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Seasonal Aerosol Classification Over South Asia by Satellite based Atmospheric Optical Data

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Abstract: Aerosol optical characteristics have been investigated to explore regional and seasonal inconsistencies of aerosols and to define the dominant type throughout South Asia from 2001 to 2021. MODIS aerosol products from collection 6.1 have been used in present study, that comprise daily values of Angstrom exponent (AE) and aerosol optical depth (AOD) data. MODIS-derived AODs are validated by using nine ground-based AERONET station data. Overall, an adequate correlation is found among the two datasets. However, an overestimation of the MODIS retrievals is found in one site named Jaipur and underestimations are found at two sites named as Gandhi-college and Karachi. The seasonal evaluation shows that aerosol distribution found between 0 and 1.05, depending on the change in geographical location. The highest AOD value originates over the Indo-Gangetic plain (IGP), mostly throughout warm season. The second maximum AOD value covers a large area of South Asia during spring, summer and autumn. The lowest values of AOD are found in winter season excluding the IGP. A region with high aerosol optical depth (AOD) values support a low value of angstrom exponent (AE) indicating the coarse aerosol during warm seasons (spring and summer) over IGP. The region with high AOD and high AE values is showing fine aerosol during the mild to cold seasons (autumn and winter). The threshold values for AOD and AE have been used to classify aerosols. The results demonstrate that urban/industrial aerosols prominent in every season across the region dominate in spring and summer due to frequent occurrence of dust events. The mixed type aerosol is second largest contributor in aerosol formation in all seasons. The Biomass burning/smoke aerosol is dominant over IGP due to open forest and crop burning in autumn. Clean and maritime aerosol has small unnoticeable involvement in the studied region.

Keywords: Aerosol, classification, IGP, South Asia.

Introduction

Aerosols are the most changeable element of the Earth's atmosphere that have been identified as a key contributor to the climate and radiative balance (Zhu, 2019). Aerosols can absorb or deflect land and solar radiation and producing the heating and cooling effect for earth system that base on their optical and physical characteristics (Giles, 2012). Hygroscopic aerosols can also contribute as condensation nuclei and affect cloud reflectance and rainfall formation in an indirect manner (Alizadeh, 2018). Different optical and microphysical properties of aerosol have been used to classify of aerosol around the world (Valentini, 2020). The AOD and AE are the two major columnar aerosol characteristics used to categorize aerosols. The first is used to calculate the amount of aerosol, whereas the second is an estimate of aerosol size. Mhawish et al. (2017) analyzed AOD retrieval algorithms for classification of aerosol, such as fine, mixed and coarse aerosols. Dust aerosols have a low AE and high AOD value, whereas maritime aerosols have a high AE and low AOD value. In contrast, Sreekanth (2014) identified the anthropogenic aerosols by using high values of Aerosol optical depth and Angstrom Exponent. The following is the most prevalent aerosol categorization in the literature: (a) desert dust; (b) industrial/urban aerosols released by burning of fossil fuel; (c) maritime aerosols; (d) smoke/BB from forest fires and open crop burning and (e) mixed type of aerosols (Hamill, 2016). Due to lack of a ground-based network, satellite network is primary method for determining spatial and temporal variability of aerosol at local to global level (Sabetghadam, 2018). Due to significant uncertainties in satellite-derived aerosol products, ground-based aerosol data have been used to validate the satellite-based aerosol data (Benkhalifa, 2017). MODIS provides significant and good worldwide coverage, as well as nearly daily AOD data, which indicates aerosol load in the atmosphere that influence the radiation budget of earth (Luo, 2014). Numerous studies have conducted to compare and evaluate satellite-derived AOD with ground-based aerosol data (Rupakheti, 2018) across the world (Boiyo, 2017; Bilal, 2018a; 2018b; 2019; Liu, 2018). Nevertheless, the satellite-derived AOD is always with some anomalies because of the diverse landform, and cloud contamination (Kang, 2016).

In the present study, aerosol parameters AE and AOD are studied over South Asian region for the past two decades; from 2001 to 2021 to examine regional and seasonal variations of aerosols. Ground-based AERONET aerosol data has been used to validate the satellite-based aerosol data to verify the accuracy of satellite-based products. The satellite-based classification technique, using AE and AOD is applied to examine the contribution of the leading type of aerosol over South Asia. The results are evaluated to provide an understanding of the spatiotemporal distribution and seasonal pattern of the region's aerosol types.

