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ORIGINAL ARTICLE

Spatiotemporal Investigations of Aerosol Optical Properties Over Bangladesh for the Period 2002–2016

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Abstract

This study investigates the aerosol optical properties over Bangladesh using Terra MODIS-based collection 06 (DT and DB) aerosol optical depth (AOD), ozone monitoring instrument (OMI)-based aerosol absorption optical depth (AAOD), emission database for global atmospheric research (EDGAR) measured black carbon (BC) and organic carbon (OC), and modern-era retrospective analysis for research and applications (MERRA) retrieved dust. In addition, ground-based aerosol robotic network (AERONET) retrieved optical properties such as aerosol volume size distribution, single scattering albedo (SSA), and asymmetry parameter (ASY) are studied in understanding the behavior of aerosol properties. Both the satellite-based MODIS DB and DT algorithms detect the high AOD (> 0.5) all over Bangladesh except for a small portion in the eastern side. High AOD is also observed in all seasons except for SON. AOD significantly (at 95% level) increased over the period 2002–2016. The correlation coefficient between MODIS and AERONET AOD at Dhaka University site is 0.78 (0.76) for DT (DB). The Expected Error envelope is found 75.70% (54.38%) with small (large) RMSE for DT (DB) product. OMI-based AAOD indicates the presence of absorbing aerosols over the study area which is confirmed with AEROENT-based SSA and ASY. Three different types of absorbing aerosols such as BC, OC, and dust are identified from the EDGAR and MERRA data. In Bangladesh, the BC, OC, and dust are significantly (at 95% level) increasing. Further work is suggested to simulate and assess aerosols against the observations, which will help projecting aerosols in the future climate.

Keywords Aerosols · Bangladesh · Collection 06 algorithm · MODIS · AEROENT

1 Introduction

Bangladesh is one of the most polluted areas in the world and has become an air pollution hotspot due to the impact of its huge population along with their activities (Emberson et al. 2009). The transportation section is one of the most important sources of air pollution in Bangladesh (Sheel et al. 2014). Moreover, air quality in Bangladesh is essentially controlled by the long-range transport of pollutants, emissions of industrial pollutants, and biomass burning from surrounding areas—especially from India (Ali et al. 2019; Almazroui 2019). Therefore, the country suffers a lot from air pollution, which consists mainly of aerosol particles. The size of aerosols varies with diameters from 10^{-3} to 10^{2} µm (Sun et al. 2016). They originate from both natural and human sources in the form of mineral dust, volcanic dust and ash, biomass burning, mist, fog, smoke, sea salt, and particulate pollution (Ali and Assiri 2016; Bilal et al. 2016). Atmospheric aerosols—especially particulate matter (PM2.5 and PM10)—can exert a significant influence on the Earth's atmospheric energy balance, and can impact visibility, air quality, hydrological cycles, ecosystems, precipitation, human health, and agriculture (Hu et al. 2014; Levy et al. 2015). Aerosols play a vital role in the Earth's climate by altering the radiative energy budget of the Earth-atmosphere system through their direct, indirect, and semi-direct effects (Ali et al. 2017). Aerosols have large spatial and temporal variability and are thought to be one of the main factors in the global climate change of recent decades (IPCC 2013). Till date, the behavior of aerosols in the atmosphere is uncertain and not well understood. To reduce aerosol uncertainty behavior, it is essential to have exact,

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reliable spatiotemporal measurements on local to global scales (Bilal et al. 2016).

Aerosol optical depth (AOD) is the principal optical parameter for aerosol measurements. Satellite remote sensing is a useful technique for the monitoring of spatiotemporal aerosol distributions at both global and local scales (Holben et al. 2001). Satellites use visible and near IR channels to achieve accurate estimates of aerosol information (Ghasem et al. 2012). For example, over land, certain arbitrariness in the computation of surface reflectance and the choice of aerosol model in the lookup table generate uncertainty in satellite retrieval of the AOD (Kaufman et al. 1997). Over the ocean, the accuracy of aerosol monitoring using satellite data is satisfactory (Tanre et al. 1997).

The National Aeronautics and Space Administration (NASA) launched both the Terra and Aqua satellites, which carry the moderate resolution imaging spectroradiometer (MODIS) under the Earth Observing System (EOS) program to monitor different atmospheric characteristics including aerosols (Salomonsen et al. 1989). The errors and uncertainties in methodology due to assumptions about the Earth's surface, aerosol types, and sensor aging are addressed in the satellite-based MODIS aerosol products (Levy et al. 2010).

Different research groups have proposed different algorithms for monitoring aerosols using satellite data. Several researchers have validated the MODIS aerosol estimation algorithm for improvement and modernization (e.g., Levy et al. 2013; Sayer et al. 2014). The dark target (DT) and deep blue (DB) algorithms are two types of independent MODIS aerosol estimation algorithms. The DT algorithm is suitable over dark land surfaces (Kaufman et al. 1997), whereas the DB algorithm is suitable for bright surfaces (Hsu et al. 2004). Subsequently, Levy et al. (2013) modified the DT algorithm, while Hsu et al. (2013) modified the DB algorithm of C-06. In this study, we used Terra onboard MODIS C-06 DT and DB AOD at 550 nm, as well as compare with ground-based AOD measurements over Bangladesh. Important to mention that the ozone monitoring instrument (OMI) is used to detect aerosol absorption optical depth (AAOD), while emission database for global atmospheric research (EDGAR) measure black carbon (BC) and organic carbon (OC). The modern-era retrospective analysis for research and applications (MERRA) is model provides the measure of dust at global scale.

Ground-based instruments provide highly accurate measurements of microphysical and optical properties of aerosols as they are based on direct measurements, though it also has many limitations, such as limited spatial coverage (Ali et al. 2019). The ground-based aerosol robotic network (AERONET) is one of the most popular worldwide ground-truth measurement networks. To the best of our knowledge, this is the first time research over Bangladesh using satellite- and AEROENT-retrieved aerosol optical properties with aerosol radiative forcing. The current study first presents the satellite-based AOD spatial distribution, temporal variations in satellite-based AOD, and its validation against AERONET AOD. Second, the study discusses AEROENT-based aerosol size distribution, single scattering albedo (SSA), and asymmetry parameters (ASY). Finally, the study displays the absorbing aerosols and their trends (i.e. AAOD, black carbon, organic carbon, and dust) over Bangladesh.

