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Variability of Aerosol Parameters Derived from Ground and Satellite Measurements over Varanasi Located in the Indo-Gangetic Basin

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ABSTRACT

Atmospheric aerosol plays a very important role in the Earth's radiation budget and global climate studies. This study reports the variability of the physical and optical properties of columnar aerosol and water vapour over Varanasi (25.2°N, 82.9°E), located in the heart of the Indo-Gangetic Basin, for the first time. The study was carried out using a MICROTOPS-II sunphotometer to measure the Aerosol Optical Depth (AOD) and metrological parameters. It is observed that the AOD loading is enhanced during the pre-monsoon and winter seasons, while it is decreased during the monsoon season. The variability of the angstrom coefficient (α) and turbidity coefficient (β) shows that in the pre-monsoon season coarse-mode aerosol particles are dominant, while fine-mode aerosol particles are dominant in the winter. We compared our MICROTOPS-II ground-based data with the level-3 data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra satellite. A good seasonal correlation (correlation coefficient, R^2 ~0.57) was observed between MICROTOPS-II and MODIS AOD data. The results of the variability of water vapor over Varanasi are also discussed. The correlation coefficient (R^2) between daily MICROTOPS-II and MODIS water vapor is found to be more than 0.85 for the year 2011.

Keywords: Aerosols; Aerosol optical depth; Indo-Gangetic basin; Angostrom exponent.

INTRODUCTION

Aerosols in the atmosphere are tiny liquid/solid particles in the air (excluding cloud particles) that have negligible terminal fall speed and which are injected by natural sources originating from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray or anthropogenic sources such as the burning of fossil fuels and the alteration of natural surface covers (Kaskaoutis *et al.*, 2007). Natural aerosols share 80% and play an important role in global scale climate through the modification of transmission of solar irradiance, cloud nucleation and electrical properties of the atmosphere. Anthropogenic aerosols dominate on regional scale (Kaskaoutis *et al.*, 2009). Aerosol play an imporatnt role in the Earth's atmospheric processes due to their direct and indirect effect (Kaufman *et al.*, 1998; Sateesh and Ramanathan, 2000; Ranjan *et al.*, 2007; Badrinath *et al.*, 2008; Pawar *et al.*, 2012) and also affect on visibility and radiation (Han *et al.*, 2012). However scientific understanding of these processes are at minimal level (IPCC, 2007, Siingh *et al.*, 2011). In view of its impact on climate, human health and enviourment, it becomes very important to improve the knowledge of characteristic of atmospheric aerosol on regional and global basis with a high spatial and temporal resolution (Smirnov *et al.*, 2002), particularly over the region where population density is high (Day and Di Girolamo, 2010).

The Indo-Gangetic Basin (IGB) traversed by the Ganga River and its tributaries is one of the largest basins in the world, which is densely populated primarily due to the presence of numerous small and large rivers and fertile soil that make this region agriculturally highly productive. Large scale uncontrolled urbanization and industrial development in this region are the major sources for air, water, and land pollution which affect aerosol distribution in space and time. The topography of the IG basin from the west to east and variable meteorological conditions control the dynamic behaviour of atmospheric aerosols in both space and time and significant uncertainty in aerosol radiative forcing limits the performance of climate models. Goloub *et al.* (2001) using limited POLDER data observed very high aerosol optical depth (AOD) over the Indo-Gangetic basin. Due to high AOD, dense fog, haze and smog are found over the IG basin during winter season (Goloub *et al.*, 2001; Massie *et al.*, 2004; Singh *et al.* 2004; Gautam *et al.*, 2007; Prasad and Singh, 2007, Ram *et al.*, 2012). Understanding of the atmospheric aerosols behaviour over the IG basin is a great challenge since numerous parameters govern the aerosols dynamics and influence the climatic change (Singh *et al.*, 2004).

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Aerosol Optical Depth (AOD) is one of the important parameter for the study of characteristic of atmospheric aerosol and it is related to the direct solar radiation by scattering and absorption process (Ranjan *et al.*, 2007). Hence it is highly dependent on meterological condition and altitude. Apart from this, there are two other important parameters Angostrom exponent (α) and Turbidity cofficient (β) which define the optical properties of aerosol. There are several studies in which both α and β are analysed in different spectral bands (Kaskaoutis *et al.*, 2009). The transportation of atmospheric aerosols over a wide range in horizental and vertical direction depends on air mass trajectories (Badarinath *et al.*, 2007, 2008, 2009; Kuniyal *et al.*, 2009).

Satellite data from the Multiangle Imaging SpectroRadiometer (MISR) and Moderate Resolution Imaging Spectroradiometer (MODIS) are available with good spatial (0.5° × 0.5° for MISR and 1° × 1° for MODIS) and temporal coverage and are being widely used to understand atmospheric processes and climate variability (Kaufman *et al.*, 2002). Satellite data needs validation using ground based measurements (Chu *et al.*, 2002; Ichoku *et al.*, 2002; Kahn *et al.*, 2005; Remer *et al.*, 2005). Recently, ground-based AERONET (Holben *et al.*, 1998; Kaskaoutis *et al.*, 2012b) and satellite data (Polarization and Directionality of the Earth's Reflectances, POLDER; Total Ozone Mapping Spectrometer, TOMS; MODIS; and MISR) have been used extensively to study the variability of aerosol optical properties over the Indo-Gangetic basin (Goloub *et al.*, 2001; Di Girolamo *et al.*, 2004; Massie *et al.*, 2004; Singh *et al.*, 2004; Prasad *et al.*, 2004; Ramanathan and Ramana, 2005; Prasad *et al.*, 2006; Tiwari *et al.*, 2009; Dey and Girolamo, 2010; Srivastava *et al.*, 2011; Kumar *et al.*, 2012) which is one of the highly polluted regions of the world. Tripathi *et al.* (2005) carried out MODIS AOD validation using 11 months data of level 2 MODIS for the year 2004; whereas Jethva *et al.* (2005) have used 22 months of level 3 MODIS data for the periods (2001–2003). However, apart from these above studies, there is an absence of indepth understanding of aerosol distribution on a local scale. Also the inter-comparison and validation of satellite derived AOD from different ground instruments is necessary to build a long term database for climatological studies and to improve the accuracy of the single sensor. Hence, in the present study, we analyzed for the first time the physical and optical aerosol parameters measured over Varanasi (latitude 25.2°N, longitude 82.9°E and above ~83 m msl) which is located in the heart of IGB. The study is based on routine measurements using MICROTOP-II sunphotometer during the year 2011 and a comparision of ground based measurements of AOD with that of satellite based level 3 MODIS data. Our analysis shows a strong spectral and seasonal variability of the optical properties of the aerosols over Varanasi and a good seasonal correlation is observed between MICROTOPS-II and MODIS AOD data.