Materials and Methods

South Asia contains the eight countries according to SAARC, named Pakistan, India, Bhutan, Nepal, Afghanistan, Bangladesh, Maldives and Sri Lanka. South Asia generally includes the land around the Arabian Sea (Fig. 1). The region has three different climate zones. The climate condition of South Asia is highly affected by the pattern of the monsoon that brings the irregular phases of dry and wet weather. Summer (JJA) in South Asia experiences the wet monsoon due to moist winds that blow from the sea, whereas due to dry winds that come from land, winter (DJF) experiences the dry monsoon in the study region (Ramachandran et al., 2015). For the detailed study, highly polluted cities that are influenced by different anthropogenic emissions, along with natural aerosols, have been selected (World Air Quality Report, 2018). According to Intergovernmental Panel on Climate Change (2014) South Asia is likely to be affected by global warming that increase the dry and hot days in this zone. South Asia has experienced the maximum increase in AOD since 2010 (Pozzer, 2015). With the growing urbanization, intense industrialization and high population, the aerosol load is continuously rising in the region, especially in IGP (Wang, 2014). In contrast, the extreme aerosol loading over South Asia has the potential to cause a great number of early mortalities, a high risk of different and sever health issues such as cancer (Behrooz, 2020). Different urban region in South Asia have different natural and man-made activities that produced different aerosol sources. Thus, aerosol properties in South Asia have been highly fluctuating on temporal and spatial scales (Lawrence and Lelieveld, 2010).

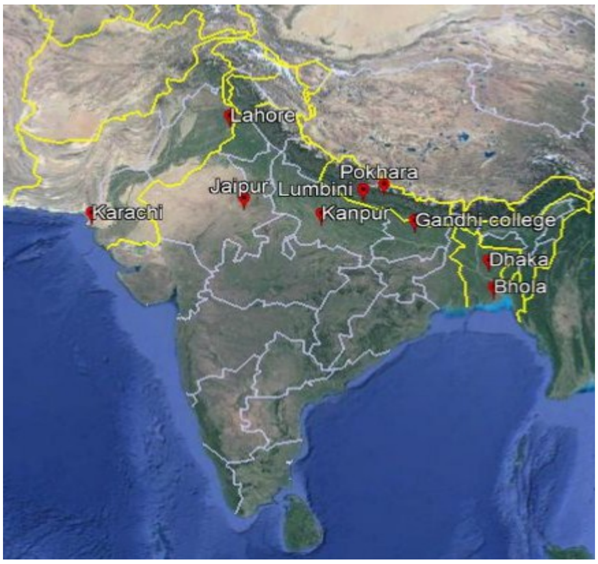


Fig. 1 Google earth-based Locations of selected AERONET sites.

Satellite Dataset

The MODIS terra and aqua satellites are optical sensor instruments that detect the related parameters of aerosol globally. In the present study, MODIS aerosol products in Level 3, collection 6.1 with 1◦ × 1◦ spatial resolution are used over a time span from January 2001 to December 2021, which includes the AE and AOD at 550 nm for South Asian region. The deep blue algorithm is utilized for the obtaining of aerosol data over the study area. The MODIS AOD was retrieved at a 550 nm of wavelength for the study region (Remer, 2008). Conversely, the Angstrom Exponen shows the size distribution of aerosols in the atmosphere. Angstrom exponent values greater than 1 are associated with the surplus of fine particles, while angstrom exponent values less than 1 demonstrate the dominance of coarse aerosol in the atmosphere (Remer, 2008). To identify the leading aerosol type, AE and AOD combinations are commonly used (Rupakheti, 2019; Chen, 2020). Daily average values of AE (Angstrom Exponent) and AOD (Aerosol Optical Depth) over South Asia from the MODIS aqua satellite are utilized in this study. Data is obtained from the website: http://giovanni.gsfc.nasa.gov/giovanni. These data sets are utilized to examine the temporal and spatial aerosol parameters and to identify the dominant type of aerosol over South Asia. Averaged data from summer (JJA; June, July, and August), spring (MAM; March, April, and May), winter (DJF; December, January, and February), and autumn (SON; September, October, and November) were examined. Furthermore, the grouping of AE and AOD data was used to identify the prominent season-based aerosol types.

AERONET Dataset

AERONET is a ground-based sky-radiometers and sun-photometers station that provides real-time aerosol and related parameter data across the world (Holben, 2001). Data is obtained from http://aeronet.gsfc.nasa.gov/. The AERONET provided data in three levels: the first is level 1.0 data that contains pre-screened data. The second type of data is level 1.5 that includes cloud-screened data (Dubovik, 2000). Third is level 2.0 data that covers quality assured and cloud screened data (Giles, 2019) and this data can be utilized for a precise measurement of aerosol parameters (Dubovik, 2002). AERONET provided level 2.0 AOD data are significantly accurate with 0.01% uncertainties (Sayer, 2014) and that is why this data is generally utilized to verify satellite observations. In the present study, AERONET level 2 version 3 daily based data is used for validation of satellite data from nine stations across Southeast Asia. The location of the selected sites (Table 1, Fig.1). These sites have been selected because of their long-term data series in South Asia.