2 Materials and Methods

2.1 Study Area

The study area of this research is Bangladesh (Fig. 1). In Bangladesh, March to June is the hottest period, while November to February is the coldest period. About 63% of the total rainfall falls in the monsoon months from June to September (Islam and Uyeda 2007). The geographical location of these main divisions of Bangladesh is shown in Fig. 1, along with ground-based AERONET station measuring AOD located in the North-central region at Dhaka University (23°43′40″N and 90°23′53″E). Dhaka is the capital city of Bangladesh and one of the world's most densely populated mega-cities. The city faces all the problems common to mega-cities, especially extreme air pollution, with very high concentrations of carbonaceous species (black and organic carbons).

2.2 Data Used

The sun-synchronous polar-orbiting Terra satellite onboard equipped with the MODIS instrument. Terra was launched on 18 December 1999. The temporal resolution of the MODIS instrument is 1–2 days. MODIS has three spatial resolutions of 250 m (Bands 1−2), 500 m (Bands 3−7), and 1 km (Bands 8−36). Many researchers throughout the world have used Level 3 gridded products from MODIS (Misra et al. 2015; Georgoulias et al. 2016). The latest collection 6 (C-06) DT algorithm is a modified and improved version of collection 5 (C-51), based on the principle of the earlier version (Kaufman et al. 1997). On the other hand, the C-06 MODIS DB algorithm has been profoundly revised and improved compared to the earlier algorithm (Hsu et al. 2013). For spatial analysis, this study uses Level 3 (spatial resolution, $1° \times 1°$) Terra MODIS C-06 DT and DB aerosol products at 550 nm over Bangladesh, during the period 2002–2016. In contrast, for evaluation, Level 2 (10 km, Best QA) Terra MODIS C-06 DT and DB AOD (point data) is downloaded from https://giovanni.gsfc.nasa.gov/mapss/. The study also used the aerosol absorption optical depth (AAOD at 500 nm) from ozone monitoring instrument (OMI) and column dust

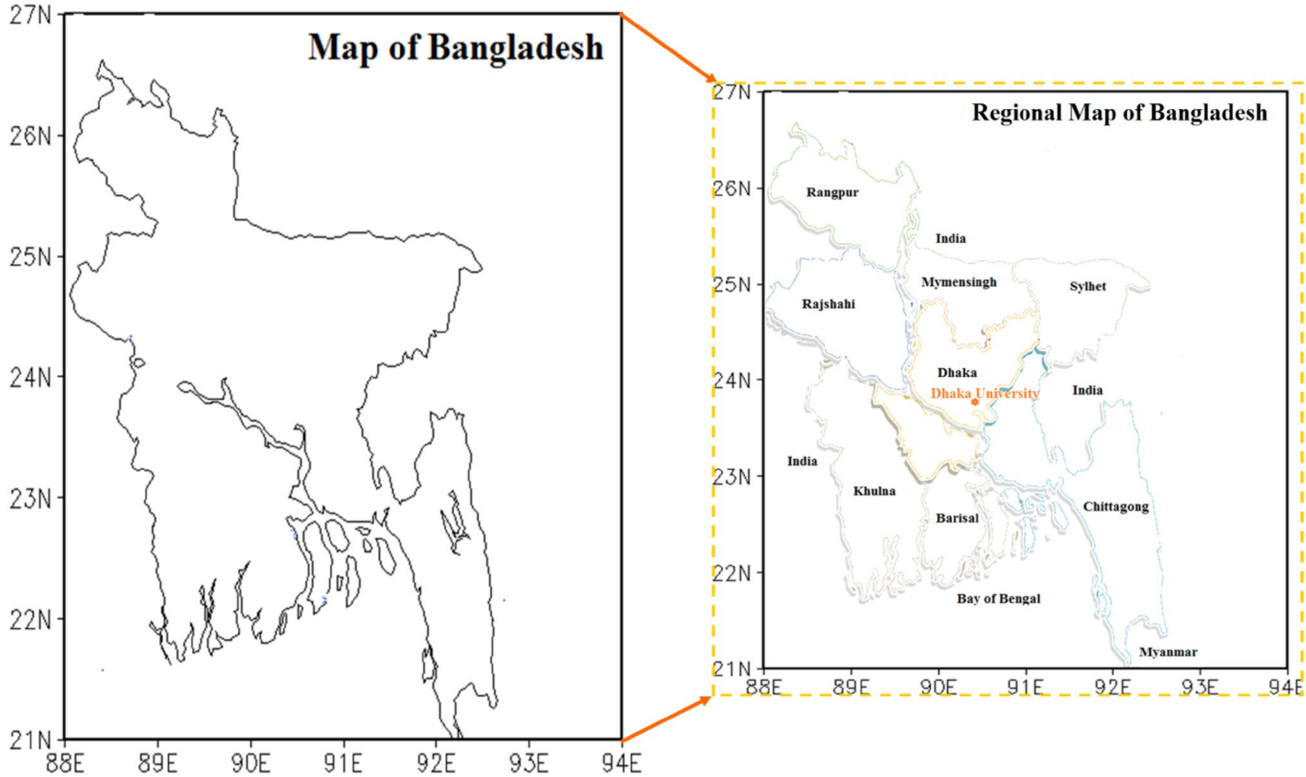

Fig. 1 Study area Bangladesh along with seven divisions and the location of AERONET station at Dhaka University

density data from the modern-era retrospective analysis for research and applications, Version-2 (MERRA-2, $0.5° \times 0.625°$). The OMI data are available from 2004 to present, whereas MERRA-2 gives data from 1980 to the present (https://giovanni.gsfc.nasa.gov/giovanni/).

AERONET level 2.0 data are cloud screened and quality assured (Holben et al. 2001), and these data are 3–5 times more precise than satellite measurements (Remer et al. 2009). AERONET measures AOD directly at 500 nm and is converted to 550 (nm) using the Ångström empirical formula (Ali et al. 2017). Several researchers have investigated the accuracy of MODIS AOD from Terra using Level 2 AERONET AOD for comparison purposes (Smirnov et al. 2000; Wei and Sun 2017). The present study uses Level 2 AERONET AOD (550 nm) from the ground station located at Dhaka University in Bangladesh to validate the satellite AOD at the same location (https://aeronet.gsfc.nasa.gov/).