SITE DESCRIPTION AND TOPOGRAPHY

The city of Varanasi (latitude 25.2°N, longitude 82.9°E and above 83 m msl) is situated on the bank of river Ganga and located in the heart of Indo-Gangetic Basin. Nearly 20% of geographical area and approximately 40% of food production of India is covered by IGB and also 40% population of India lie in IGB. IGB is bounded by Himalaya to the North, Vindyana – Satpura range to the south, Thar Desert and Arabian Sea in western part, while eastern part is surrounded by the Bay of Bengal. So IGB has a unique topography due to which natural and anthropogenic both aerosols show the strong seasonal variability (Massie *et al.*, 2004; Singh *et al.*, 2004; Dey and Tripathi, 2008; Misra *et al.*, 2008; Srivastava *et al.*, 2011; Kaskaoutis *et al.*, 2012a). The IGB experiences four seasons annually, summer or pre-monsoon (March–June), monsoon (July–August), post-monsoon (September–October) and winter (November–February). During the pre-monsoon, air mass carries dry dust particles from the western Thar desert to the region which produces frequent dust storms and dry weather. Monsoon wind arrives in the region from the eastern part of the Ganga basin during June to early July carrying moisture, and as a result the relative humidity increases drastically and reaches up to 60–90%. During the post-monsoon and winter seasons the whole region is dominated by aerosols of anthropogenic sources loaded by local and northerly winds. The western disturbances during winter season load the region with intense fog and haze (Pasricha *et al.*, 2003). At Physics Department, Banaras Hindu University Varanasi MICROTOPS-II sunphotometer was purchased and measurements were carried out on routine basin during the whole year 2011. The daily mean maximum temperature was 46.3°C while minimum temperature was 15.7°C during the year 2011.

INSTRUMENTATION AND DATA

The ground based measurements were carried out using hand held and portable multiband sunphotometer MICROTOPS-II which is developed by Solar Light Company, USA. It contains five different interference filters at 380, 440, 500, 640, and 870 nm wavelengths and provides the corresponding AOD. The additional 940 nm channel is used for perceptible water vapour contents. The sunphotometer works on the principle of extension of solar radiation intensity at a certain wavelength and calculates the corresponding optical depth by using the knowledge of the solar intensity at the top of the atmosphere. The same is calculated easily by Langley method (Schmid and Wehril, 1995). The details of MICROTOPS–II, its calibration and performance are given in Morys *et al.* (2001). The data were collected using MICROTOPS-II at every half hour for each clear sky day throughout the whole year 2011. We have taken proper care about the MICROTOPS-II observations and proper cloud screen was done. We maintain a log book for each MICROTOPS observation and noted the cloud condition and sunshine for each measurement. In the present study, we have selected only those measurements which were taken during proper sunshine.

Satellite based AOD data have been obtained using level-3 MODIS Terra (MOD08_M3, in HDF format) as a monthly gridded average in 1° × 1° spatial resolutions (http://modis.

gsfc.nasa.gov/) (Chu *et al.*, 2002; Ichoku *et al.*, 2002, 2004; Remer *et al.*, 2005). The retrieval of AOD is not possible under cloudy conditions. The AOD algorithms for application over land and sea surfaces are mutually independent due to contrast in the radiative properties of water and land. The retrieval is more accurate over ocean compared to the land because of the low albedo values of the water compared to high albedo values of land and land cover. The MODIS retrieval (v4.2) of the AOD over land employs primarily three spectral channels centred at 0.47, 0.66, and 2.1 µm. AOD is derived at 0.47 and 0.66 µm, and interpolated to 0.55 µm. The AOD is only retrieved for cloud-free pixels in a 20 × 20 pixel area at 500 m resolution and reported at 10 × 10 km^2 resolution. Only when > 12 pixels are classified as cloud free, retrieval is attempted. The AOD is retrieved over surfaces that are not highly reflective (hence snow or ice covered surfaces and desserts are excluded) (Schaap *et al.*, 2008). The algorithms are described by Kaufman and Tanre (1998), and updates are discussed by Remer *et al.* (2005). We have also used Level-3 MODIS terra (MOD08_D3, http://modis-atmos.gsfc.nasa.gov) daily global grid product of near infrared water vapor with clear column available at spatial resolution of 1° × 1° and validated it with MICROTOPS-II derived water vapor. To identify the origin of source regions and the transport pathways of aerosols to reach the measurement site, we have used the seven days air mass back trajectories at three different height 500 m, 1 km, and 1.5 km based on National Oceanic and Atmospheric Administration (NOAA) Hybrid Single Particle Lagrangian Integrated Trajectories (HYSPLIT) model (website http://ready.arl.noaa.gov/HYSPLIT.php).

RESULT AND DISCUSSIONS

Fig. 1 shows satellite derived mean AOD at 550 nm over the Indian sub-continent during 2011 using MODIS data. From the figure it is observed that AOD over IGB is much higher than the rest part of India. The reason for high AOD over the IGB is due to the large influx of desert dusts from the western arid and desert regions of Arabia, Africa and Thar (Rajasthan) regions during the pre-monsoon season (April–June) (Dey *et al.*, 2004; El-Askary *et al.*, 2004, 2006; Gautam *et al.* 2009). Recently, Kumar *et al.* (2012) have studied the seasonal variation of AOD over IGB during 2005–2009 and reported high loading of aerosols over IGB compared to the other parts of India during the winter and summer seasons.