Verification of Satellite AOD with AERONET AOD

The long-term seasonal variation of AE and AOD is investigated over the study region. The uncertainty in satellite measurements can be found by comparing ground-based and satellite-derived aerosol data. In the present study, Nine AERONET sites (Table 1), are

Table 3 Summary of statistical metrics between the AERONET and MODIS AOD at each site.

Sr.	Sites	Days	r	RMB%	RMSE	EE %within (EE)	EE %above (+EE)	EE %below (-EE)
1	Bhola	193	0.80	17.4	0.26	62.7	3.6	33.7
2	Dhaka	349	0.77	17.2	0.38	64.7	2.6	32.6
3	Gandhi-College	1162	0.32	-35.1	0.41	35.8	8.4	56.7
4	Jaipur	520	-0.04	25.6	0.44	35.6	43.0	21.3
5	Kanpur	2603	0.80	11.0	0.15	69.7	7.4	22.9
6	Karachi	1673	0.32	-31.9	0.23	31.7	7.5	60.7
7	Lahore	1583	0.78	4.0	0.18	68.1	20.8	11.1
8	Lumbini	111	0.68	17.9	0.39	43.2	12.6	44.1
9	Pokhara	912	0.54	-67.8	0.53	18.1	1.8	80.1

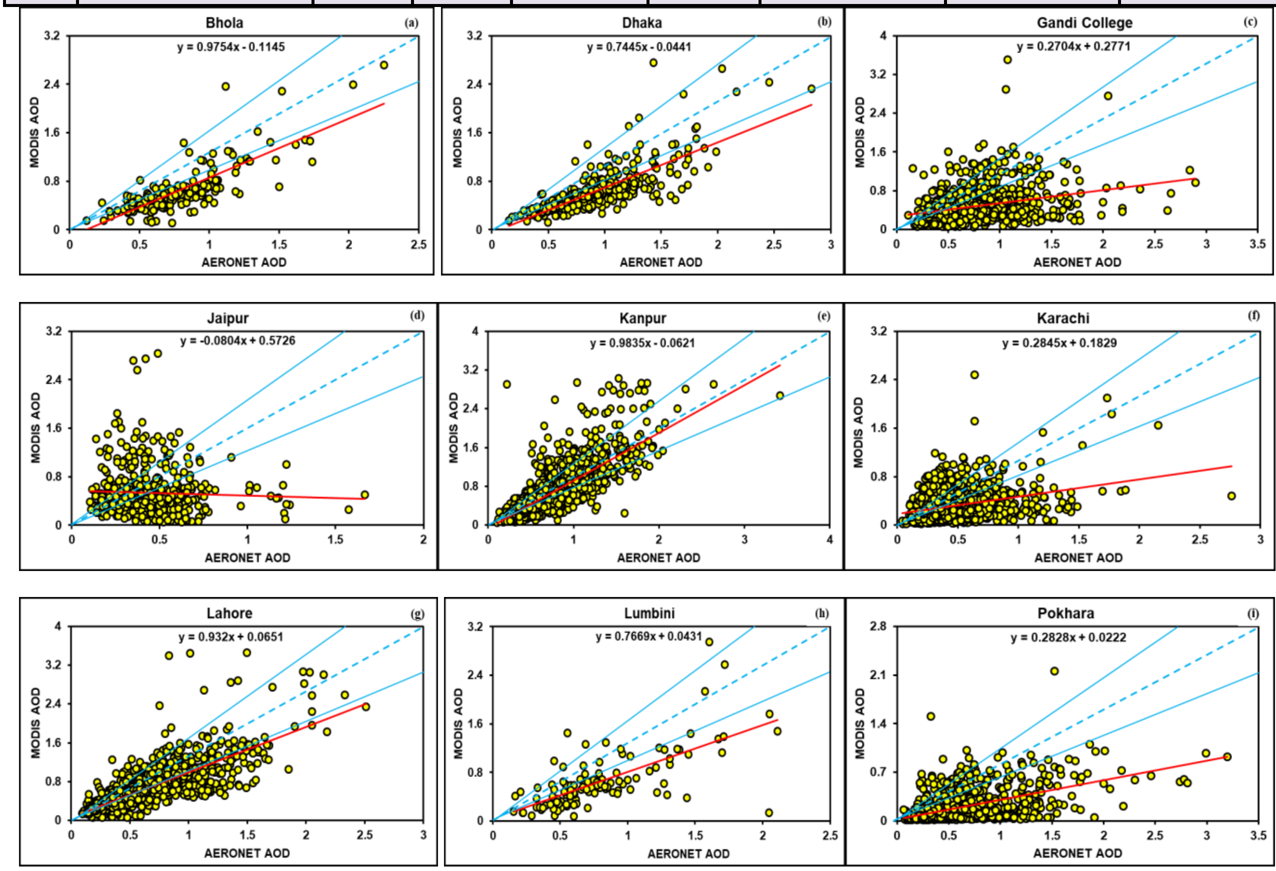


Fig 2: Scatter plots between AERONET and MODIS AOD at 550 nm (λ) at the selected sites over South Asia including (a) Bhola, (b) Dhaka, (c) Gandhi-College, (d) Jaipur, (e) Kanpur, (f) Karachi, (g) Lahore, (h) Lumbini and (i) Pokhara. The r value is significant (p value <0.01) for all sites. The dashed blue lines illustrate the identity line, the solid blue line depicts the lower and upper Estimated Error area and the red line indicate the regression line.

utilized for the assessment of the satellite-based (MODIS) data over South Asia. It is important to change the MODIS AOD and AERONET values on the same wavelength to achieve the purpose. AERONET AE (440–870 nm) and AOD 500 nm are used to convert the AERONET AOD 500 nm at the wavelength of 550 nm (Bibi, 2015):

