MODIS Dark Target and Deep Blue aerosoloptical depth validation over Bangladesh

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Abstract

This study seeks to examine the aerosol optical depth (AOD) climatology of Bangladesh over the time period 2003-2014 using Moderate Resolution Imaging Spectroradiometer (MODIS) collection 5.1 level-3 data, and Dark Target (DT) and Deep Blue (DB) methods. The results showed that the DT approach was capable of reconstructing the AOD over the whole of Bangladesh, while the DB method was limited only to the eastern, northeastern, and southeastern parts of the country. The AOD derived from the Terra MODIS DT revealed a decreasing trend in the morning, while AOD derived from the Aqua MODIS (DT and DB) showed an increasing trend in the afternoon. The seasonal anomaly of AOD revealed a great variation with different seasons. MODIS (DT and DB) AOD_{550} data for both satellites were validated with AERONET AOD_{550} for the period 2012-2013. The validation study showed that the Terra DT (R=0.749) performed better than the Aqua DT at 550nm (R=0.730). On seasonal scale, Terra DT(R=0.841) was found to perform better in winter, Aqua DT (R=0.692) in pre-monsoon and Aqua DT(R=0.979) in monsoon. The study concluded that MODIS DT product could be used to monitor aerosol over Bangladesh.

Keywords: aerosol, aerosol monitoring, Bangladesh, MODIS, Dark Target approach, Deep Blue algorithm

Introduction

The aerosols in the climate system interact with the incoming solar radiation by absorbing and scattering it (Haywood & Ramaswamy 1998; Hatzianastassiou et al., 2007). In addition, it changes the atmospheric aerosol loads, land surface properties and greenhouse gases, which in turn contribute to global warming. Therefore, aerosols in the atmosphere are a growing concern across the world (Papadimas et al., 2009). According to the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (i.e. Climate Change, 2007), the cloud microphysical properties and their life spans are influenced by aerosols (Solomon et al., 2007). How the amount of aerosol and their properties affect climate should, therefore, be considered as a significant study (King et al., 1999). The major challenge for such research is the measurement and depiction of aerosols. With the assistance of its great swath and automatically scheduled observation, satellites can provide a complete description of the aerosol data with larger space- and time-scale compared to other conservative measurements. Therefore, satellites can play a significant role in the research of aerosol climatology. In the past, the aerosol monitoring using satellite over oceans has been found with adequate accuracy (Tanre et al., 1997). The quality of aerosol retrieval over land mainly relies on aerosol model selection and surface reflectance (Kaufman et al., 1997). Therefore, it is important to have an accurate retrieval of aerosol optical depth (AOD) using appropriate models. Aerosol models based on MODIS early version depend on the best available data. Conversely, the MODIS modified algorithm uses the aerosol climatology that is obtained by the AERONET network (Levy et al., 2007a). Due to the incomplete global coverage of this network, it has an issue of uncertainty, particularly

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over highly heterogeneous areas. It has been reported that the Deep Blue (DB) aerosol optical depth has acceptable uncertainties over the desert and semi-arid areas than the traditional DT approach, which uses mid-visible and red-wavelengths (Shi et al., 2011; Qian et al., 2012). Conversely, the traditional DT retrieval has been also reported unsuccessful over bright surfaces, for example, in Saharan and Gobi deserts due to high surface reflectance (Remer et al., 2005). This highlights the needs to assess and compare the performance of BD and DT in an area of interest.

In order to validate the aerosol retrieval parameters and other releasing products, ground-based measurement data are necessary. The aerosol optical properties retrieved using direct solar radiations from the sun-photometers are free from surface reflectance error and cloud contamination. Therefore, AERONET dataset is widely used to evaluate the efficiency of satellite based aerosol retrieval algorithm as well as to develop new algorithm (Misra et al., 2015). Several approaches have been proposed for the validation of MODIS aerosol retrieval algorithm for the purpose of renovating and improvement [Chu et al., 2002; Ichoku et al., 2002; Levy et al., 2005; Levy et al., 2010). (Kaufman et al., 1997) proposed the first algorithm which was later modified by (Levy et al., 2007b) and (Hsu et al., 2004) by proposing two different methods for aerosol retrieval. Concurrently, (Levy et al., 2007a) proposed improvement of the initial approach, and (Hsu et al., 2004) developed completely a different and unconventional method to solve the problem. The current study provides the first attempt on AOD climatology analysis over the whole Bangladesh as well as validation of MODIS DT and DB collection 5.1 for both Terra and Aqua satellite based AOD with AERONET at 550nm product over Dhaka for 2012-2013. The latest version of MODIS DT (Levy et al., 2007b) and DB algorithms (Hsu et al., 2004) were used for this purpose.