The daily mean variation of AOD at 500 nm over Varanasi measured by ground based MICROTOPS-II sunphotometer during the year 2011 is shown in Fig. 2, which shows a large variation of AOD during 2011 over Varanasi. The daily mean of AOD over Varanasi lies between 0.2 and of 1.8. The AOD loading is found to be enhanced during the pre-monsoon (May, June) and winter (November–January) season, while it decreased during the monsoon season. This could be due to recent changes in land use and land cover during monsoon period. Even land surface becomes wet and part of atmospheric aerosols may be removed along with precipitation. During pre-monsoon season, enhancement in AOD is attributed to aerosol loading due to dust-storm events (Gautam *et al.*, 2010) from far source region, Arabia peninsula and African regions.

Fig. 3 shows the monthly mean spectral variation of AOD at five different wavelengths 380, 440, 500, 640, and

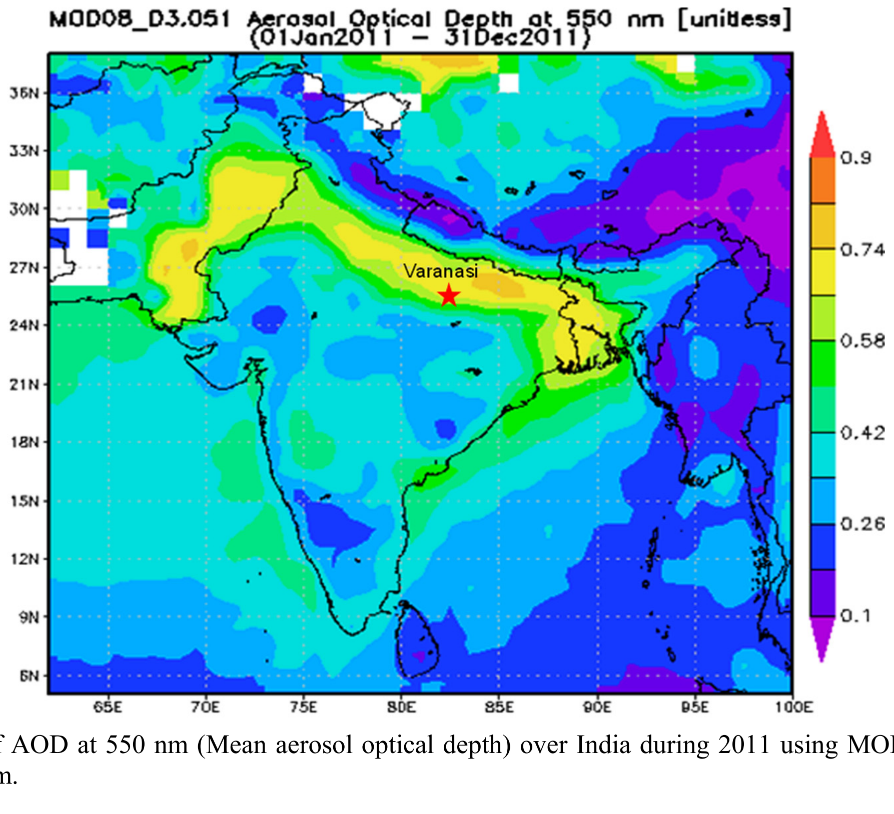

Fig. 1. Variation of AOD at 550 nm (Mean aerosol optical depth) over India during 2011 using MODIS level 3 data on board Terra platform.

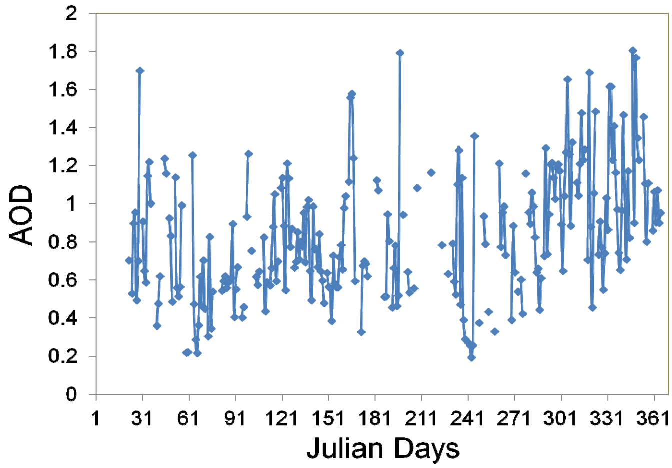

Fig. 2. Variation of daily mean AOD over Varanasi using MICROTOPS-II Sunphotometer at wavelength 500 nm during 2011.

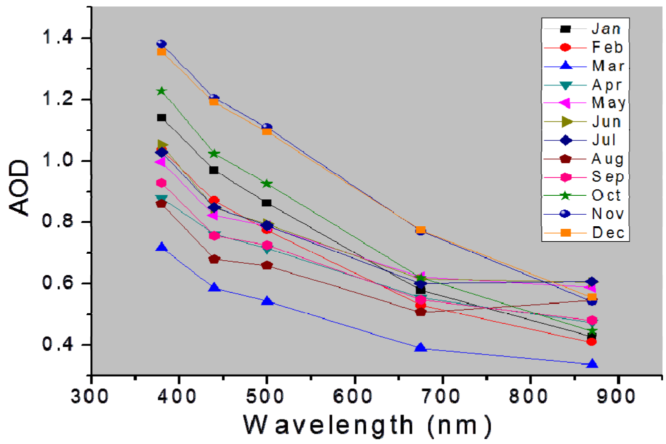

Fig. 3. Spectral variation of AOD at different wavelength 380, 440, 500, 640 and 870 nm over Varanasi during 2011.

