Discrimination of Aerosol Types and Validation of MODIS Aerosol and Water Vapour Products Using a Sun Photometer over Central India

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ABSTRACT

Aerosol optical properties were studied using handheld Microtops II sun photometer over Nagpur (79.028°E, 21.125°N) located in central India, suggests highest Aerosol Optical Depth (AOD) (0.64 ± 0.08) during Pre-Monsoon Season (PMS) and lowest AOD (0.38 ± 0.06) during Summer Monsoon Season (SMS). Using the scatter plot of AOD500 versus Angstrom exponent (\(\alpha\)), dominating type of aerosol, during the most of the seasons is found to be urban/industrial and biomass burning (UB). Moderate Resolution Imaging Spectroradiometer (MODIS) active fire data suggests a large amount of biomass burning in different parts of India during PMS compared to other seasons. Aerosol transport analysis suggests during PMS, the air masses were originated from the biomass burning regions, desert regions and also from marine regions. Seasonal variation of AOD550 over India using MODIS data indicates significant AOD (> 0.7) over northwest during SMS, Indo - Gangetic region during Post Monsoon Season (PoMS) and north east region during winter. Southern part of India shows relatively less AOD (< 0.45) compared to north India during all the seasons. MODIS derived AOD and water vapor (NIR), compared against the ground-based observations from sun photometer, indicates an underestimation of 35% lower AOD compared to sun photometer and overestimation of 20% higher water vapor with correlation coefficients of 0.75 and 0.89 respectively. In view of the sizeable contribution of biomass burning aerosols, we suggest the use of a more absorbing type of aerosol model for central India, for an accurate retrieval of AOD from MODIS.

Keywords: Aerosol types; central India; Validation; MODIS; Water vapor.

INTRODUCTION

Natural and anthropogenic aerosols are highly variable in space and time and play a significant role in the earth’s radiation budget and climate change (Wild, 2009). Precipitation frequency and rain rate are altered by aerosols (Li et al., 2011). Black-carbon aerosols absorb solar radiation, and thus warm the surface while sulfate and organic aerosols reflect solar radiation and cool the surface. Climate-change mitigation policies are aimed at reducing fossil-fuel black-carbon emissions, together with the atmospheric ratio of black carbon to sulfate (Ramana et al., 2010). The high extinction values observed in the Indian subcontinent and surrounding regions have a strong impact on regional climate (Franke et al., 2003). Both the aerosol optical depth and angstrom exponent depend on the wavelength; hence both these parameters can be used for the characterization of aerosol optical properties (Holben et al., 2001). This lead to a discrimination of the different aerosol types occurring in various locations over the globe into four main types: namely biomass-burning aerosols produced by forest and grassland fires, urban/industrial aerosols from fossil-fuel combustion in populated urban/industrial regions, desert dust blown into the atmosphere by the wind and aerosol of maritime origin (Kaskaoutis et al., 2007). Efforts have been made by Indian scientists to carry out annual and inter annual variability of aerosol parameters using multi-wavelength radiometer (MWR) since 1980 under the Indian Space Research Organization (ISRO) Geosphere Biosphere Program (Murthy et al., 1999). Even so, in view of the strong spatial and temporal variability of aerosols, the existing ground-based aerosol-monitoring networks in India are not sufficient to establish aerosol climatology of the whole country (Tripathi et al., 2005). Aerosol measurements were reported from several places within the country, but such data and results are sparse in a dry tropical region in the central India.

Ground-based observations are important in order to
verify the accuracy and validity of satellite-based retrievals. An extensive validation exercise tests the efficacy of the retrieval algorithm, conditions under which it works satisfactorily and cases where further improvement is needed (Mishra et al., 2008). India has a wide variety of ecosystems, surface conditions, and emission sources. So it is important to validate the satellite-based estimates using ground-based observations for different climatic/ecological regions throughout the country in order to evaluate and improve the existing MODIS products. We report the validation of the MODIS derived aerosol optical depth and water vapor over the central Indian region.