Materials and methods

Bangladesh is located between 20^0 to 27^0N latitude and longitude 88^0 to 93^0E. This region is a riverine country situated in South Asia; surrounded by India to its east, west and north; and the Bay of Bengal in the south. The climate of the country is mainly characterised by four seasons; namely, winter (December to February), Pre-Monsoon (March to May), Monsoon (June to September) and Post-monsoon (October to November). In addition, Bangladesh is exemplified by a warm, humid, and tropical climate. The climate is affected mostly by the monsoon cycle which mainly initiates from the Indian Ocean and bring unstable, warm and moist air (Rashid, 1991).

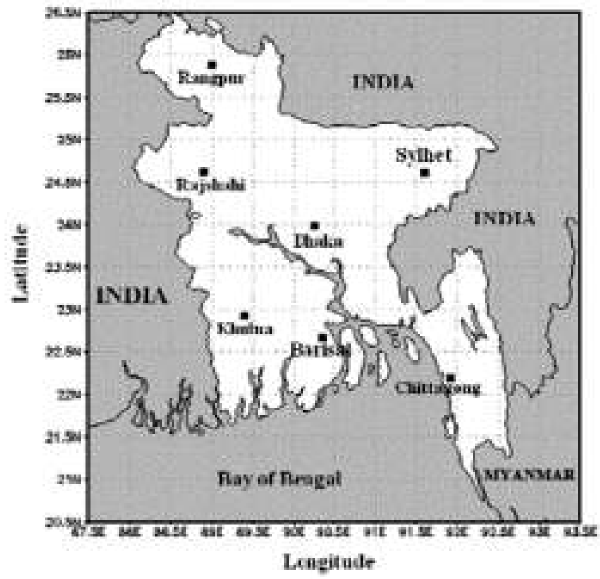

Figure1. *Map of study area*

MODIS is the key sensor for both Terra (EOS-AM) and Aqua (EOS-PM) sun-synchronous polar orbital satellites that were launched in 1999 December and 2002 May respectively. The temporal resolution of the instrument is 1 to 2 days and delivering 36-channels recognition data started from 0.41 to 14.4 micrometer. MODIS level-3 collection5.1 with spatial resolution 1^0x 1^0 at 550nm aerosol data product has been downloaded for both DT and DB (Hsu et al., 2004) algorithms from (http://disc.sci.gsfc.nasa.gov/giovanni/). In addition, MODIS level-2 collection 5.1 with a spatial resolution 10km x10km at 550nm aerosol data product has been downloaded for both DT and DB algorithms from (http://giovanni.gsfc.nasa.gov/mapss/).The550nm wavelength is used because it is consistent with the main wavelengths. To achieve the best level of accuracy for AOD retrievals, MODIS uses various ranges of quality flags such as 3(high confidence) to 0 (low confidence) Levy et al., 2010). In this study, quality flags have filtered all MODIS data.

The Aerosol Robotic Network (AERONET) AOD operates based on direct sun-photometer measurements at different wavelengths (Holben et al., 1998). The AERONET data are available at three levels; Level 1.0 (unscreened), Level 1.5 (cloud screened) and Level 2.0 (quality assured) which can be downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov/). Only quality assured AERONET level-2 data are used to validate the MODIS aerosol products for both DT and DB algorithms.

Before launching of Terra satellite, the original DT algorithm was envisaged and developed and used for both Terra and Aqua before it is tested on MODIS (Kaufman et al., 1997; Remer et al., 2005). The DT algorithm C5 has been improved significantly based on C4 (Levy et al., 2007a; Levy et al., 2007b) and this new version has been evaluated (Zhanqing et al., 2007; Wen et al., 2007). The MODIS DT algorithm is described as follow: Ozone, water, and $CO_2$are corrected in the MODIS DT algorithm. Then, the 500m spatial resolution reflectance at three bands such as 470, 650, and 2130 nm are pre-arranged into nominal 10 x 10 Km^2 boxes corresponding to 20 x 20 or 400 pixels per box. After deleting the cloud, snow/ice, and water pixels, the stable pixels retrieve AOD in four important steps: (1) to identify dark pixels at 2130nm which reflectance cascades are within the range of 0.01-0.25 and are within 20% to about 50% of the consequence 650nm (i.e. red band); (2) to parameterise the surface reflectance at visible bands (470 and 650 nm) for the short wavelength i.e. infrared surface (SWIR, 2130nm) and the consequent "surface greenness", the normalised ratio of the measured reflectance based on the two different wavelengths as 1240 and 2130 nm channels (Levy et al., 2007b); (3) to select suitable aerosol models and type which is the function of the geography and season; (4) to obtain the aerosol optical depth and mass concentration of the accumulation and coarse mode using radiance. The detailed information on DT algorithm can be found in (Kaufman et al., 1997; Remer et al., 2005; Levy et al., 2007b).