870 nm derived from MICROTOPS-II sunphotometer. The spectral variation of AOD clearly shows that at shorter wavelengths AODs are higher while at longer wavelengths they are relatively lower attributing to the presence of fine to coarse particles (Reddy *et al.*, 2011). The presence of high concentration of the fine-mode particles selectively enhances the irradiance scattering at lower wavelength and therefore, the AOD values are high at the shorter wavelengths. Likewise, the coarse-mode particles provide similar contributions to the AOD at relatively larger wavelengths (Schuster *et al.*, 2006). It is noticed that the magnitude of mean AOD is higher at lower wavelengths on July and August months, which indicates the dominance of coarse-mode aerosols due to the condensation growth and coagulation mechanism of submicron aerosols, which are more efficient in producing larger aerosols (Reddy *et al.*, 2011). Larger aerosols are useful in cloud nucleation. In IGB region July and August months are relatively cloudier.

Apart from AOD, Angstrom exponent (α) and turbidity coefficient (β) are another two important parameters for the study of atmospheric aerosol properties. Angstrom exponent (α) provided the aerosol particle size and can be easily obtained by the angstrom power law (Angstrom, 1964),

$$\tau = \beta\lambda^{-\alpha} \quad (1)$$

where λ is the wavelength in micrometer, τ is AOD, α is angstrom exponent and β is turbidity coefficient which is equal to columnar AOD at λ = 1 µm. Parameter τ gives an indication of the amount of the aerosol present in the atmosphere, and α is a good indicator of the fraction of accumulation mode particles (r < 1 µm) to coarse-mode particles (r > 1 µm) which describes the aerosol size distribution. Therefore, for the determination of aerosol size distribution and total columnar aerosol loading over Varanasi, α and β are calculated for wavelength pair 380–870 nm using MICROTOPS-II sunphotometer data and plotted against the Julian days for the whole year 2011, which is shown in Fig. 4. The higher value of α implies the dominance of smaller size aerosols particles and vice versa. The value of α lies in between 0.25 to 1.8 which indicate that there are different types of aerosols which are present in the atmosphere over Varanasi. The aerosols may have different sources, which depends on weather parameters. In this figure we also see that in pre-monsoon season α value is relatively smaller with α < 1.0 (r ≥ 0.5 µm) which indicate the existence of bigger size of aerosol particles that may be due to the burning of agricultural field products that generate plenty of biomass burning aerosol and also due to dust aerosol coming from Thar desert and Sahara desert (Singh *et al.*, 2004). On the other hand in winter season α value are higher α > 1.0 (r ≤ 0.5 µm) indicating that in winter small aerosols particle are dominant. The Fig. 4 shows that the variation of β values lies between 0.10 and 1.44 which shows the nature of variation of AOD. It is observed that the temporal variation of α was almost opposite in nature to that of the β. Higher values of β were associated with the lower values of α. Thus we conclude that α and β show nearly anti-correlation to each other which agreed with the earlier observations (Satheesh *et al.*, 2006; Reddy *et al.*, 2011).

To validate the MODIS derived AOD data we have used ground measured AOD by MICROTOPS-II sunphotometer. MODIS AODs are derived at 550 nm while MICROTOPS-II AODs are derived at 500 nm. In order to compare AODs at the same wavelength MICROTOP-II AOD at 500 nm were interpolated to a common wavelength of 550 nm by using Angstrom power law (Prasad and Singh, 2007):

$$AOD_{550nm} = AOD_{500nm}\,(550/500)^{-\alpha} \quad (2)$$

Fig. 5 shows the variation of daily AODs at 550 nm retrieved from MICROTOPS-II at the time of pass of Terra satellite over Varanasi and MODIS level 3 data onboard Terra satellite during the year 2011. AOD loading is found to show strong seasonal variations which is enhanced during pre-monsoon (May, June) and winter season (November, December) while decreased during the monsoon season During pre-monsoon season, enhancement in AOD is attributed to aerosol loading transported from the neighbouring Thar desert region (Dey *et al.*, 2004; Lee *et al.*, 2011; Srivastava *et al.*, 2011) as well as from far source region, Arabia peninsula and African regions. Similar variation of AOD over Varanasi was observed by Kumar *et al.* (2012) using only satellite data of MODIS and MISR during 2005–2009. We observed that there is a good overall one-to-one correlation with satellite and ground measured

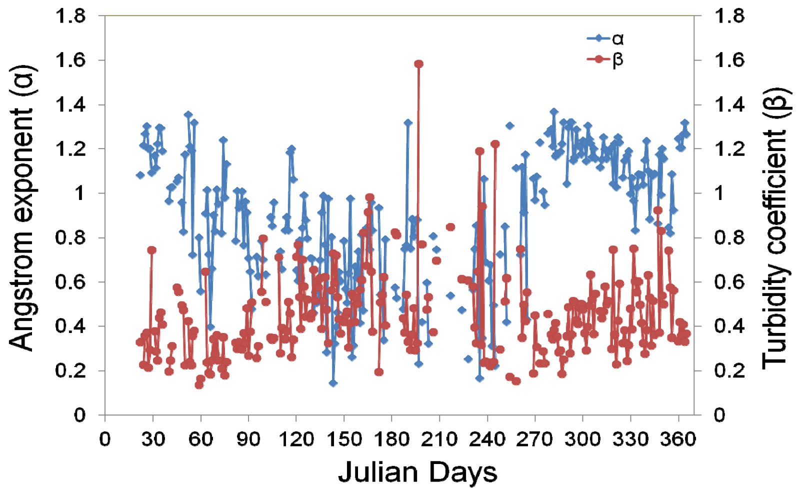

Fig. 4. Variation of Angstrom exponent (α) and Turbidity coefficient (β) over Varanasi during 2011.