Furthermore, the data of Black Carbon (BC) and Organic Carbon (OC) were obtained from the Emission Database for Global Atmospheric Research (EDGAR) V4.3.2. The EDGAR provides $0.1° \times 0.1°$ global emissions inventory for different types of air pollutants for the period 1970–2012 (http://edgar.jrc.ec.europa.eu/overview.php?v=432_AP).

2.3 Assessment Methods

In this study, the slope, intercept, and significance of the datasets are computed using a linear regression method (Wilks 2006). The correlation coefficient (r) between satellite-derived AOD and AERONET-based AOD (550 nm) is calculated using a Pearson correlation coefficient (r, (1)) method. root-mean-square error (RMSE, (2)), mean absolute error (MAE, (3)), relative mean bias (RMB, (4)), and the expected error (EE, (5)) over land are also used to estimate uncertainty in the AOD retrievals (Ali and Assiri 2019). The equations for the above-mentioned methods are as follows:

$$r = \frac{\sum_{i=1}^{n} \left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2 \sum_{i=1}^{n} \left(y_i - \bar{y}\right)^2}}, \tag{1}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{AOD}_{\mathrm{Satellite}} - \mathrm{AOD}_{\mathrm{AERONET}}\right)^2}, \tag{2}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|\left(\mathrm{AOD}_{\mathrm{Satellite}} - \mathrm{AOD}_{\mathrm{AERONET}}\right)\right|, \tag{3}$$

$$\mathrm{RMB} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\mathrm{AOD}_{\mathrm{satellite}}}{\mathrm{AOD}_{\mathrm{AERONET}}}\right|, \tag{4}$$

$$\mathrm{EE} = \pm\left(0.05 + 0.2 \times \mathrm{AOD}_{\mathrm{AERONET}}\right). \tag{5}$$

3 Results and Discussion

3.1 Spatial Distribution of Satellite-based Mean Annual AOD

Spatial distribution of AOD over Bangladesh shows how the density and characteristics of aerosols have changed over the study period (Fig. 2). Both the DB and DT algorithms detect high AOD (> 0.5) all over Bangladesh except for low-to-moderate AOD (~ 0.1 to 0.5) in the eastern side of the country. Due to the differences in the algorithms, some discrepancies in the DT and DB AOD spatial patterns are observed. Overall, the DT algorithm detects higher AOD than the DB. According to de Leeuw et al. (2018) and Sogacheva et al. (2018), the aerosol patterns from ATSR-2, AATSR, and MODIS Terra detect higher AOD over Bangladesh. Moreover, C-51 DT product detected the higher aerosol over the North-west and South-west regions of Bangladesh, especially over Rajshahi, Jessore, and Khulna (Ali et al. 2015, 2019). On the other hand, C-51 DB product was unable to derive AOD. They also mentioned that AODs have a perceptible impact on the urban, suburban, coastal, and mountain areas with impenetrable inhabitants of Bangladesh. Low rainfall, high temperature, a dryer, and arid environment, and pollution from India might be responsible for higher AODs over the regions mentioned above (Islam et al. 2017).

3.2 Temporal Variations in Satellite-based AOD

It is evident from Fig. 3a–d that the DT and DB have AOD peak in June over Bangladesh as well as at Dhaka University site. Over Bangladesh, both DT and DB show lowest AOD in October (Fig. 3a, c). However, at Dhaka University, the DT shows the lowest AOD in August, while DB shows in September (Fig. 3b, d). Seasonally, a distinct peak of AOD is recorded in DJF (0.80) followed by MAM (0.76), JJA (0.66), and SON (0.55) for the DT, while the order for the DB is DJF (0.70), MAM (0.70), JJA (0.63), and SON (0.41) at Dhaka University (Table 1). Furthermore, DT shows the AOD annual peak in 2015, the lowest in 2003 and 2005 over Bangladesh, while DB shows the peak AOD in 2015 with lowest in 2003 and 2007 (Fig. 4). At Dhaka University, DT shows the AOD annual peak in 2015 with lowest in 2006, whereas DB displays the annual peak in 2016 with lowest in 2003. Besides, AOD significantly (at 95% level) increasing over Bangladesh at the rate of 0.012/year (both DT and DB) while at Dhaka University, the increasing (significant at 95% level) rate is 0.014/year for DT and 0.019/year for DB (Fig. 4).

In light of the above, the most common characteristic is observed that the DJF, MAM, and JJA seasons show a distinct peak in AOD values (with the SON season displaying the minimum AOD) which is considered to be the seasonal

