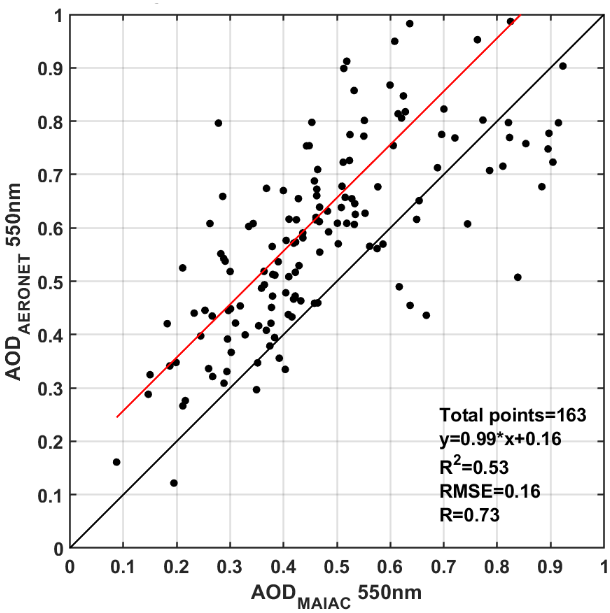
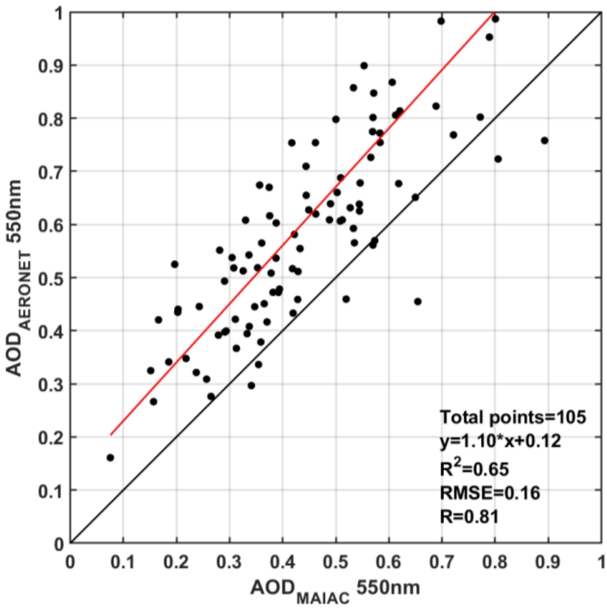


Fig. 4: Point validation of AODMAIAC against AODAERONET over Amity University and Gual Pahari, Gurugram. The red line represents a regression line, and the solid black line is 1:1 line.



Considering the validation of AOD_{MAIAC} using a 3x3 pixels buffer around AERONET sites from the AERONET sites, correlation coefficient have been observed to be low than point-based validation. While the number of matchups for point-based validation is less than that of buffer-based validation (Table 2, Table 3). As a result of these findings, it has been confirmed that the applicability of any type of validation is based on the parameter selected for assessment on a regional scale. The EE has been taken as a primary parameter for validation, therefore, buffer validation is considered as more accurate validation method for the current sites used in the present study over other methods.

Table 2: Statistical summary of point validation for AOD_{MAIAC} and $AOD_{AERONET}$ for Amity University and Gual Pahari, Gurugram

(N: Matchups, MB: Mean Bias, PWE: Percent Within Expected Error, PAE: Percent Above Expected Error, PBE: Percent Below Expected Error, RMSE: Root Mean Square Error, R: Correlation coefficient).

	Amity University	Gual Pahari
PWE	78.85	73.58
PAE	0	0
PBE	21.15	26.42
N	52	53
R	0.86	0.73
RMSE	0.15	0.24
MB	-0.11	-0.22
Equation of Linear Regression	1.07*x+0.083	1.47*x-0.029