The MODIS DT AOD retrieval is only valid over the most vegetated land but not suitable over urban, arid, semi-arid, and desert areas (Hsu et al., 2004). To retrieve aerosol properties over brightly reflecting surfaces such as desert areas using blue bands, MODIS Deep Blue (DB) is required because of its low surface reflectance, which makes it possible to extract expected aerosol information (Hsu et al., 2006). The major steps of DB algorithm applied in the satellite are as follow: (1) Rayleigh correction is applied for terrain elevation to measure the variation of reflectance due to the disparities in the surface pressures; (2) cloud is screened by separating the clear and cloudy pixels using reflectance at 412nm, and absorbing aerosol index (i.e. ratio of 412and 490nm) to distinguish thick dust from cirrus cloud; (3) the surface reflectance is calculated at 412, 470 and 650nm for 0.10 x 0.10 grid from clear-scene database of surface reflectivity that is based on its geolocation; and finally (4) the reflectance measured by satellite is compared with the consequent values in the look up table, which gives the aerosol optical depth and single scattering albedo with the help of maximum likelihood method. The detailed information on the DB algorithm can be found in (Hsu et al., 2004).

Results and discussion

Figure 2 shows the plot of annual mean AOD at 550nm over Bangladesh derived from Terra MODIS DT and Aqua MODIS (DT and DB) aerosol products. The annual mean AOD climatology was obtained using

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MODIS level-3 monthly mean data from 2003-2014. It was found that Terra DT has maximum AOD value (0.6-0.7) over Rajshahi, Jessore and Satkhira districts of the Bangladesh. On the other hand, Aqua DT showed maximum AOD range (0.6-0.7) over Joypurhat, Nagoan, Bogra, Rajshahi, Natore, Kustia, Jessore and Satkhira. Aqua DB also derived maximum AOD range (0.6-0.7) over Lalmonirhat, Rangpure and Gaibanda. Both Terra (DT) and Aqua (DT and DB) showed the same AOD values range (0.4-0.6) over the northern, northeastern, northwestern, western and southern parts of Bangladesh. Aqua DT derived AOD over the maximum areas of the country in the afternoon, while Terra DT in the morning.