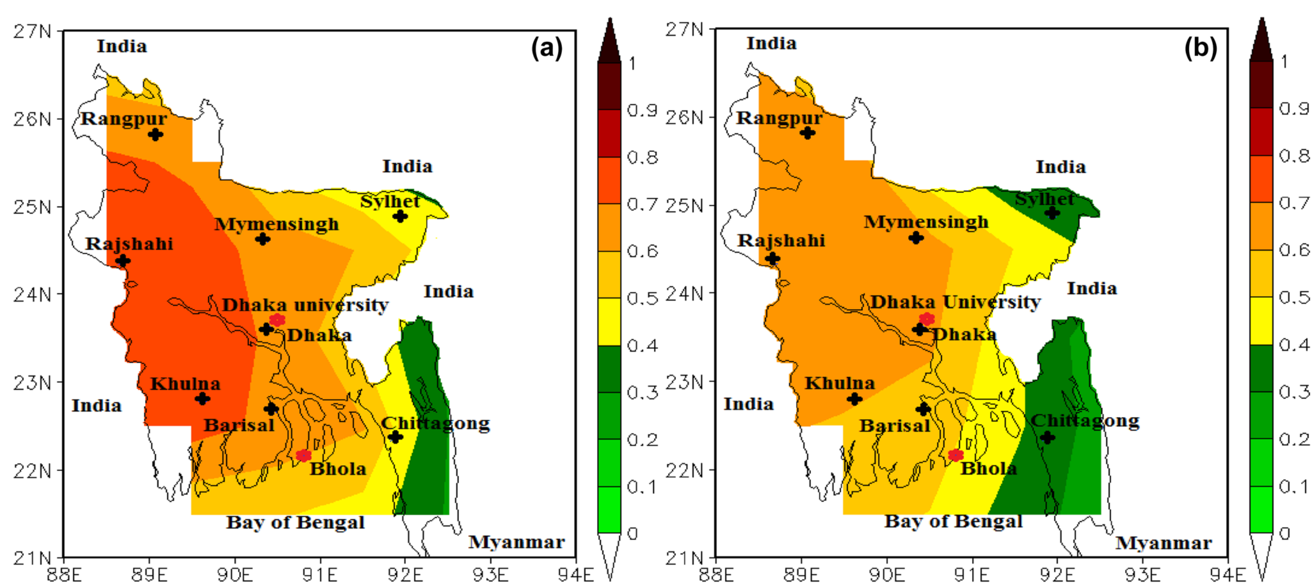

Fig. 2 Spatial Distributions of mean annual MODIS DT and DB AOD at 550 nm over Bangladesh for the period 2002–2016. **a** Corresponds to DT algorithm and **b** belongs to DB algorithm

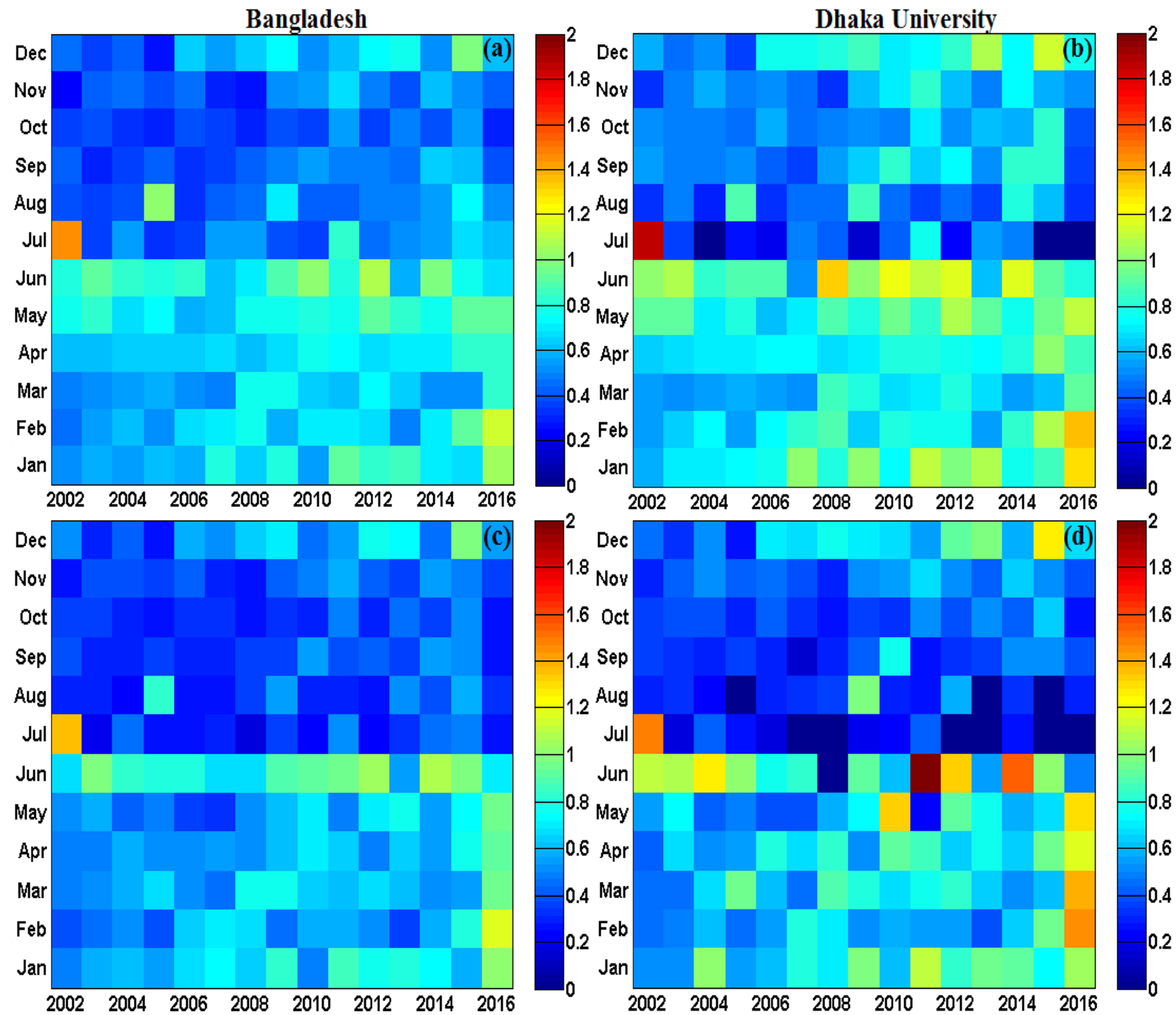

Fig. 3 Temporal discrepancies of areal averaged AOD (550 nm) over Bangladesh and Dhaka University obtained from Terra MODIS sensor for **a**, **b** correspond to DT algorithm and **c**, **d** are based on DB algorithm

Table 1 Seasonal variations of averaged AOD obtained from Terra MODIS DT and DB algorithms over Bangladesh and Dhaka University for the period 2002–2016

Season	Bangladesh		Dhaka University	
	DT	DB	DT	DB
DJF	0.66	0.61	0.80	0.70
MAM	0.69	0.60	0.76	0.70
JJA	0.63	0.54	0.66	0.63
SON	0.43	0.38	0.55	0.41

trend in Bangladesh (Mehta et al. 2016). The main culprits for high AOD values are anthropogenic activities and meteorological conditions that concentrate the aerosol load in the East Indo-Gangetic Plain (Mehta et al. 2016). A similar study has been done by de Meij et al. (2010) and Kaskaoutis et al. (2011). They found that the seasonal high aerosol loading is observed in the surrounding Indian region. Moreover, Begum et al. (2010) noted that the sources of aerosols are dust, biomass burning, traffic, and industrial emissions.