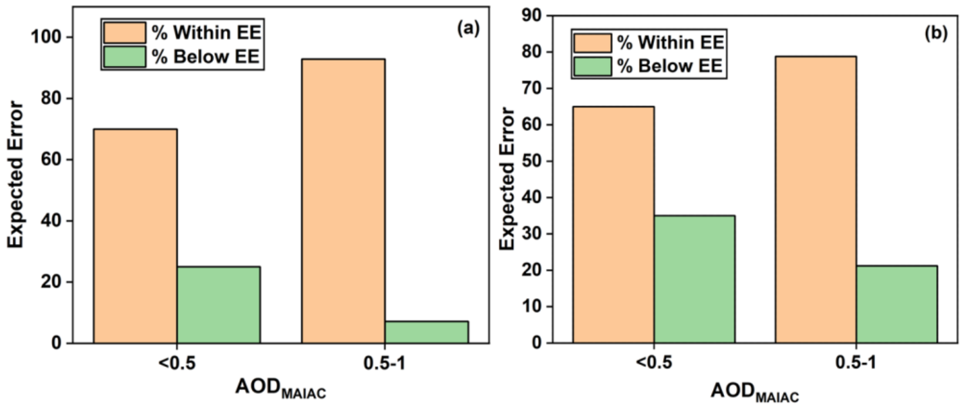
Table 3: Statistical summary of buffer validation for AOD_{MAIAC} and $AOD_{AERONET}$ for Amity University and Gual Pahari, Gurugram

(N: Matchups, MB: Mean Bias, PWE: Percent Within Expected Error, PAE: Percent Above Expected Error, PBE: Percent Below Expected Error, RMSE: Root Mean Square Error, R: Correlation coefficient).

	Amity University	Gual Pahari
PWE	80.85	73.91
PAE	0	0
PBE	19.15	26.09
N	94	69
R	0.71	0.72
RMSE	0.20	0.30
MB	-0.11	-0.24
Equation of Linear Regression	1.21*x+0.011	1.63*x-0.011

Lack of enough $AOD_{AERONET}$ for validation could also affect the accuracy of the validation. To compare AOD_{MAIAC} with $AOD_{AERONET}$, two bins were used, AOD *0.5 and 0.5<AOD>1 (Figure 5). The relationship between AOD_{MODIS} and $AOD_{AERONET}$ can be seen in Figure 2 as a linear one. The highest population for the Gual Pahari site occurs in the AOD values of 0.5-1 and the lowest in AODs greater than 1, while the opposite scenario can be observed for the Amity University site. AOD retrievals in the bin 0.5-1.0 range account for greater than 70 % of all EE retrievals. The atmospheric environment also affects secondary chemical changes in aerosols (Zheng *et al*., 2002). The aerosol size and geometric angle of the satellite also affects the retrieval accuracy of algorithm (Qin *et al*., 2021). Despite MAIAC AOD retrievals being less accurate over bright surfaces than those obtained over dark surfaces, they are still significantly superior to those obtained by either the DT or DB algorithms (Qin *et al*., 2021). Such less explored AERONET sites like Amity University should be considered for study to create local or regional level validations database for further research.

Fig. 5: Expected error representation of AOD_{MAIAC} in AOD bins of <0.5, 0.5-1.0 and >1.0.