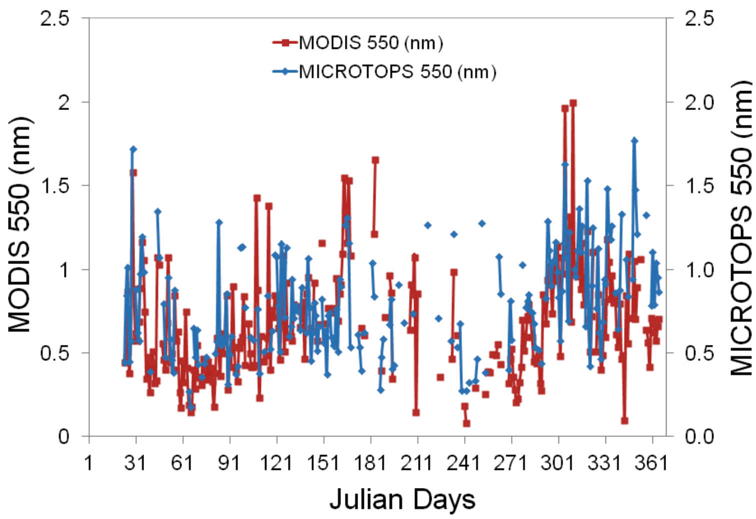

Fig. 5. Comparison of AOD at 550 nm with the MODIS and MICROTOPS-II at time of pass of Terra satellite over Varanasi during 2011.

AOD data over Varanasi. The overall correlation coefficient between MODIS and MICROTOPS-II AOD data is found to be 0.57. For better correlation study between MICROTOPS-II and MODIS AOD data we have also computed seasonal correlation for the summer (March–June), monsoon (July–August), post-monsoon (September–October) and winter (November–February) seasons which are shown in Fig. 6. The number of data point taken in each season is denoted by 'N'. Regressions are also shown in Fig. 6, with regression line parameters and R^2 values (Table 1). We observed that in summer, winter and post-monsoon the correlation coefficient (R^2) is found nearly 0.47, 0.57 and 0.69 respectively. In contrast, during the monsoon (July–August) season we observed much better correlation with R^2 values nearly 0.69. These good correlation results enable us to validate the satellite data. A slope of the regression line that is different from unity indicates that there may be some inconsistency between aerosol microphysical and optical retrieval algorithm and that in the real situation (Zhao *et al.*, 2002). The observed slopes are lower than unity during the summer (~0.70), winter (~0.69), and post-monsoon (~0.86) seasons (Fig. 6). This indicates an underestimation of AOD by MODIS with respect to MICROTOPS-II retrieval, whereas a high slope (~1.08) during the monsoon season indicates an overestimation of AOD by MODIS with respect to MICROTOPS-II retrieval. Khoral *et al.* (2011) used both Level 2 and Level 3 Terra/Aqua MODIS derived AODs at 550 nm and compares them with ground-based MICROTOPS-II, sunphotometer measured AOD at 550 nm during the period 2002–2008 over Hyderabad, India and observed that the correlation coefficient (R^2) in all seasons ranges from 0.30 to 0.46. However, during pre-monsoon both MODIS Terra/Aqua Level 2 and Level 3 AOD show better correlations (R^2 ~0.55) with MICROTOPS-II compared to those in winter (R^2 ~0.30) and post-monsoon (R^2 ~0.46). Misra *et al.* (2008) compared MODIS AODs against the MICROTOPS AOD over Ahmadabad in Western India during 2002–2005 and observed that pre-monsoon (April to May) has the best

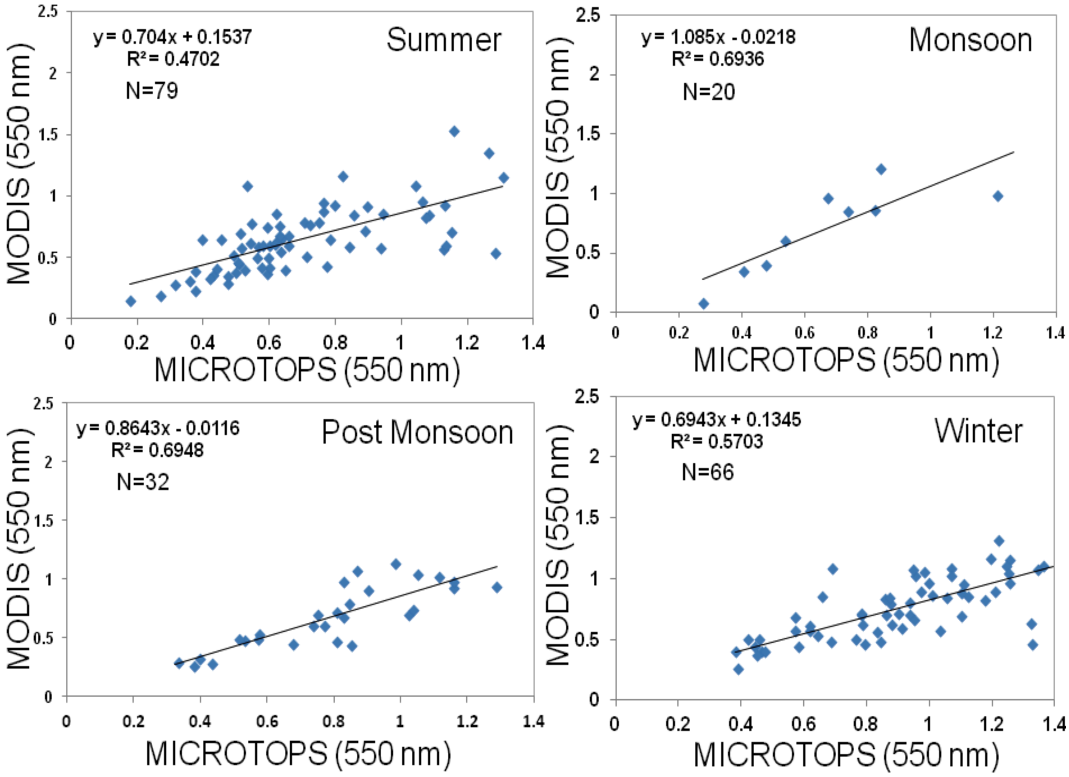

Fig. 6. Validation of level 3 MODIS AOD over Varanasi using MICROOPS-II AOD, at 550 nm, during the summer (March–June), monsoon (July–August), post-monsoon (Sep.–Oct.) and winter (Nov.–Feb.) season during 2011.