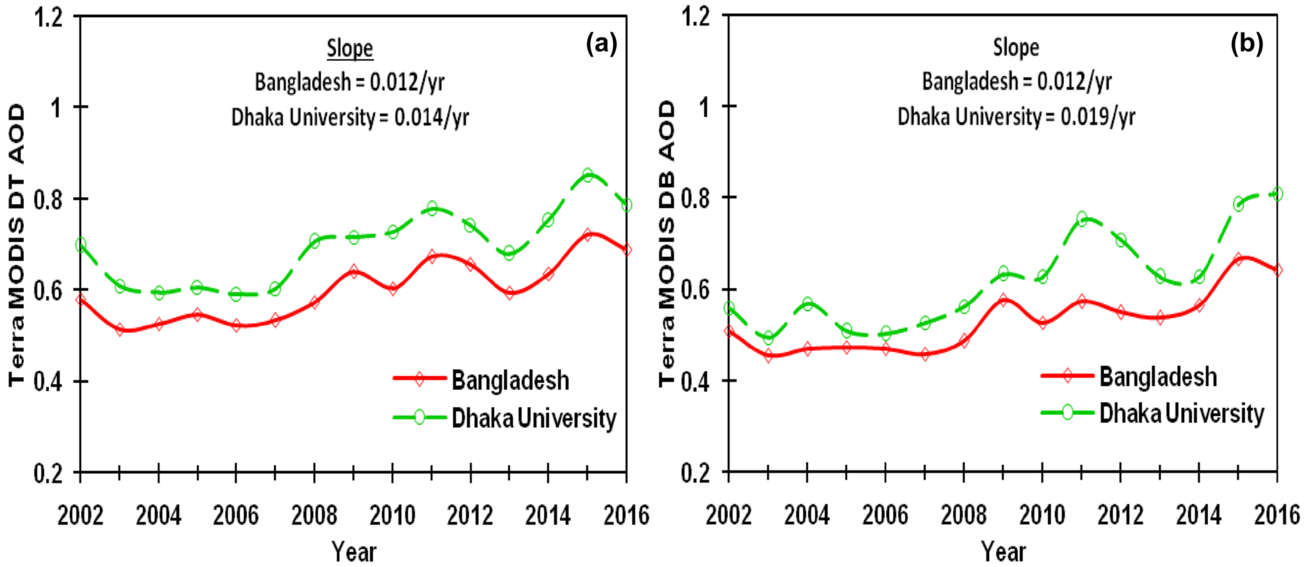

Fig. 4 Intra-annual variations of areal averaged AOD over Bangladesh and Dhaka-University obtained from Terra MODIS DT and DB algorithms for period 2002−2016

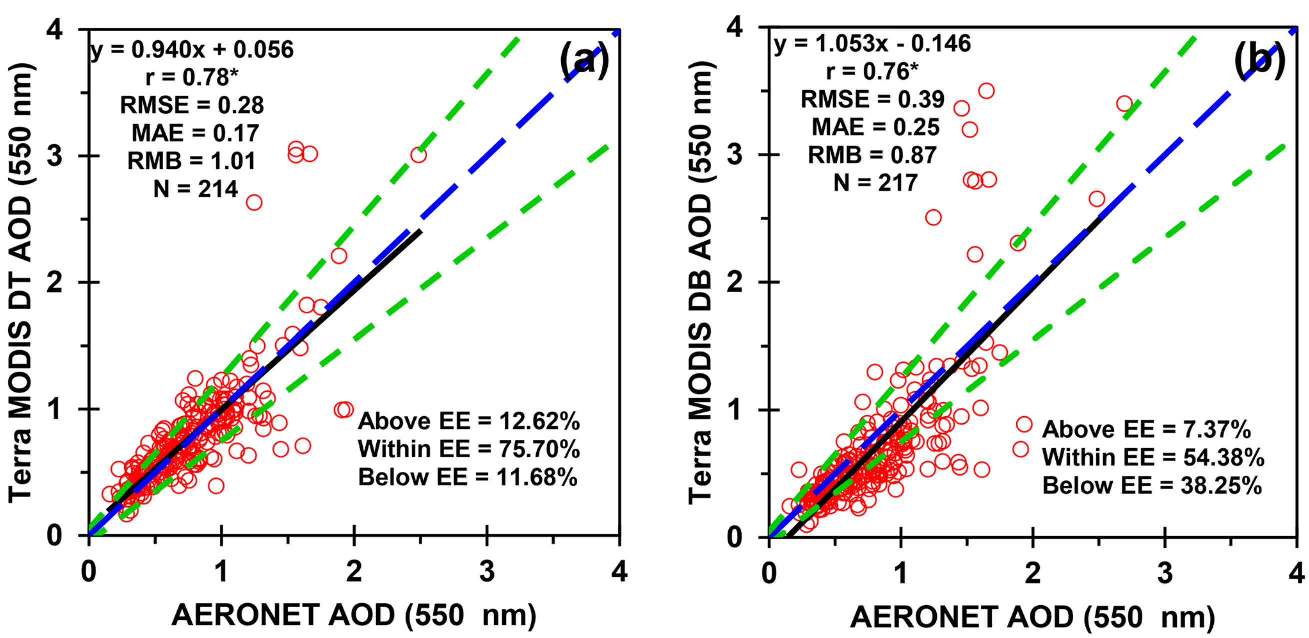

Fig. 5 Validation of Terra MODIS (DT and DB) AOD against ground-based mesasurement AERONET AOD at 550 nm over Dhaka University station. The blue dash line = 1:1, green dash lines = EE lines, and black solid line = regression line. Asterisk indicates the result is significant

3.3 Comparison of Terra MODIS (DT and DB) AOD Against AERONET AOD

Figure 5 shows the comparison between the Level 2 MODIS (DT and DB) and AEROENT AOD (550 nm) at the Dhaka University site. The slope is 0.940 and 1.053 for DT and DB, respectively. These distinct slopes indicate that some corrections are necessary to the way that the aerosol model is chosen in the look-up table. Misra et al. (2015) also reported similar results. In contrast, the intercept is 0.056 and − 0.146 for DT and DB, respectively (Fig. 5). The intercept indicates the necessity of surface reflectance correction for the DT (DB), because of its underestimation (overestimation). A significant (at 95% level) correlation 0.78 (0.76) is observed for DT (DB). RMSE (MAE) is calculated 0.28 (0.17) for DT, while it is 0.39 (0.25) for DB. A higher percentage of AOD retrievals are observed for DT (75.70%) which fall within the EE envelope compared to the DB (54.38%). The 12.62% of AOD retrievals for DT fall above the EE envelope show an average overestimation of 1% (RMB = 1.01) when compared to the AERONET measurements at Dhaka University. Bilal et al. (2016) reported similar results over Lahore and Karachi in Pakistan. Overestimation might be skewed due to imperfect aerosol model selection and underestimation of surface reflectance in the lookup table (Mei et al. 2014). Other researchers also reported similar results (e.g. Xie et al. 2011; More et al. 2013). In addition, the 38.25% of AOD retrievals for DB fall below the EE envelope with an average underestimation of 13% (RMB of 0.87). To the best of our knowledge, this study is the most comprehensive report to date on the variability in satellite-retrieved MODIS AOD (DT and DB) including a comparison with AERONET-based AOD over Bangladesh.