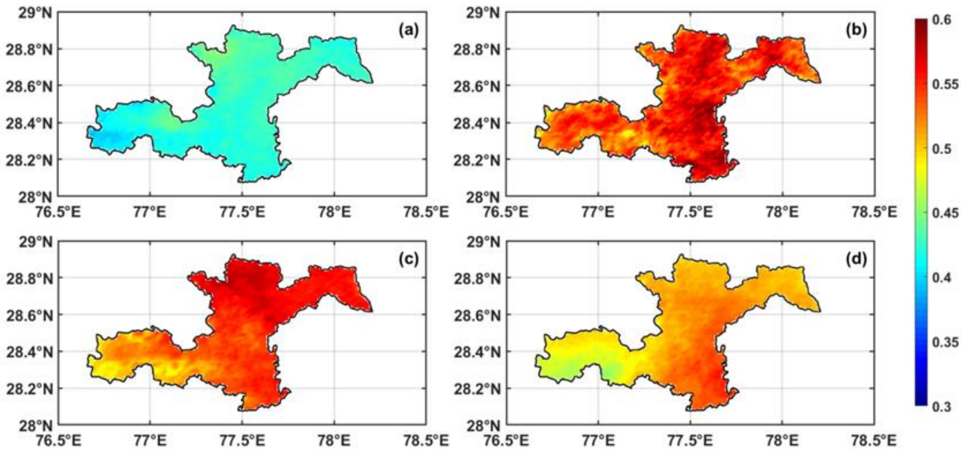


Variations in AOD by season and region

An illustration of the spatial and seasonal variations in AOD from 2010 to 2019 is shown in Figure 6. Variations associated with season can be attributed to a variety of factors, such as conditions related to meteorology, the sources of aerosol, area covered by vegetation, and different phases of crop growth, the present study region contains all of these factors (Dey *et al*., 2020; Mangla *et al*., 2020; Mhawish *et al*., 2017). The results indicated that during the monsoon and the post-monsoon season AOD is high. Earlier studies on the Indian scenario have found similar findings (Kharol *et al*., 2013; Sharma *et al*., 2021). Despite the concept and belief that cloudy days and rainy days can eliminate aerosols, a convincing relationship between aerosols and precipitation has not yet been established over the Indian scenario. This is largely due to erratic rainfall conditions (Kharol *et al*., 2013). The elevated humidity in the air results into more concentrated aerosol particles which are bonded by light rain droplets. During the past several years, the population density of the current study region has increased, and anthropogenic activities as a consequence have also increased in the study area, which has increased the aerosol load also (Ghosh *et al*., 2021; Kumar *et al*., 2021; Kumar & Rao, 2012; Ranjan *et al*., 2022). The spatial variation can be due to emission sources, meteorological conditions, monsoon rains and seasonal variation of dispersion (David *et al*., 2018).

To analyze the AOD_{MAIAC} over a period of many years, the AOD_{MAIAC} has been averaged over the years 2010-2019. This analysis indicates that the monsoon and post-monsoon seasons exhibited high AOD retrievals. To account for the emissions during monsoon season an attribution study would be beneficial to identify the specific contribution due to dust transport and land use. During post-monsoon season, the northwesterly winds transport the aerosol produced due to agricultural stubble burning over the central IGP which could be one of the probable reason for high AOD concentration during that season (David *et al*., 2018). AOD has been observed to increase slightly during the winter season in the current study area compared to the pre-monsoon season (Fig. 6). This region is part of the central IGP, and the shallow atmospheric boundary layer traps pollutants during the winter, leading to hazy conditions (David *et al*., 2018).

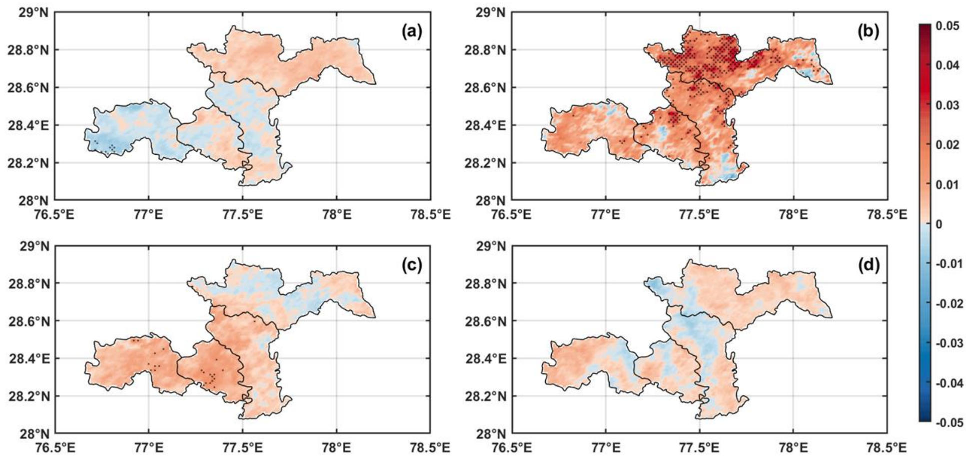
Fig. 6: Seasonal means of AOD_{MAIAC} retrieved over Amity University and Gual Pahari from 2010 to 2019 (a) Pre-Monsoon (b) Monsoon, (c) Post-Monsoon and (d) Winter.



Despite this, the seasonal validation of AOD_{MAIAC} cannot be convincingly quantified due to irregular ground observations and thereby unavailability of $AOD_{AERONET}$ in the current study region. AOD_{MAIAC} and $AOD_{AERONET}$ may be correlated seasonally if AERONET observations are available on a regular basis. While an attempt is made to provide statistics for the available data in data-scanty site which highlights the need of comprehensive web of AERONET sites and regular monitoring of AOD.