Table 1. Regression coefficients of correlation analysis between MODIS and MICROTOPS-II AOD data over Varanasi for different seasons during 2011 (Fig. 6).

Seasons	Correlation Parameters		
	Correlation Coefficients	Slope	Intercept
Summer	0.470	0.704	+0.153
Monsoon	0.693	1.085	–0.022
Post-monsoon	0.695	0.864	–0.011
Winter	0.570	0.694	+0.134
Overall (2011)	0.575	0.873	+0.087

seasonal correlation and dry season (December to March) the least. Yang *et al.* (2010) compared the AOD Level 2 from MODIS Terra and Aqua with that of MICROTOPS-II sunphotometer over Sanya, a tropical coastal site in China, from July 2005 to June 2006. They observed that the Terra and Aqua MODIS AOD retrievals at 550 nm have good correlations with MICROTOPS-II having the correlation coefficients for the linear regression fits (R^2) 0.83 for Terra and 0.78 for Aqua. However, the Terra and Aqua MODIS were found to consistently underestimate AOD with respect to the MICROTOPS-II sunphotometer, with slope values of 0.805 (Terra) and 0.767 (Aqua). Gulleria *et al.* (2011) observed the correlation coefficient of 0.76 using daily level 3 MODIS Terra AOD and ground based multi-wavelength radiometer (MWR) data over Mohal, located in the Kullu valley of north-western part of the Indian Himalayas. Prasad and Singh (2007) reported correlation coefficient of 0.29 and 0.47 respectively for summer and winter season based on a validation exercise carried out using daily level 3 MODIS Terra AOD and AERONET data over Kanpur located in IGB. They found MODIS overestimating the AOD values during summer and underestimating during winter with slope in the two cases 0.51 and 0.48 respectively. Using MODIS Level 2 AOD data and AERONET data at 550 nm over Kanpur for 2004, Tripathi *et al.* (2005) found an overestimation by MODIS during dusty period and an underestimation during non-dust seasons with slopes in the two cases 2.46 and 0.69 respectively having the R^2 values 0.72 and 0.71 respectively. It is noticed that R^2 values remained nearly same. Jethva *et al.* (2005) compared the monthly mean AOD at 550 nm computed from MODIS Level 3 daily gridded data with the AERONET derived monthly mean AOD values from Kanpur, India for the period January 2001 to July 2003. They found a systematic overestimation by MODIS during summer and an underestimation during winter.

The frequency distribution of AOD values for all the data points of MODIS and MICROTOPS-II is presented in Fig. 7. From this figure, it is clear that the AOD probability distribution is narrow, with a maximum at 0.6–0.9, and that the majority of AOD values are less than 0.9. In the range of AOD < 0.6, the frequencies of the MODIS AODs are considerably higher than those of the MICROTOPS-II AODs and the frequency differences reach maximum of 8.5% while in the other higher AOD ranges, the frequencies of MODIS AOD are relatively lower than those of the MICROTOPS-II AODs. In the AOD range of 0.6–0.9, the frequencies of MODIS AODs are well matched with those of the MICROTOPS-II AODs (maximum difference of 2.5%). Yang *et al.* (2010) reported the frequency distribution after comparing the AOD from MODIS Terra and Aqua with that of MICROTOPS-II over Sanya, China and observed that the probability distribution was narrower with maximum at 0.15–0.25 and that the majority of AOD values were less than 0.25. Using MODIS Level 2 AOD data and AERONET data at 550 nm over Kanpur for the year 2004, Tripathi *et al.* (2005) observed that the frequency distribution were well matched (maximum difference of 2%) for AOD < 0.75. However, for AOD > 1.25, the difference was found to be maximum (6%). Guleria *et al.* (2011) studied the frequency distribution of AOD values for the data points of MODIS Terra AOD and MWR over Mohal, located in the Kullu valley of north-western part of the Indian Himalayas and observed that the majority of AOD values were between 0.10–0.20 (maximum difference of 2%). The observed differences in our study using MICROTOPS-II and MODIS AOD measurements could be explained by various factors such as retrieval algorithm, total area under observation during measurement, and platform (ground and space based).

The variation of daily mean water vapour content measured by MICROTOPS-II as well as MODIS data over Varanasi during the whole year 2011 is shown in Fig. 8. Water vapour content measured by MICROTOPS-II varies in the range 0.4–4.9 cm, with the maximum peak during the July–September months, the monsoon season. During, the pre-monsoon season (March–June), it shows higher fluctuation, which may be due to dust events in the year 2011. During the monsoon season the MODIS derived water

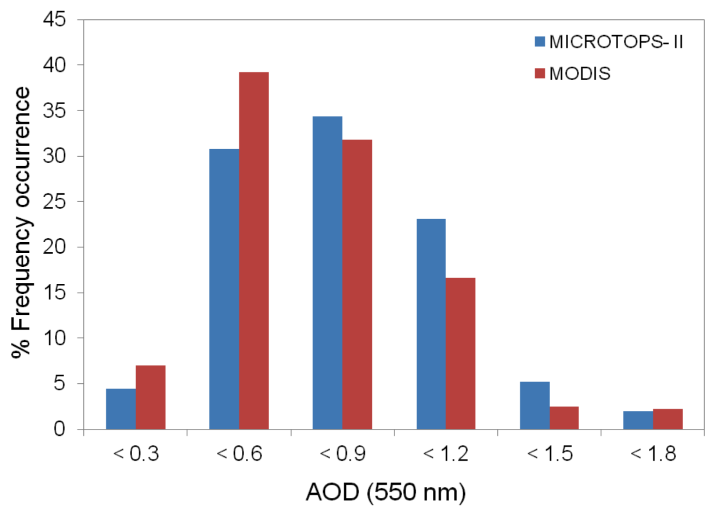

Fig. 7. Frequency distribution of terra MODIS and MICROTOPS-II occurrence of AOD at 550 nm over Varanasi during 2011.