3.4 AEROENT-Derived Aerosol Optical Properties

Aerosol volume size distribution (VSD) is a crucial parameter in understanding the behavior of aerosol properties for their impacts on climate. Across the world, a two-mode lognormal aerosol size distribution is noticed: fine-mode particles having radii < 0.6 μm and coarse-mode particles with radii > 0.6 μm (Dubovik et al. 2002). At Dhaka University site, aerosol size within a range of 0.05–11.43 μm is observed (Fig. 6a). The peak value of fine mode is

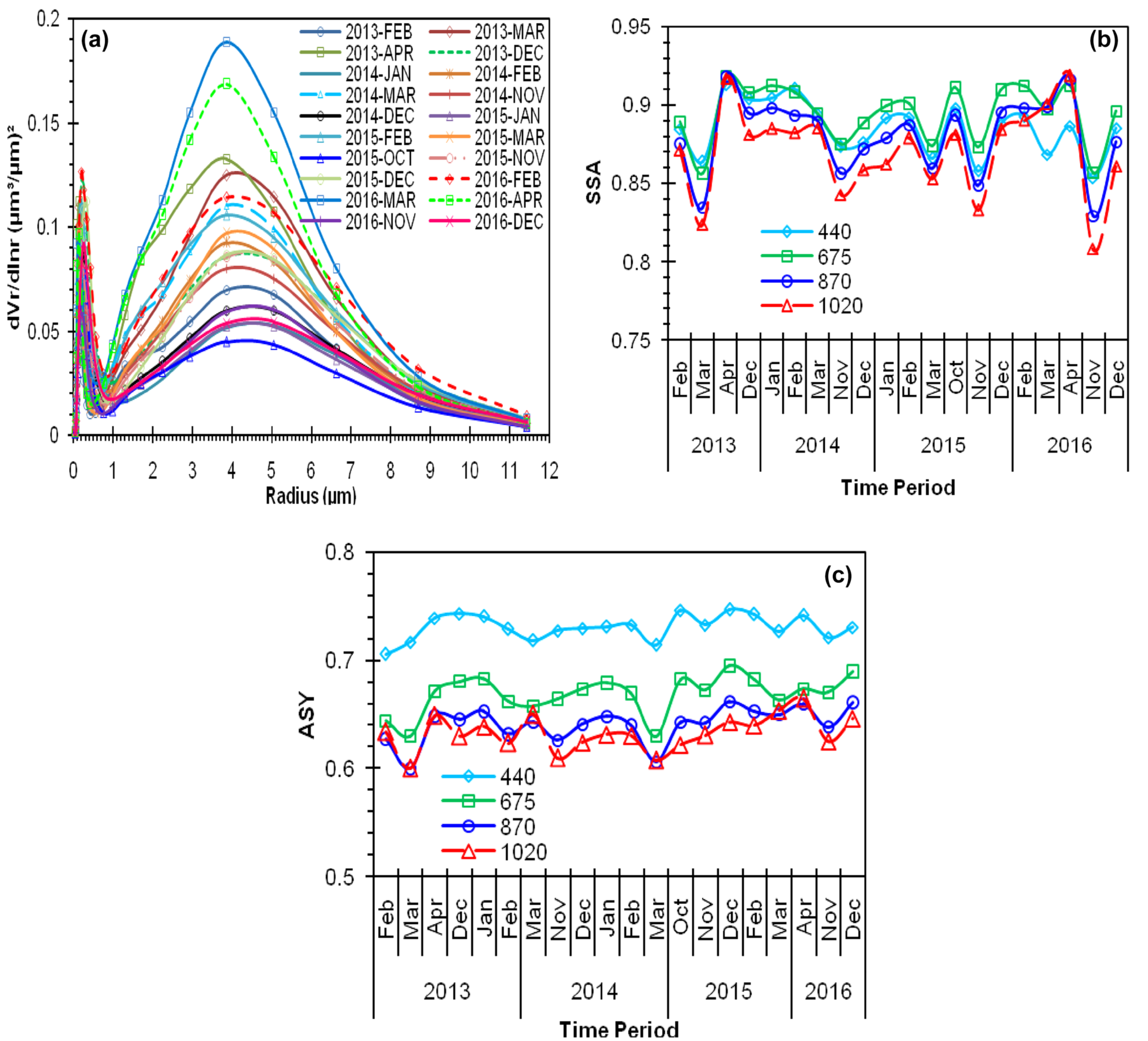

Fig. 6 AEROENT-derived aerosol optical properties over Dhaka University for **a** VSD, **b** SSA, and **c** ASY

found at a radius of 0.19 µm in February 2016 (Fig. 6a). This might be due to the foggy conditions. Dumka et al. (2014) reported that fine-mode intimates an increase of aerosol particles generally formed by manmade sources over the study region. In contrast, it is evident from Fig. 6a that coarse mode shows its peak at a radius of 3.86 µm in 2016 March, which indicates the domination of the coarse particles at Dhaka University. The little fluctuation in size distribution in fine mode and elevated variations in the coarse mode in different months and years are also observed (Fig. 6a).