Long range transport of aerosols plays a significant role in the observed aerosol loading at a measurement location. To understand and locate the possible sources, back trajectory analysis is used. We also used MODIS detected fire locations in order to understand the contribution of biomass burning aerosols. The present study is for the first time over this region focusing on the classification of aerosol types, validation of MODIS AOD and water vapor products and the role of aerosol transport.

**OBSERVATIONAL SITE AND LOCAL METEOROLOGY**

Central India is bordered with the Great Indian Desert in the northwest, Indo Gangetic Plain (IGP) in the north and coastal India in east, west and south. The amazing fact of the geography of the Nagpur city (21°06'N, 79°03'E), is that it lies at the center of India (Fig. 1) and zero milestone of India is situated within the city. It has a mean altitude of 310 m above sea level and lies on the Deccan plateau of Indian peninsula and surrounded by plateaus of Satpura range. The city of Nagpur enjoys a very dry and semi humid climate throughout the year except in the monsoon season (June–September). Dry and hot weather make the climate scorching almost throughout the pre monsoon (PMS) season (March, April, May). The maximum temperature remains more than 42°C and at times; it may reach to 48°C. Summer Monsoon (SMS) advances in June and extends up to September. Maximum rainfall occurs during July and August months. During the post monsoon (PoMS) season (October and November), the maximum temperature is about 33°C. Winter season (December, January and February) of Nagpur is spine chilling with minimum temperatures around 12°C and at times even dip below that level.

**MEASUREMENTS AND DATA ANALYSIS**

Data from both the ground-based and satellite-based instruments are used to study aerosols over the central Indian region.

**Ground Based Measurements**

*Sunphotometer: Model 540 MICROTOPS-II* (microprocessor-based Total Ozone Portable Spectrometer) sun photometer is a compact, portable and multi-channel sun photometer, which has been operated, for the first time over this region focusing on the classification of aerosol types, validation of MODIS AOD and water vapor products and the role of aerosol transport.
time, at regional remote sensing center (central), Nagpur (21.125°N, 79.028°E and ~330 m above mean sea level), a tropical semi-urban station, situated in the central part of India, to study the characteristics of columnar aerosols and water vapor and to validate the satellite products.

The physical and operational characteristics of the instrument are described in the user’s guide (http://www.solar.com/manuals.htm). The sun photometer measures solar irradiance in five spectral wave bands from which it automatically derives AOD. Each has five channels with peak wavelengths of 440, 500, 675, 870, and 936 nm. The filters used in all channels have a peak wavelength precision of ± 1.5 nm and a full width at half maximum (FWHM) coverage. It employs CIMEL sun-sky spectral radiometer which measures the direct sun radiances at eight spectral channels centered at 340, 380, 440, 500, 670, 870, 940 and 1020 nm.

Derivation of AOD and water vapor using a sun photometer has been clearly explained by Ichoku et al. (2001) and Morys et al. (2001). However, here brief summary is given.

At 440, 500, 675 and 870 nm wavelengths, AOT is derived based on the Beer-Lambert-Bouguer law as follows:

\[ V_{\lambda} = V_{\text{air}} D^{-2} \exp(-\tau_{\lambda} M), \]  

where, for each channel (wavelength),
\[ V_{\lambda} \] is the signal measured by the instrument at wavelength \( \lambda \),
\[ V_{\text{air}} \] is the extraterrestrial signal at wavelength \( \lambda \),
\[ D \] = Earth-Sun distance in astronomical units at the time of observation,
\[ \tau_{\lambda} \] = total optical thickness (\( \tau_{\lambda} = \tau_{\text{O3}} + \tau_{\text{A}} + \tau_{\text{O3A}} \)) at wavelength \( \lambda \),
\[ \tau_{\text{O3}} \] = aerosol optical thickness (AOT) at wavelength \( \lambda \),
\[ \tau_{\text{A}} \] = Rayleigh (air) optical thickness at wavelength \( \lambda \),
\[ \tau_{\text{O3A}} \] = Ozone optical thickness at wavelength \( \lambda \),
\[ M \] = the optical air mass.