$$AOD_{550} = AOD_{500}\,(550/500)^{-AE}$$

Algorithm for Aerosol Classification

Assessment of various aerosol types is a significant problem for the climatic researcher that may give the detailed evaluation of the impact of radiation on aerosol (Satheesh, 2005). Gobbi and Barnaba (2004) have introduced a very appropriate algorithm to determine the different classes of aerosol based on AOD and AE. MODIS satellite retrievals are utilized for the aerosol classification over South Asia, where air masses and atmospheric circulation also affect aerosol types (Valentini, 2020). In this study, aerosols have been categorized into six classes, such as urban, smoke/biomass burning, clean, desert dust, maritime and mixed type aerosols. AE and AOD threshold values have been used for aerosol classification that mentioned in Table 2. This classification based on a literature review (Higurashi, 2002; Barnaba, 2004; Pace, 2006; Kaskaoustis, 2007; Mulcahy, 2009; Pathak, 2012; Pawar, 2015; Penning, 2015; Alam, 2016; Sabetghadam, 2020). It is important to mention that different threshold values may change the occurrence rate of each type. Thus, there are no set standards for these critical thresholds. These are generally site-specific (Patel, 2017).

Table 2. Threshold for Aerosol Classification.

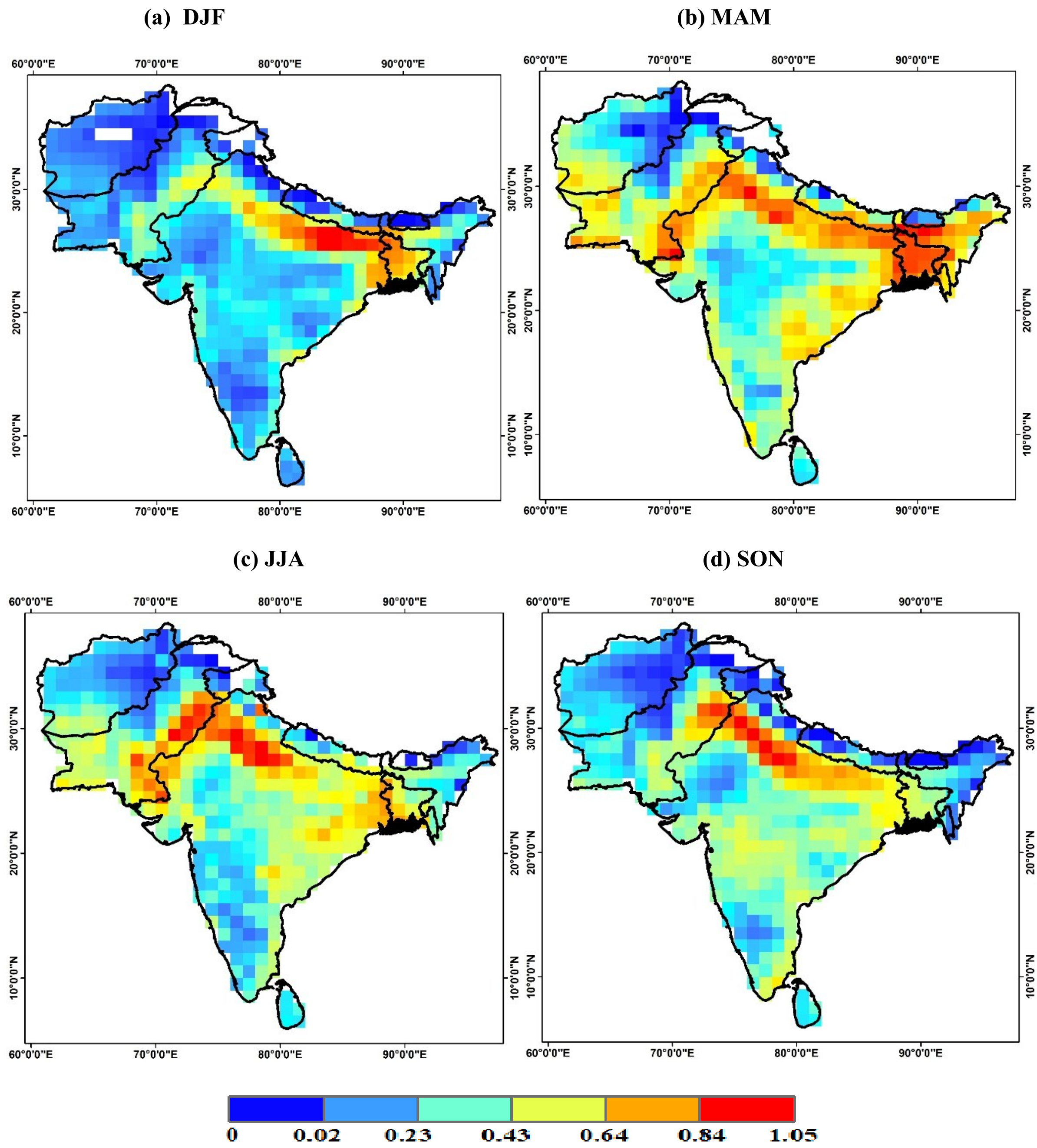
Aerosol type	AE	AOD
Urban	>0.8	>0.25
Biomass burning/smoke	>1.3	>0.4
Maritime	<0.9	<0.15
Desert dust	<0.6	>0.4
Clean	<1	<0.2
Mixed type	Remaining	Remaining