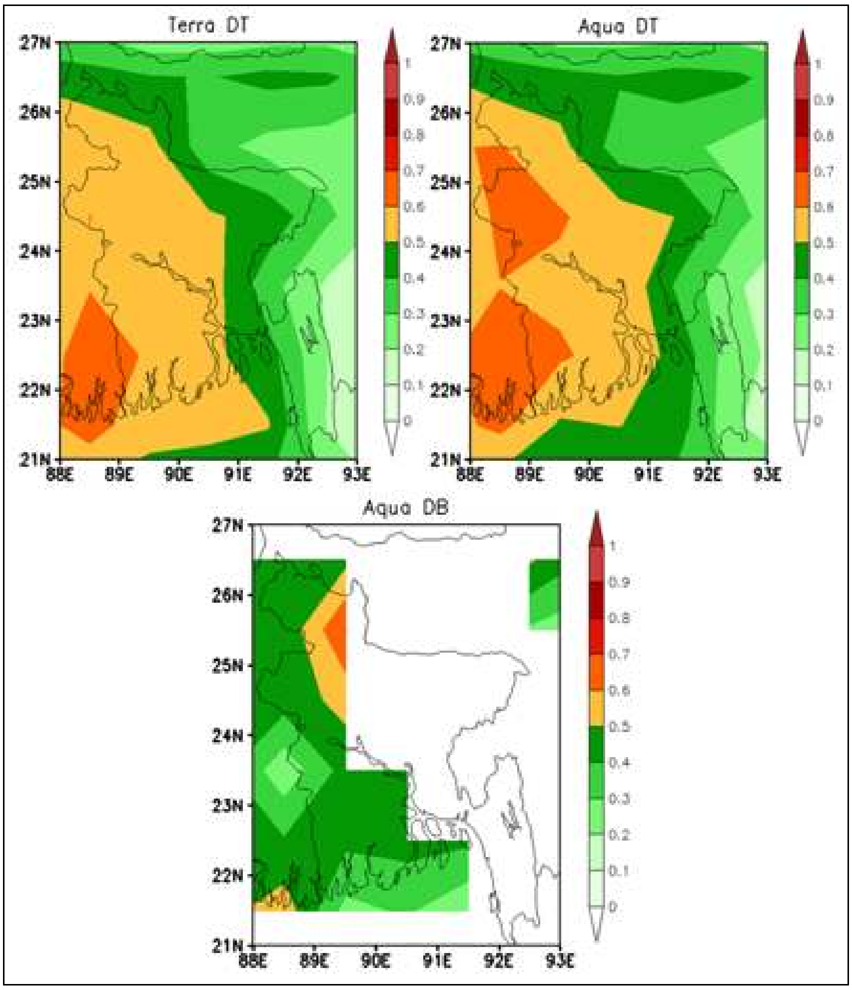

Figure 2. *MODIS annual mean AOD Climatology at 550nm over Bangladesh derived from satellite data for the period 2003-2014*

Figure 3 shows monthly mean AOD trends of Terra DT, Aqua DT and DB at 550nm for the period 2003-2014. Terra DT AOD at 550nm was found the lowest in October 2008 (AOD=0.185) and the highest in June 2012 (AOD=0.709). The patterns were the same for Aqua DT AOD the lowest in October 2008 (AOD=0.18) and the highest in June 2012 (AOD=0.696). On the other hand, Aqua DB AOD at 550nm was found the lowest in July 2009 (AOD=0.153) and the highest in July 2004 (AOD= 0.639). It can be concluded that both Terra DT and Aqua DT have the lowest AOD in October and the highest in June. It was also observed that the AOD derived from Aqua (DT and DB) shows a slight increasing trend, while it is decreasing for Terra DT over the period 2003-2014. This trend analysis discloses that the amount of aerosol is relatively higher in the afternoon compared to morning.

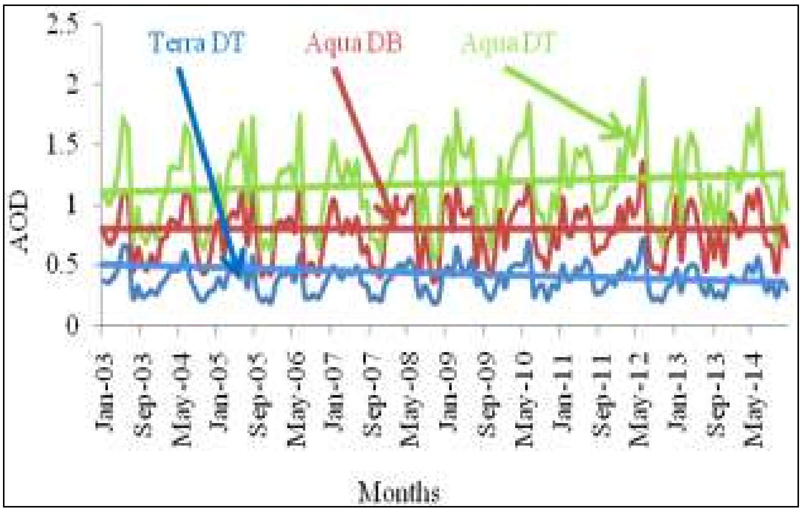

Figure 3. *Trend of Monthly mean MODIS AOD at 550nm for both Terra and Aqua satellites over Bangladesh during 2003-2014*