The single scattering albedo (SSA) gives constructive information about scattering and absorption of aerosols. It has also been recognized as the key parameters for estimating direct aerosol radiative forcing. The SSA value of 0 and 1 represent the purely absorbing and scattering of aerosols. Figure 6b shows the SSA value ranges from 0.81 to 0.92 at Dhaka University. It is noted that longer wavelength shows the lower value of SSA as well as it decreases with the increases in wavelength. For example, longer wavelength (1020 nm) displays the lower SSA mean value of 0.871 rather than 870 nm (0.881), 675 nm (0.895) and 440 nm (0.885) as shown in Fig. 6b. This might be due to least prospect for interaction between absorbing aerosols and solar radiation. In addition, this study indicates the presence of absorbing aerosols (i.e. biomass burning, vehicular emissions, and industrial pollutants). Similar information is stated by Sumit et al. (2012).

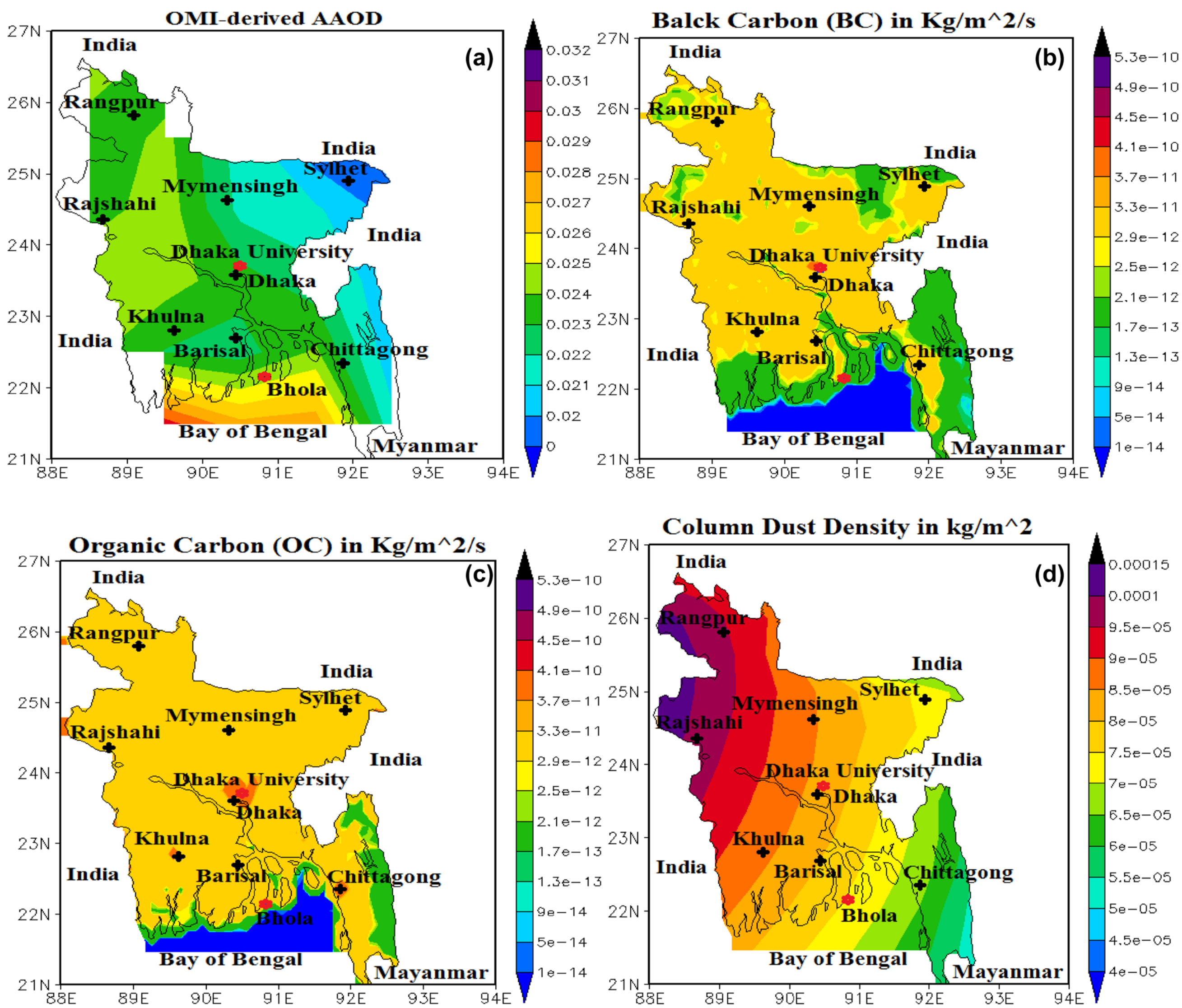

Fig. 7 Spatial distributions of absorbing aerosols over Bangladesh obtained from OMI (AAOD, 2004–2016), EDGAR (BC and OC, 1970–2012) and MERRA-2 model (dust, 1980–2016)

Asymmetry parameter (ASY) also provides constructive information about the scattering of radiation by aerosols. The ASY value of 1 indicates forward scattering, -1 means backward scattering, and 0 defines scattering is the same in all direction. In addition, the value of ASY of 0.1 indicates the clean condition, while 0.75 signifies the polluted atmosphere (Zege et al. 1991). It is noted from Fig. 6c that ASY decreases with the increases in wavelength and overall range in four wavelengths is seen to be 0.81–0.92. This study indicates the presence of absorbing aerosols at Dhaka University as well as the polluted atmosphere. For example, shorter wavelength (440 nm) displays the peak ASY mean value of 0.73 rather than 675 nm (0.66), 870 nm (0.63), and 1020 nm (0.62) as shown in Fig. 6c.