Results and Discussion

Validation of AODs

Before the validation of MODIS satellite AOD retrieval over South Asia, it is important to note that the sampling techniques of satellite data are relatively different from AERONET (Sayer, 2014). Nevertheless, it contributes to a rough evaluation of the satellite demonstration in the aerosol optical depth (AOD) retrieval algorithm. There are limited AERONET sites and only a few give long-term data series for study, which makes it challenging to properly assess the errors in satellite retrievals. Fig.2a to Fig.2i show the validation of the daily average value of AERONET

Seasonal patterns of AOD and AE over study area



AOD and MODIS AOD with the regression equation at nine selected sites. Table 3 shows the related statistical metrics at the respective sites. The results show the justified correlation between the AERONET and MODIS AOD data almost all over the selected sites in South Asia. The correlation coefficient value is >0.6 at five sites named Bhola, Dhaka, Kanpur, Lahore and Lumbini, representing the good correlation between MODIS AOD and AERONET data and has a high % of retrievals within the EE 62.7%, 64.7%, 69.7%, 68.1% and 43.2% respectively. Variances in correlation coefficient may be caused by various aerosol types that cover the study area. Furthermore, it seems that the satellite-based AOD is influenced by the land cover type (Holben, 2001). Conversely, the r-value is found to be <0.6 at Gandhi-College, Karachi and Pokhara due to predominance of coarse aerosol because the adjacent area is covered with desert (Zia et al., 2017; Alam et al 2011a). The MODIS-based AOD is significantly overestimated (RMB = 25.6%), with 43% of the data being above the EE (+EE) at Jaipur and underestimates (RMB = -35.1%, -31.9%) with 56.7%, 60.7% of the data below the EE (− EE) at Gandhi-College and Karachi, respectively. Rupakheti (2019) and Bilal (2016) evidently mentioned in their studies, that high underestimated AOD values are generally produced as a result of errors in the aerosol technique utilized for aerosol inversion along with the