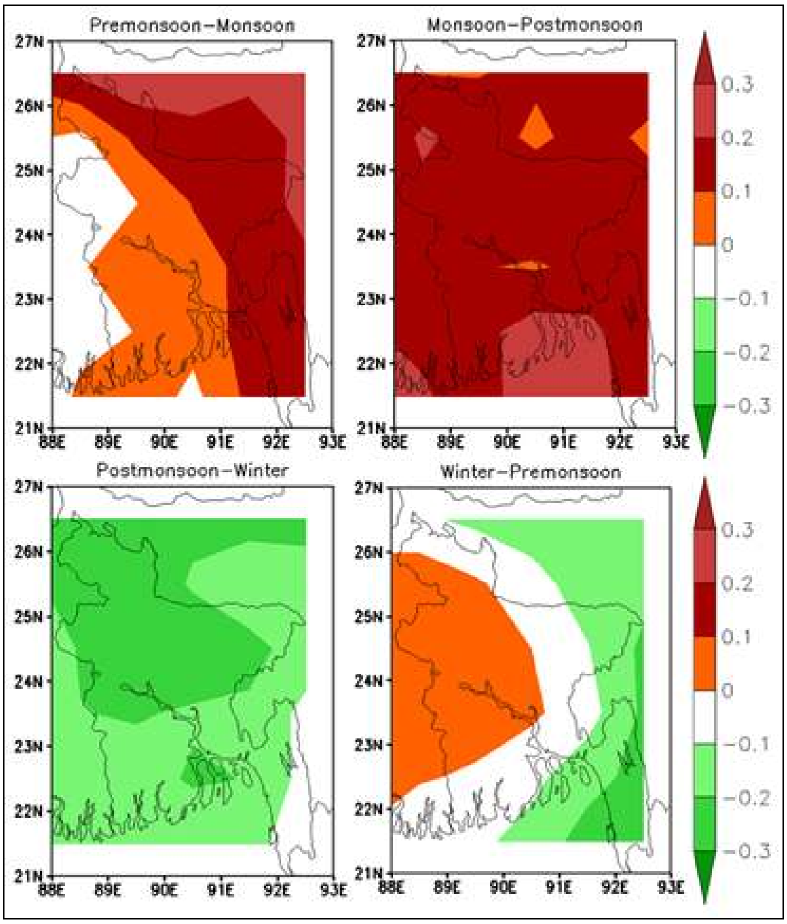

Figure 4. *MODISDT seasonal mean AOD anomalies over Bangladesh for the time period 2003-2014 derived from Aqua Satellite*

Aqua MODIS (DT and DB) AOD at 550nm was selected over Bangladesh to analyse the seasonal anomaly. Figure 4 shows the seasonal anomaly of Aqua MODIS DT AOD at 550nm for 2003-2014. The largest variation was observed over Bangladesh based on seasonal cycle. The first anomaly between pre-monsoon and monsoon showed AOD is higher over Slyhet during the pre-monsoon season. The second anomaly between monsoon and post-monsoon showed AOD is higher over Dinajpur, Barguna, Jhalokathi and Patuakhali areas during the monsoon season. The third anomaly between the post-monsoon and winter revealed that AOD over east, south, southeast and southwest of the country are the highest during the post-monsoon season. The fourth and final anomaly between winter and pre-monsoon also showed that winter AOD is higher over west, southwest, northwest and central parts of the country during the winter season. It can be concluded that MODIS DT AOD at 550nm was more in monsoon season is then in pre-monsoon, winter and post-monsoon seasons.

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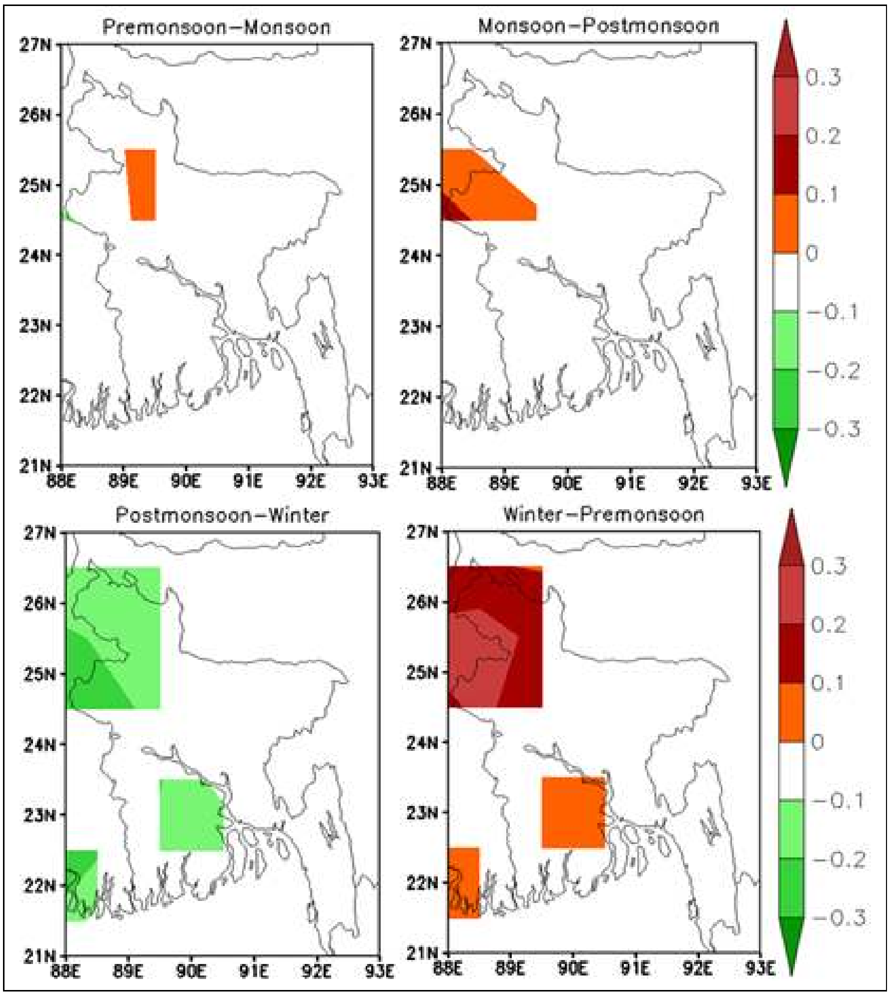