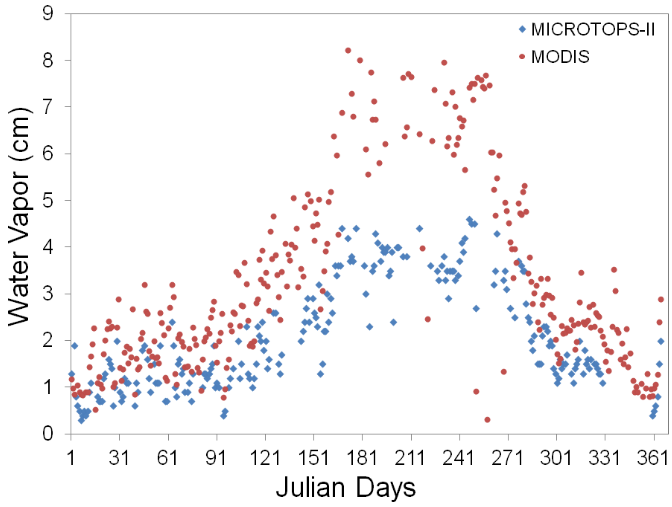

Fig. 8. Variation of daily mean water vapour content measured by MICROTOPS-II as well as MODIS Terra data over Varanasi during 2011.

vapor shows comparatively larger values of water vapor over Varanasi. The correlation coefficient (R^2) between daily MICROTOPS-II and MODIS water vapor is found to be more than 0.85 for the year 2011 (Fig. 9). In general, a high slope (~1.63) of the regression line (Fig. 9) indicates an overestimation of water vapour by MODIS with respect to MICROTOPS-II retrieval during the whole year 2011. Kumar *et al.* (2010) have compared the variability of water vapor over Varanasi and Kanpur obtained from global positioning system (GPS) and MODIS water vapor data for the year 2007 and reported the correlation more than 0.97. The daily variation of GPS water vapor for the year 2007 was found to vary in the range (0.4–6.8 cm) over Varanasi and 0.5–6.7 cm over Kanpur. Prasad *et al.* (2007) have made comparison of GPS and MODIS water vapor over India during the year 2004 and 2005 and have found correlation more than 0.95.

The seven days air mass back trajectories at three different height 500 m (red), 1 km. (blue) and 1.5 km. (green) were also calculated based on National Oceanic and Atmospheric Administration (NOAA) Hybrid Single Particle Lagrangian Integrated Trajectories (HYSPLIT) model (Draxler and Rolph, 2003). The back trajectory analysis provides a three-dimensional (latitude, longitude and altitude) description of the pathways followed by air mass as a function of time by using National Centre for Environmental prediction (NCEP) reanalysis wind as input to the model. The back trajectories are very important to identify the origin of source regions and the transport pathways of aerosols to reach the measurement site and also to investigate the aerosol properties and types (Bian *et al.*, 2011). Seven days air mass back trajectories for four typical high aerosol loading days of measurements during the year 2011 on 9th April (AOD = 1.26), 16th July (AOD = 1.79), 1st November (AOD = 1.65) and 15th December 2011 (AOD = 1.77) are shown in Fig. 10. The air masses from different source regions lead to the formation of different aerosol types (Reddy *et al.*, 2011). On 9th April 2011 the air masses seem to be transported from the western region of Pakistan and Turkmenistan at high altitudes (1500 m and 1000 m) and passes over Thar desert before interring into IGB whereas at low altitude (500 m) from nearby regions of Uttarakhand and western Uttar Pradesh. On 16th July, 2011 the air masses (for all three levels) seem to come from marine environment (Arabian sea as well as Bay-of-Bengal) and carry mostly sea salt aerosols while traversing through the continental mainland before they reach the measurement site (Reddy *et al.*, 2011). On 1st November, 2011 the air masses seem to be transported from the farther region of Iran at high altitudes (1500 m) whereas at low altitudes (500 m and 1000 m) from nearby sources of Jammu and Kashmir. Similarly on 15th December, 2011 the sources of aerosols extend farthest up to Libya in Africa and Saudi Arabia at higher altitudes (1500 m and 1000 m) which indicate the possible sources to be Sahara desert which passes over Thar desert before interring into IGB. The arid regions of the Thar Desert, Afghanistan, Middle East and the Africa (Saharan Desert) have been found to be major contributors of the mineral dust over the IG plains during the pre-monsoon and winter seasons whereas marine sources from Arabian sea and Bay-of-Bengal for monsoon season (Prasad and Singh, 2007; Reddy *et al.*, 2011).

SUMMARY AND CONCLUSION

The first time results of variability of atmospheric aerosol optical properties over Varanasi located in the heart of IGB during 2011 using ground and satellite based measurements are presented. We also compared the AODs of Terra MODIS retrievals with ground measurements using MICROTOPS-II. The main conclusions drawn from the present study are:

- IGB is the highest aerosol loaded region of India during 2011 due to its unique topography and different sources of anthropogenic aerosols.
- The aerosol optical properties over Varanasi are found to show a large variation with a seasonal effect. The AOD loading is found to be enhanced during pre-monsoon and winter season while decreased during the monsoon season over Varanasi.