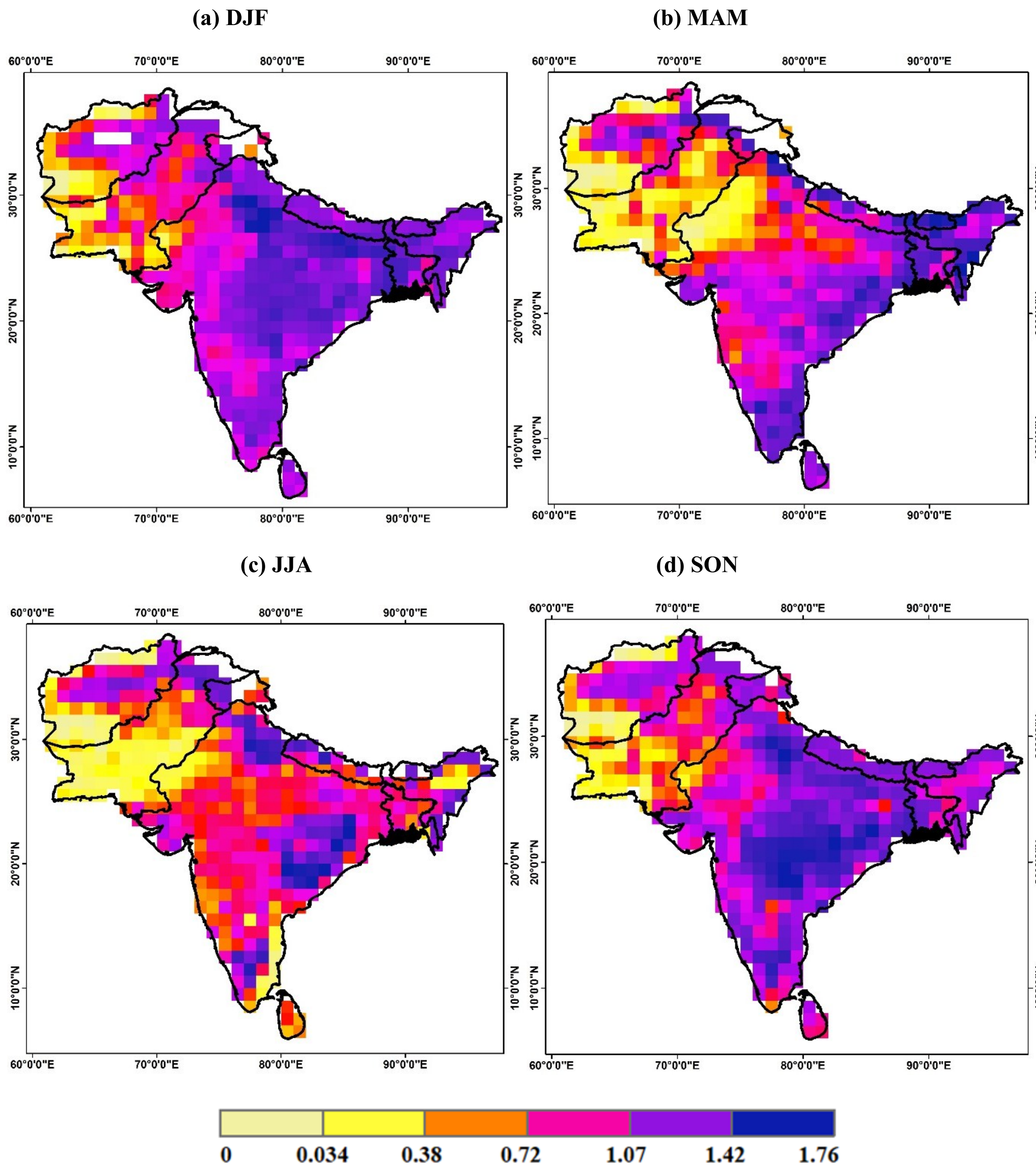


Fig. 4 Seasonal pattern of Angstrom exponent (AE, 470–660 nm), Like Fig. 3

effect of the planetary boundary layer on MODIS-based AOD.

Figure 3 represents the seasonal pattern of AOD as to describe the amount of aerosol over South Asia from January 2001 to December 2021. AOD values ranging from 0 to 1.05 show the inconsistency of aerosol loadings over the study area as a result of diverse topography (Fig. 3). Seasonal evaluation (Fig. 3a to d) indicates the maximum values of aerosol loads over IGP generally found in summer, spring and autumn, whereas the winter season also shows high value of AOD over the eastern side of IGP in South Asia. Afghanistan has the lowest value of aerosols in all seasons. This is constant with earlier researches that found high value of AODs over South Asia as a result of forest and crop-residue burning events during autumn and dust storms during the warm (summer and spring) season (Zia, 2017). Seasonal AOD may be inconsistent due to various seasonal phenomena for the development and elimination of aerosols in the atmosphere, accompanied by air masses that transference aerosols from distant sources in individual seasons (Kaskaoutis, 2012). Dust events eventually increase over a major part of South Asia in spring and summer, as a result an increase in AOD in warm season (Alam et al., 2011c). Alam (2014) concluded that dust activities occurring due to Thar and Thal