Figure 5. *MODISDB seasonal mean AOD Climatology anomalies over Bangladesh for the period 2003-2014 derived from Aqua Satellite*

Figure 5 shows the seasonal mean of DB AOD at 550nm over Bangladesh for 2003-2014. The first anomaly between pre-monsoon and monsoon showed AOD is higher over Joypurhat areas of the country during the pre-monsoon season. The second anomaly between monsoon and post-monsoon showed AOD is higher over Joypurhat and Naogoan areas of the country during the monsoon season. The third anomaly between the post-monsoon and winter revealed that AOD over Naogoan, Joypurhat, Dinajpur, Thakurgaon, Panchagarh, Nilphamari and Lalmonirhat areas of the country are the highest during post-monsoon season. The fourth and final anomaly between winter and pre-monsoon also showed that winter AOD is higher over Dinajpur, Joypurhat and Naogoan areas of the country during the winter season because of the foggy weather. In addition, seasonal anomaly of MODIS DB AOD at 550nm reveals that DB cannot find out AOD over the maximum areas of the country due to the humid climatic condition

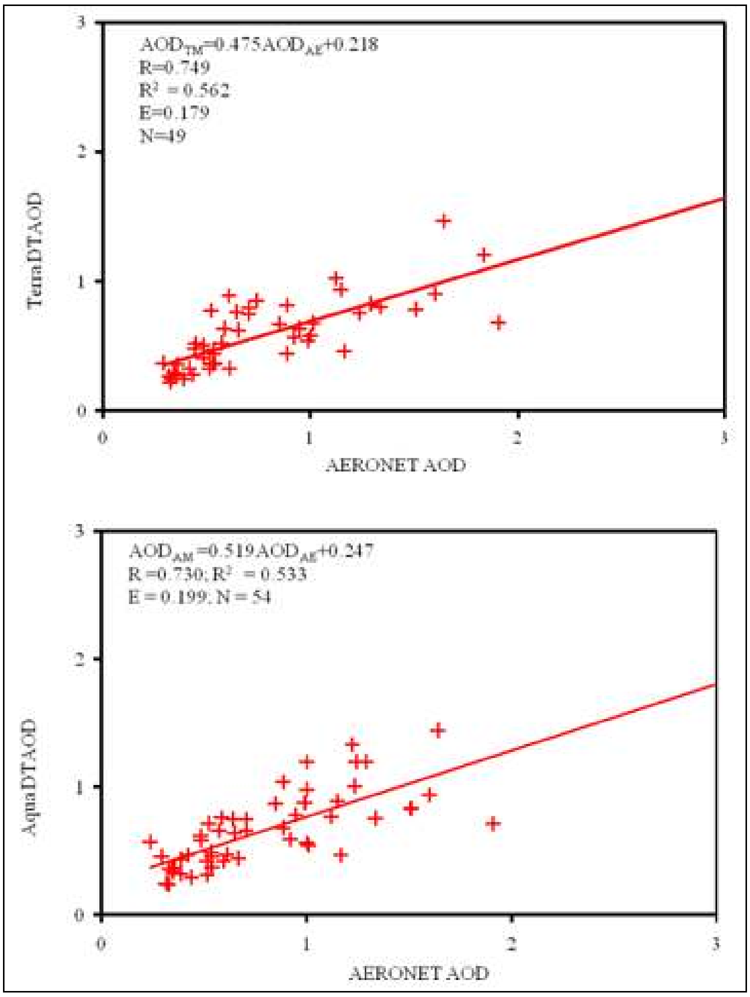

Figure 6. *Overall comparisons between Terra- and Aqua- MODIS and AERONET AOD at 550nm for the period 2012-2013. Where AOD_{TM} is Terra MODIS, AOD_{AM} is the Aqua MODIS satellite and AOD_{AE} is AERONET*

MODIS DB AOD at 550nm for Aqua has missing data over Dhaka, Bangladesh during 2003-2014 as shown in Figure 2. Therefore, MODIS DT AOD at 550nm for both Terra and Aqua satellites over Dhaka for 2012-2013 was used. The next step was to examine the validation of overall and seasonal (i.e. pre-monsoon, monsoon, winter and post-monsoon) MODIS DT AOD for both Terra and Aqua satellites with AERONET AOD at 550nm using level-2 daily dataset. The linear regression method was used for this purpose. The linear regression line in the scatter plot (i.e. slope (m) and intercept (c)) represents two key factors i.e. the aerosol model and the surface reflectance, which mostly affect