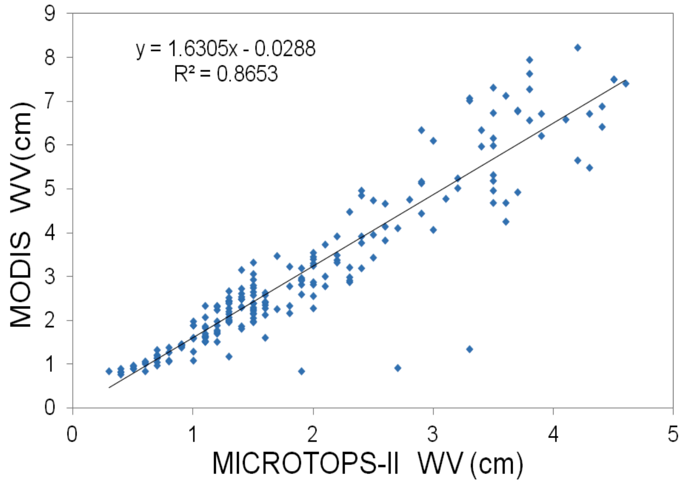

Fig. 9. Comparison of water vapour (WV) derived from MICROTOP-II and MODIS over Varanasi during 2011.

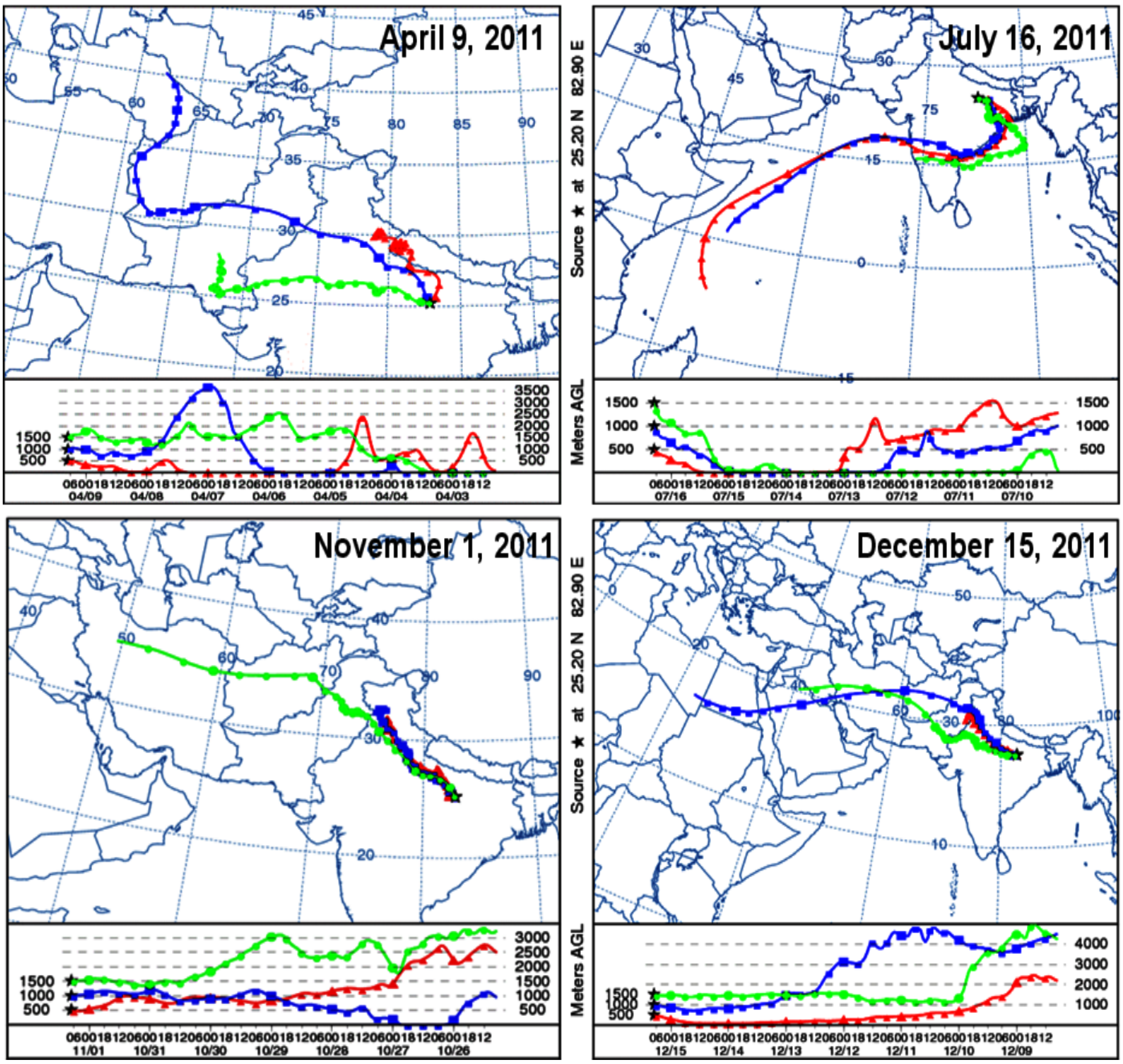

Fig. 10. Seven days back trajectories derived from HYSPLIT model for Varanasi for four typical days having large aerosol loading on 9th April, 16th July, 1st November and 16th December, 2011.

- The spectral variation of AOD clearly shows that at shorter wavelengths AODs are higher while at longer wavelengths they are relatively lower attributing to the presence of fine to coarse particles.
- The value of Angstrom exponent α lies between 0.25 and 1.8 which indicate that there are different types of aerosols present over Varanasi and may have different sources and weather parameters. In pre-monsoon season coarse-mode aerosol particles are dominant while in winter fine-mode particles are dominant over Varanasi.
- Comparison between AOD derived from MODIS and MICROTOPS-II over Varanasi shows that the Terra MODIS AOD retrievals are well correlated with the MICROTOPS-II measurements (R^2 ~0.57) over IGB. However, during the summer, winter, and post-monsoon seasons Terra MODIS underestimates AOD with respect to MICROTOPS-II, whereas during the monsoon season it overestimates.
- The seven days back trajectories analysis show that the arid regions of the Thar Desert, Afghanistan, Middle East and the Africa (Saharan Desert) have been found to be major contributors of the mineral dust over the IG plains during the pre-monsoon and winter seasons whereas marine sources from Arabian sea and Bay-of-Bengal for monsoon season.

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