The trend of AOD_{MAIAC} was analyzed by examining the annual interval variation of AOD. We calculated the statistical significance using the T-test and stippled the areas with a significant linear trend at 95 % confidence level ($p<0.05$). The statistically significant increasing aerosol trend can be analyzed as the value of p goes greater than 0.05. In addition to the declining trend in aerosol, the negative change has been noted. Monsoon has shown a generally increasing trend, while other seasons have shown relatively less increasing trend (Figure 7). The increasing trend can be contributed by increased instances of agricultural fires as major factors, fossil fuel burning as well as dust transportation and vehicular emissions. Therefore, it becomes necessary to study seasonal and annual trends of AOD at regional or local level. AOD_{MAIAC}'s linear trend, on a regional basis, is 0.00045 (pre-monsoon), 0.0148 (monsoon), and 0.0093 (post-monsoon), 0.0014 (winter) per year. Earlier studies also stated that aerosol levels increase during monsoon for Indian regions because of the anthropogenic sources (Wei *et al*., 2019). Urbanization levels in the NCR reached 62.5 % in 2011 and are expected to reach 71 % by 2021, showing an unexpected increase over the past decade. There are several factors that contribute to this development, including the establishment of center of industries which includes 53 industries from large to small-scale industries, as well. The construction of brick kilns in the current region has also contributed to increased anthropogenic activities (Kumar & Nivit, 2018; Kumar *et al*., 2022; Verma, 2017). During the monsoon season, aerosol loading is extremely high in northwestern India because of severe agriculture and fertilizer use in rural areas (Kuttippurath *et al*., 2020)**.** It may be appropriate to conduct further research into the factors contributing to the substantial rise in AOD as a future focus of the study.

Fig. 7: Statistical significance and trend for AOD_{MAIAC} (a) Pre-Monsoon (b) Monsoon, (c) Post-Monsoon and (d) Winter during the period 2010-2019.



DISCUSSION

The MAIAC algorithm was developed to overcome the limitations of low retrieval accuracy, low retrieval coverage, and coarse resolution of traditional MODIS algorithms. Amongst the traditional algorithms, DT algorithm cannot retrieve the optical properties of aerosols on urban environments (Hsu *et al*., 2004). By refining aerosol optical properties, MAIAC was able to overcome such limitation and meet the needs of regional aerosol monitoring at a more precise spatial scale (Tao *et al*., 2019). Therefore, in the highly urbanized NCR, MAIAC functions better compared to conventional algorithms (Mhawish *et al.*, 2019).

In our previously published research focusing on the performance of the traditional algorithms in the air quality analysis for the present study area, DT has performed better than DB. DT_{3K} has been reported as best compared to other two traditional algorithms (DB_{10K}, DT_{3K}) with R value of 0.70 for Amity University and 0.85 for Gual Pahari. Additionally, an overestimation of 15 % retrievals have also been reported based on the matchup points around 39 and 26 for Amity University and Gual Pahari University (Sharma *et. al*. 2021). While no overestimation has been observed for AOD_{MAIAC} in the present research for the same study area. However, $AOD_{AERONET}$ - AOD_{MAIAC} correlations calculated the R value 0.86

for Amity University and 0.73 for Gual Pahari in the present research. Further, in Shrama *et. al*. (2021), DT_{10K} stood out as the most effective algorithm for both the stations with respect to percentage of retrievals within expected error PWE (63.27 %) for Amity University and for Gual Pahari PWE (100 %). Whereas in the current study for AOD_{MAIAC} data, the PWE for Amity University is 78.85 % and Gual Pahari is 73.58 %, respectively. Therefore, it can be remarked that, AOD_{MAIAC} having the resolution of 1 km outperformed DT AOD product (with the resolution of 10 km and 3 km) in case of Amity University but not in Gual Pahari.

Results of the present research has confirmed the hypothesis that better resolution of satellite derived AOD product is not only factor that will decide its potential in micro studies compared to other AODs with poor resolution. Retrieval uncertainties can differ within neighboring regions with the variation of natural and anthropogenic parameters.