the quality of AOD retrieval (Chu et al., 2002; Zhanquing et al., 2007; Misra et al., 2015). The slope (m) indicates errors caused by the inaccurate assumptions of the aerosol model; while intercept (c) denotes the imperfect surface reflectance parameterisation. For corresponding matches between the satellites and AERONETS AOD measurements, the values of m and c will be1 and 0, respectively. Figure 6 shows the value of m=0.519

for Aqua which means that aerosol model performed well for 51.9% data, whereas Terra performed well in only 47.5% (i.e. m=0.475). The value of c=0.218 for Terra reveals 21.8% fault of surface reflectance parameterisation that is less than Aqua where c=0.247 (24.7%).Additionally, the correlation (R) value 0.74 and standard error (E) 0.179 was estimated for Terra while for Aqua, R value 0.73 and E value 0.199, respectively. The results revealed that Terra MODIS DT performs better to retrieve AOD at 550nm compared to Aqua satellite for 2012-2013.

Figure 7 shows the seasonal validation of MODIS DT AOD for Terra and Aqua satellite with AERONET AOD at 550nm. During pre-monsoon, the values of m=0.566, c=0.177, R=0.622, and E =0.190 were estimated for Terra, while m=0.569, c=0.192, R=0.692, and E =0.199 for Aqua. It is clear that Aqua MODIS DT performed well to retrieve AOD at 550nm than Terra during pre-monsoon. Whereas in Monsoon, Terra MODIS DT retrieved only two days AOD at 550nm and therefore, regression analysis could not be performed. However, for Aqua, m=0.607, c=0.383, R=0.979, and E =0.092 were estimated. It indicates that Aqua MODIS DT performs well to retrieve AOD at 550nm than Terra satellite during monsoon. In addition, MODIS DT AOD data was missing in post-monsoon season for both satellites. Finally, the values m=0.425, c=0.218, R=0.841, and E =0.132 were estimated during winter using Terra, while m=0.465, c=0.279, R=0.717, and E =0.198 for Aqua. It means that Terra MODIS DT performs better to retrieve AOD at 550nm than Aqua satellite during winter.