The Rayleigh and Ozone optical thickness, \( \tau_{\text{A}} \) and \( \tau_{\text{O3A}} \), are obtained from atmospheric models as below:

\[ \tau_{\text{O3}} = R_4 \exp(-h/29.3/273) \]  
\[ \tau_{\text{O3A}} = O3\text{abs} \times DOBS/1000 \]

where,
\[ h \] = altitude of the place of observation in meters,
\[ R_4 = 28773.6 \times (R_2 \times (2 + R_2) \times \lambda^{-2})^2, \]
\[ R_2 = 10^{-8} \times \{ 8342.13 + 2406030/(130 - \lambda^2) + 15997/(38.9 - \lambda^2) \}, \]
\[ \lambda \] = wavelength in microns,
\[ O3\text{abs} \] = Ozone absorption cross section, extracted from a lookup table based on wavelength,
\[ DOBS \] = Ozone amount in Dobson units, extracted from a lookup table based on latitude and date of observation.

Calibration of the MICROTOPS II sun photometer was performed at the Mauna Loa observatory, Hawaii, a noise-free high-altitude site, by its manufacturer (M/s Solar Light Control, USA) for reliable results before the measurements commenced in 2011 at our measurement site. Apart from this, we continuously monitored the MICROTOPS-II output at zero air mass (extra-terrestrial constant), which serves as calibration constant for each channel AOD and columnar water vapor. Other measurement errors arise due to filter degradation, temperature effects and poor pointing toward the sun. When the Microtops is well calibrated and properly cleaned, its AOT retrievals can be of comparable accuracy to those of CIMEL sun photometers used in the AERONET network, with uncertainties in the range of 0.01 to 0.02 (Holben et al., 2001). AERONET stands for Aerosol Robotic NETWORK conceived and maintained by NASA/GSFC (Holben et al, 1998) and is expanded by collaborators from other agencies in order to incorporate a large spatial coverage. It employs CIMEL sun-sky spectral radiometer which measures the direct sun radiances at eight spectral channels centered at 340, 380, 440, 500, 670, 870, 940 and 1020 nm.

The data set used here to cover the time period from January 2011 to December 2011 with total 116 observations. The ground-based sun photometer measurements are taken in cloud-free conditions so that there is no cloud patch covering the line of sight with the sun. For the present study, sun photometer observations have been selected from the condition that the time difference between ground based observation and MODIS overpass time is less than 15 minutes. The data set was used as the ground truth in the validation of the Terra MODIS AOD\(_{550}\) in this study.

### Determination of Angstrom Parameters

Spectral changes in measured AOD values can be quantified using the angstrom parameters (Angstrom, 1961) which are estimated using Eq. (4).

\[ \tau_{\text{A}} = \beta \lambda^{-\alpha}, \]  

In Eq. (4), \( \tau_{\text{A}} \) represents the AOD. The angstrom wavelength exponent (\( \alpha \)) indicates the size distribution of aerosol particles. The turbidity parameter \( \beta \) is a measure of the aerosol loading and is equal to the AOD measured at one µm wavelength. The parameters (\( \alpha \), \( \beta \)) were obtained using the least-squares fit to the plotted logarithm of AOD versus the logarithm of wavelength.

For validation, AOD from the sun photometer and MODIS satellite needs to be compared to which AOD from the sun photometer has been interpolated to a common wavelength of 550 nm using the following relation,

\[ \tau_{550} = \exp[\ln(\tau_{500}) - \ln(550/500)\alpha], \]  

where \( \alpha = \ln(\tau_{500}/\tau_{570})/\ln(675/500) \).

### SATELLITE MEASUREMENTS

#### MODIS

The Moderate Resolution Imaging Spectroradiometer (MODIS) flies on board the polar orbiting EOS Terra and Aqua satellite and measure aerosol optical depth and optical properties on a global scale daily since the year 2000. Terra and Aqua operate at an altitude of 705 km, with equatorial crossing time at 10:30 Indian Standard Time (IST) ascending towards north and at 13:30, IST descending towards south, respectively. MODIS has 36 bands ranging from 0.4 to
14.4 µm wavelengths with three different spatial resolutions (250, 500 and 1000 m).