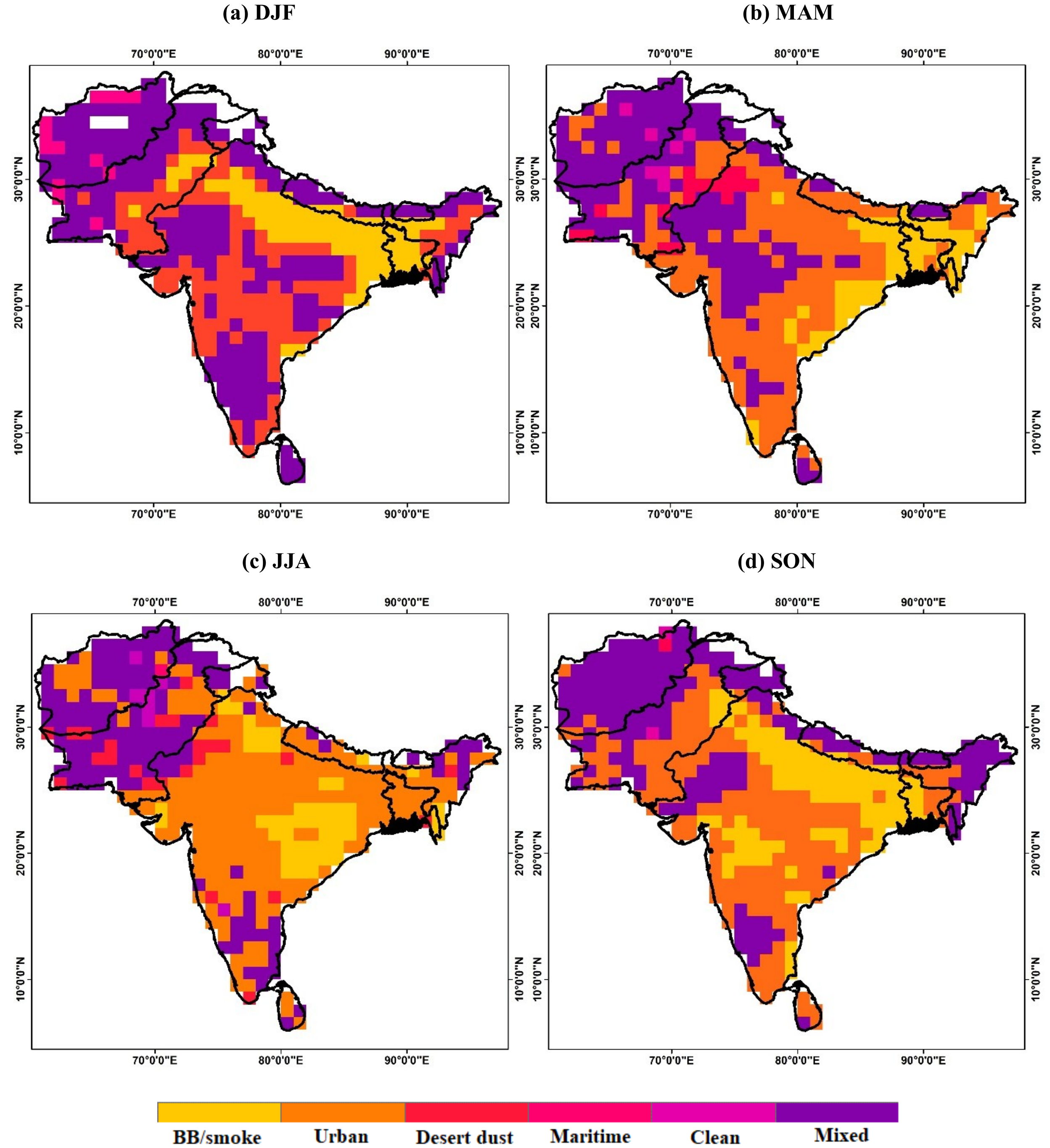


Fig. 5 Seasonal aerosol classification over the South Asia averaged during 2001–2021.

Deserts in northeastern and southeastern Pakistan and India are common in the warm season than in cold season. Moreover, aerosols are transferred or removed by rainfall and wind, which primarily reduce the values of AOD because of the clear sky in winter. The spatial distribution of AOD values indicates the highest and second highest values of AOD range between 0.65 to1.05 primarily originate over the IGP in South Asia, and the third-highest AOD value lies between 0.44 to 0.64, almost covering the entire subcontinent during the spring, summer, and autumn seasons (Fig. 3b, c, and d). This is similar to previous studies that IGP is recognized as a hot-spot region in South Asia with the maximum rate of dust events in the warm season and open crop burning in autumn (Zia, 2017; Alam, 2011c). The third maximum AOD value is visible throughout India and Pakistan, and it is especially noticeable in the spring, summer, and autumn.