3.5 Identifications of Absorbing Aerosols Using OMI, EDGAR, and MERRA-2

Absorbing aerosols mostly comprise black carbon (BC), organic carbon (OC) and dust. BC and OC generally form from deficient combustion of biomass burning and fossil fuels, whereas dust origins from natural (wind attrition) and anthropogenic sources (modifying landscape/disturbing oil). To investigate the presence of absorbing aerosols over Bangladesh, this study uses OMI AAOD. Moreover, EDGAR-based BC and OC emissions and MERRA-2-based column dust density are also investigated in understanding the long-term behavior of absorbing aerosols. Satellite-based OMI AAOD data effectively detect the absorbing aerosols over

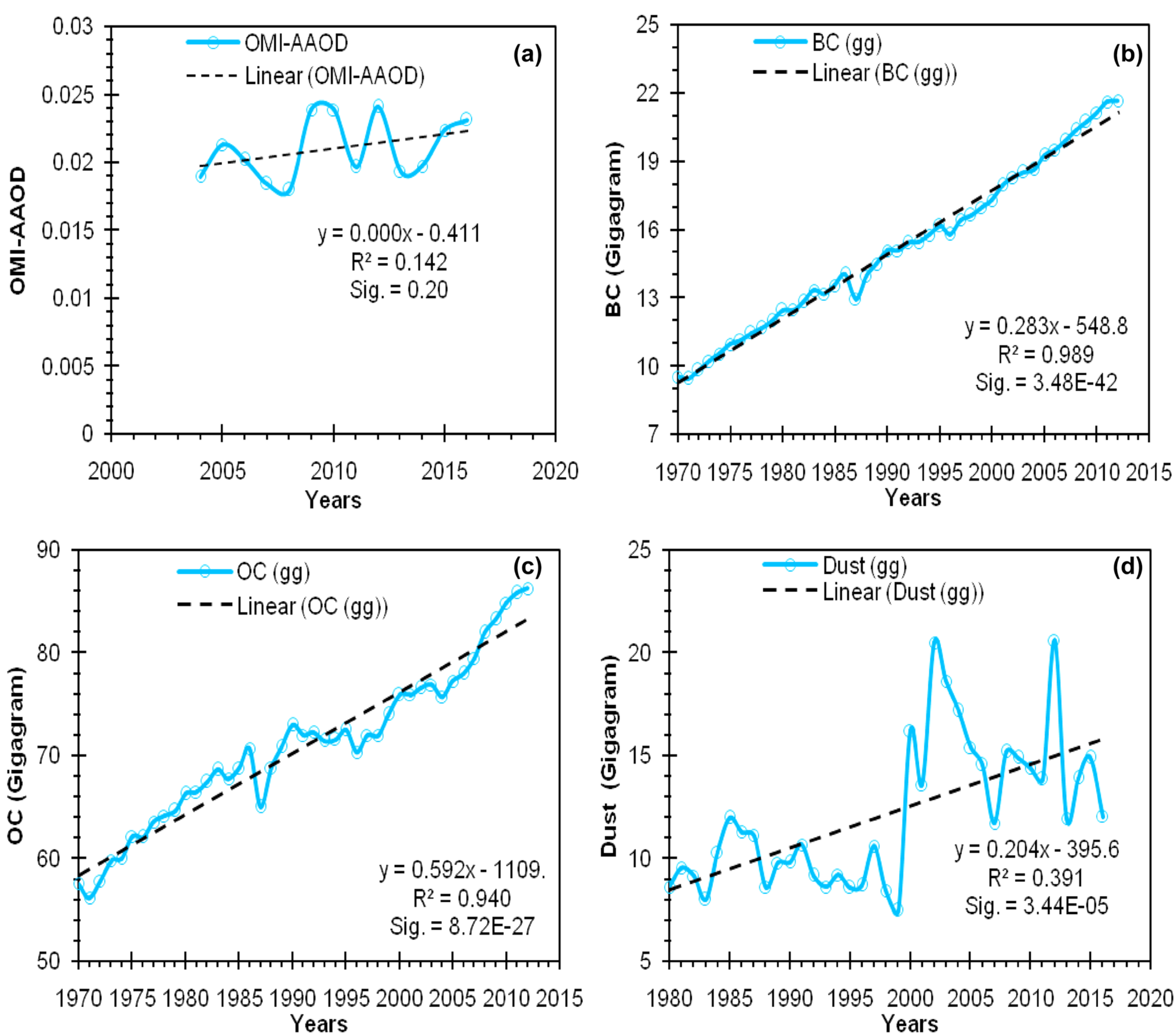

Fig. 8 Linear trends of absorbing aerosols over Bangladesh obtained from OMI (AAOD, 2004–2016), EDGAR (BC and OC, 1970–2012) and MERRA-2 model (dust, 1980–2016)

Bangladesh. Furthermore, EDGAR and MERRA-2 datasets confirm the presence of three types of absorbing aerosols which are BC, OC, and dust (Fig. 7). The significant (at 95% level) increasing trends of BC, OC, and dust are observed over Bangladesh except for an insignificant increasing trend for AAOD (Fig. 8). However, further study is required using climate model simulation (e.g. Almazroui et al. 2017; Ehsan et al. 2017), which will help in simulating (Islam and Almazroui 2012) and projecting AOD in the future climate. Wang et al. (2018) mentioned that built-up areas are primarily responsible for the highest AOD, which notting the impact of anthropogenic emissions on the AOD spatial pattern. In contrast, the impact of topography is relatively more powerful rather than land use (built or vegetated). The impacts of urbanization diversify with the aerosol natural emission sources and need to be evaluated with attention. The vegetation impact on easing air pollution through wet and dry depositions can overbalance its inherent organic emissions. It is stronger rather than urbanization effect.

4 Conclusions

The Terra satellite-based MODIS (DT and DB) aerosol products, Ozone Monitoring Instrument (OMI) based AAOD, EDGAR-based BC and OC, MERRA-based dust, and AERONET-retrieved optical properties (i.e. AOD, VSD, SSA, and ASY) are used to study the variability of aerosol optical properties in Bangladesh. The spatial distribution of Terra MODIS (DT and DB) AOD shows the high AOD (>0.5) all over Bangladesh except for a small portion in the east side of the country shows low AOD. Similarly, the AOD temporal study demonstrates the high AOD in DJF, MAM, and JJA except for low AOD in SON. Regression analysis shows that the AOD is significantly increasing for the period 2002–2016. It is noted from the validation results that DT (DB) algorithm shows a correlation of 0.78 (0.76). The Expected Error envelope is found 75.70% (54.38%) with small (large) RMSE for DT (DB) product. The inappropriate use of aerosol model schemes and an inadequate calculation of surface reflectance in the look-up table may be responsible for the low correlation between MODIS AOD and AERONET AOD. AAOD from OMI to AEROENT-based SSA and ASY demonstrate the presence of absorbing aerosols over the study area. Moreover, EDGAR and MERRA data show the existence of three different types of absorbing aerosols (BC, OC, and dust). It is important to note that the BC, OC, and dust are significantly (at 95% level) increasing over Bangladesh. Further study is required using climate model simulation which will help in simulating and projecting AOD in the future climate.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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