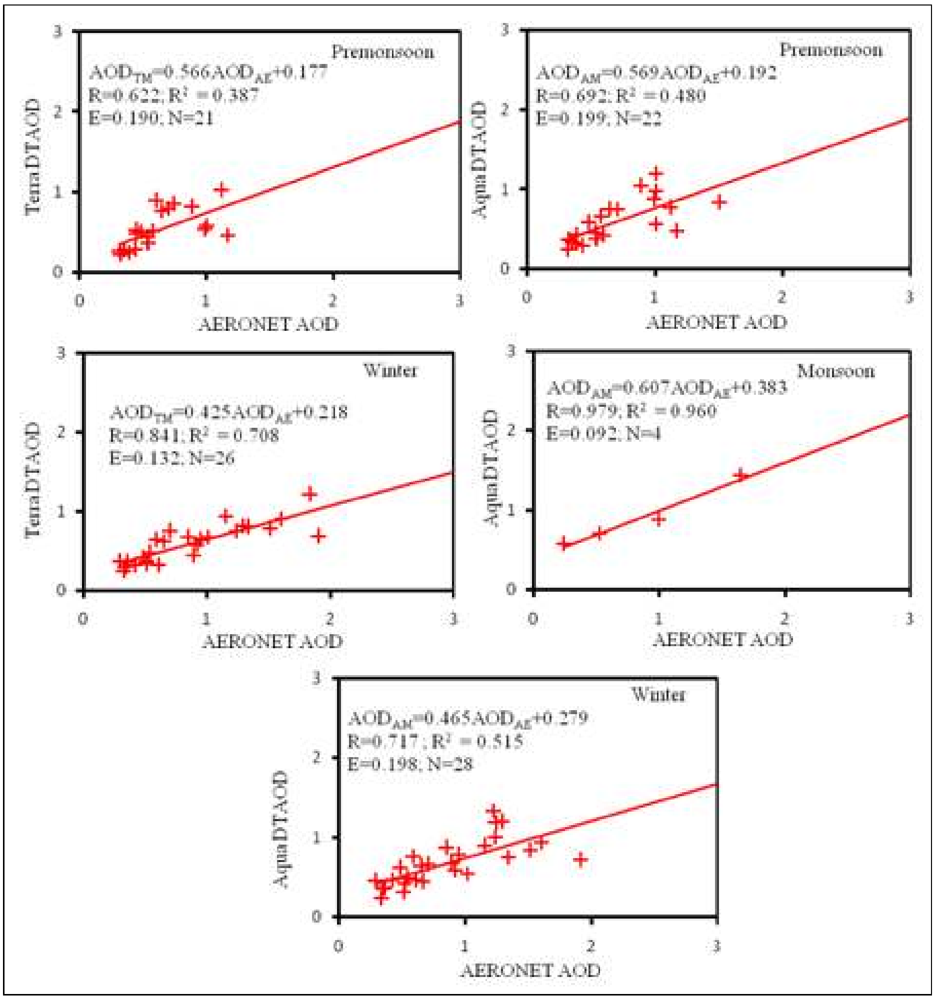

Figure7. *The seasonal comparisons between Terra- and Aqua- MODIS and AERONET AOD at 550nm for the period 2012-2013. Where* AOD_{TM} *is Terra MODIS,* AOD_{AM} *is the Aqua MODIS satellite and* AOD_{AE} *is AERONET*

Conclusion

Level-3 Terra MODIS DT and Aqua MODIS (DT and DB) AOD at 550nm collection 5.1 data products have been used in this study to assess annual and seasonal AOD climatology over Bangladesh. The result of AOD climatology analysis shows that Terra and Aqua MODIS DT are able to significantly detect AOD over Bangladesh for the period 2003-2014. On the other hand, Aqua MODIS DB can only perform over the eastern, northeastern, and southeastern parts of the country due to the humid climatic condition. The seasonal anomaly of AOD showed large variations into seasons. The seasonal anomaly also revealed more aerosols in Bangladesh during the monsoon is then pre-monsoon, winter and post-monsoon seasons. The trend analysis of Terra DT revealed a lower observation of aerosol concentration in the morning. Aqua (DT and DB) showed increasing trend from 2003-2014. The obtained results were validated by AERONET AOD at 550nm data over Dhaka, Bangladesh for 2012-2013. DB Level-3 AOD once again showed that DB is unable to retrieve AOD over Dhaka because it is a vegetation areas and due to the humid condition. However, the derived AOD over Dhaka using DT was validated by AERONET AOD. The validation is performed on the overall data set, which stipulates that Terra MODIS DT (Correlation, R=0.749) shows its performance is better to retrieve AOD than Aqua MODIS DT (Correlation, R=0.73) for 2012-2013. In addition, Aqua MODIS DT (R=0.692) is better to retrieve AOD than Terra MODIS DT(R=0.622) in pre-monsoon. In monsoon, Aqua MODIS DT (R=0.979) shows an excellent performance to retrieve AOD than Terra satellite in monsoon. In winter, Terra MODIS DT(R=0.841) showed better performance in retrieving AOD than Aqua MODIS DT (R=0.717). Therefore the key conclusion is that MODIS DT product for both satellites can be used effectively for aerosol monitoring over Bangladesh.

Acknowledgements

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