The seasonal distribution of the averaged Angstrom Exponent values is shown in Fig 4 for the period of 2001-2021. The AE values lie between 0 to1.76, indicating the extensive range of aerosol sizes over the South Asia. Seasonal AE variation indicates the areas with the maximum values of AOD in Fig. 3 have significantly lower AE values (i.e., coarse aerosols) over some parts of South Asia that are more noticeable in warm season (summer and spring). The loading of coarse aerosols is possibly released from the deserts in the region. Moreover, areas with higher values of AOD and with higher values of AE (Fig 3 and 4) covers a major part of South Asia and shows the predominance of fine aerosols as a result of open crop and forest burning in autumn and winter. The size parameter AE is usually found to be larger during open burning activities, indicating the high proportion of finer aerosols (Kumar, 2015; Kumar, 2018a). The IGP is a significant aerosol hotspot region with annual average value of AOD > 0.5 throughout the year (Kumar, 2018a). The aerosol load increases even more through open burning months, with AE > 1.2 and AOD values > 1.0 (Kaskaoutis et al., 2014). The concentration of finer aerosol increased over IGP toward the open-burning downwind areas, assisted by north-westerly airflow (Kumar et al., 2018a).

Classification of Aerosol

Classification of aerosol over South Asia in four seasons based on the threshold values (Table 2, Fig.5). Aerosol types have the same spatial resolution that is 1◦X1◦ as the actual satellite data, utilized for the analysis. Seasonal aerosol types reveal that mixed aerosol type dominates over Afghanistan in every season. Industrial/Urban aerosol types cover a major portion of South Asia in all seasons (Fig. 5a and d). This result is similar to the aerosol classification where BB/smoke and urban aerosol types are prominent aerosol types in South Asia (Ramachandran, 2020).

In South Asia during winter (Fig. 5a) and spring (Fig. 5b), mixed type aerosol is the second-highest contributor in aerosol formation after urban aerosols. IGP is known as an industrial hub in South Asia that may cause urban industrial and BB/smoke aerosol over the IGP zone. Different anthropogenic activities may cause urban/industrial aerosol over the entire study area, and crop-residue burning, particularly in India and Pakistan, is the main source of BB/smoke aerosol throughout the autumn and winter (Kumar et al., 2018). Aforementioned studies have also shown the excessive contribution of urban and BB/smoke aerosols over the study area (Azhar, 2019) that is also shown in the spatial distribution of AOD in Fig. 3. Alizadeh-Choo bari et al. (2016) show the westward transport of dust from the desert land of India to eastern Pakistan. The occurrence of frequent dust storms during spring and summer, a small amount of desert dust aerosols is also dominant in some parts of India and some parts of southern Pakistan. The long-range transport of different fine aerosols such as local pollution and regional sea/maritime aerosol from the Arabian sea may lead to the mixed type of aerosols into the local region (Eck, 2008; Basart, 2009). During winter and spring (Fig. 5a and b), the western parts of Pakistan and the middle parts of India are dominant by mixed-type aerosol in all seasons but experience more load of mixed type of aerosol during winter and spring. During summer and autumn, the mixed type of aerosol is leading over some parts of the area, although the distribution of remaining types is comparable to detected in the other three seasons, although with a decreased spatial variation. However, clean and maritime aerosols have a small measurable influence on aerosol spreading over the whole region.

Conclusion

Aerosol parameters such as AE and AOD have been studied over South Asia to observe the regional and seasonal variation of aerosols and to classify the aerosol from 2001 to 2021. There is a rational correlation between the satellite-derived AODs and the AERONET-derived AODs. Nevertheless, underestimation of MODIS AOD retrievals is found on two sites, Gandhi College and Karachi, where high AERONET AOD values are identified and overestimated on one site, Jaipur. Seasonal AOD patterns have been studied over South Asia. The highest values of AOD are found over IGP in South Asia during spring, summer and autumn seasons, while the eastern side of IGP in the winter season has the highest value of AOD. Second and third maximum AOD values are found over the rest of Pakistan and India, while Afghanistan, Bangladesh, Nepal and Bhutan experience the lowest values of AOD during all seasons. This seasonal variability is because of different seasonal phenomena that occur in the region, such as dust storms in spring and summer, crop and forest burning in autumn. Seasonal average value of AE lies between 0 and 1.76 that indicate the variation in aerosol size over the region. High values of Angstrom Exponent are found in autumn and winter over the eastern side of the region depict the dominance of fine aerosol because of crop burning and biomass burning, while low values of AE in summer indicate the high amount of coarse aerosol due to desert dust. The seasonal aerosol classification demonstrates the high proportion of urban/industrial aerosol type during each season that almost cover the entire region. The mixed aerosol is the second-largest contributor in aerosol composition in each season, particularly in spring and winter. IGP experienced the biomass burning/smoke aerosol during autumn and winters. Afghanistan regularly experiences mixed aerosol types during the whole year. Lastly, clean and maritime aerosols have less noticeable involvement in the aerosol loading of the entire region.

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