Present study has also observed underestimation of AOD retrieved by MAIAC. The bias of the MAIAC algorithm increases as the AOD value exceeds 0.5. In several global and regional studies, the uncertainty of the MAIAC algorithm has been obtained and increases with rising AOD (Qin *et al*., 2021; Mhawish *et al*., 2019). A number of other factors also affect the accuracy of retrieval at regional scales, including secondary chemical changes, aerosol size, and geometric angle, as has been observed in other studies (Qin *et al*., 2021; Zheng *et al*., 2002). In the present study area, the accuracy of AOD retrieval over bright surfaces is lower than that of AOD retrieval over dark surfaces (moderate vegetation). However, it is still better than DB and DT retrieval over bright surfaces. Recent worldwide studies focusing on South Asia reported similar findings (Mhawish *et al*., 2019; Qin *et al*., 2021). According to the results, AOD is high during the monsoon and post-monsoon seasons.

In the current study the significant increasing trend during monsoon was observed. Evidences of increased AOD during the monsoon season due to anthropogenic sources and other factors has also been reported in previously published research for Indian regions (Kharol *et al*., 2013; Mhawish *et al*., 2021; Ramachandran *et al*., 2020; Sharma *et al*., 2021; Wei *et al*., 2019). Based on a global study concerning MAIAC retrieved AOD, an overestimation was found (more than 21.64 %) for the entire semi-arid zone, whereas no overestimation was detected in the present study. Global studies have the limitation of categorizing a wide area into one zone, while the situation at the local level may differ. In the studies of South East Asia aiming on semi-arid areas of China and Pakistan, MAIAC retrieved more than 70 % of the AOD within EE (Mhawish *et al*., 2019; Qin *et al*., 2021; Zhang *et al*., 2019). Similar observations have also been obtained for the semi-arid areas of NCR in the present study. The results of several previous studies, indicate that a certain amount of uncertainty remains due to assumptions made in the algorithm based on regional factors (Choudhry *et al*., 2012; Sayer *et al*., 2013; Zhang *et al*., 2019). In future work, the accuracy of MAIAC AOD should be compared with the magnitude of the AOD, the aerosol size, the season, the surface type, and other considerations.

CONCLUSIONS

Newly launched high-resolution MAIAC aerosol product has been validated in the present research in highly urbanized and polluted areas of Faridabad, Ghaziabad, Gautam Budh Nagar, Gurugram, which are the constituent districts of NCR. This group of four highly industrialized districts with heavy aerosol loading is afflicted by the poor spatial network of AERONET stations and thus lack continuous monitoring of aerosol pollution. Further, due to the coarse resolution of the existing satellite-based aerosol product theses four district have always been studied as a part of the entire NCR along with Delhi. Therefore, long-term aerosol monitoring exclusively in these districts are rare due to the lack of high-resolution aerosol product. With this study, we have validated high-resolution MAIAC aerosol product for the present study area, so that in addition to global applications, such products can also be used to monitor aerosol pollution at meso- and micro-scales in India.

Such evaluation reveals that 77 % MAIAC retrieved AOD are within expected error, while 21 % are underestimated as compared to $AOD_{AERONET}$. Further, present research proves the efficacy of AOD_{MAIAC} by estimating high correlation between AOD_{MAIAC} with $AOD_{AERONET}$ from 2010 to 2019 (R: 0.73 and 0.86 at AU and GP respectively). It is important to remark that satellite-derived AOD maintains high correlation with in-situ observations both at a rural site of Amity University and a semi-urban site of Gual Pahari. Moreover, the spatio-seasonal variations in AOD from 2010 to 2019 has demonstrated an increasing trend in AOD during the monsoon season due to the erratic rainfall and anthropogenic activities that result from unplanned urbanization in the current study area. Further the interannual variability of AOD has exhibited an increasing trend of AOD in all the seasons, especially in the monsoon which emphasized the poor air quality in the present study area. Present research drew the attention towards underexplored study area, identifies it as hot spot of aerosol loading and provides a baseline for further research on air quality using high-resolution MAIAC derived AOD which can contribute to achieve clean air. Moreover, this study prioritizes the need for good spatial network of AERONET stations which provides continuous in-situ observations which can be integrated with satellite-derived observations to strengthen such long-term monitoring of aerosol loading.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript.

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