In this study, MODIS daily level-3 collection version 005 AOD data at 550 nm averaged at a 1degree latitude/longitude grid to produce daily MOD08_D3.005 products from Terra satellite were used. For general climate modeling, the level 3 data provide a convenient source of data that has land and ocean measurements at a 1-degree scale combined into one file. Remer et al. (2005) provided global validation of Collection 004 (C004) product over both land and ocean (compared to AERONET) and reported the expected error bars of AOD values as $\tau_{p,\lambda} = \pm 0.05 \pm 0.15\tau_{p,\lambda}$ over land, where $\tau_{p,\lambda}$ is the ground-based AOD value. The updated C005 algorithm needs to be validated, to account for local biases. The aerosol properties contained within the lookup table (LUT) algorithm needs to be updated for as many sites as possible, in order to make the retrieved AOD more accurate (Levy et al., 2010).

In order to assess the contribution of forest fires and agricultural residue burning (which emit black carbon and other pollutants in to the atmosphere) to the variation of the aerosol optical depth over India, we used MODIS active fire data sets downloaded from Fire Information for Resource Management System (FIRMS) (Davies et al., 2009).

Aerosol Transport: Mapping the Source Locations

The back trajectories are very important to identify the origin of source regions and the transport pathways of aerosols reaching the measurement site and also to investigate the aerosol properties and types (Bian et al., 2011). 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 or The Global Data Assimilation System (GDAS) wind as input to the model. The five days air mass back trajectories at the height 500 m above the ground level were calculated based on National Oceanic and Atmospheric Administration (NOAA) Hybrid Single Particle Lagrangian Integrated Trajectories (HYSPLIT) model (Draxler and Rolph, 2003).

RESULTS AND DISCUSSION

Seasonal Variation of Aerosol Optical Depth, Angstrom Parameters

High AOD sub (0.64 ± 0.08) (Fig. 6(c)) is observed during PMS. High temperature, in association with strong surface winds, during summer plays an important role in heating and lifting the loose soil. The incursion of moisture either from the Bay of Bengal or Arabian Sea and/or operation of any trigger mechanism create conditions conducive for the explosive convective phenomenon. This high convective activity and frequent occurrence of long range transport of dust from northwestern India lead to increase in AOD during this season (Flossman et al., 1985).

The monsoon usually advances over central India during the end of second week or in the third week of June and this is characterized by severe weather activity like heavy rain, thundershowers, squally wind, etc. AOD sub values (0.38 ± 0.06) are observed to be lower during the monsoon season due to stronger upper winds, cloud scavenging and rain wash out processes (Badarinath et al., 2007). The withdrawal of monsoon is characterized by the reversal of winds from South West to North East. During the post monsoon, aerosols build up slowly and possibly undergo hygroscopic growth in water vapor (RH > 50%) leading to increase in AOD sub (0.5 ± 0.02). The winter season is characterized by dry and cold weather. In the winter season, AOD sub is less (0.42 ± 0.15) compared to post monsoon season.

Seasonal Variation of Angstrom Exponent (α) and Turbidity Parameter (β)

Higher values of $\alpha$ (> 1) (Fig. 2(a)) during PoMS and winter indicate larger abundance of sub micron aerosols (fine mode aerosols) originating mainly from biomass burning and fossil-fuel combustion sources. This also shows that the influence of the dust aerosols is very limited during this season. The dominating aerosols are in the fine-mode range formed in-situ by secondary gas-to-particle conversion process of the precursors (Kaskaoutis et al., 2009).

The values of $\alpha$ are moderate (~0.95) during PMS and SMS indicating an abundance of coarse mode aerosol particles and also a reasonable contribution from fine mode aerosols such as biomass burning. Greater $\beta$ during these seasons indicates more aerosol loading. This further indicates that as the aerosol loading increases, the relative dominance of fine aerosol decreases. Similar observations with dominance of fine mode aerosols during winter and post monsoon (coarse mode aerosols during summer and monsoon) over other locations namely Gurushikar and Ahmadabad (Kedia and Ramachandran, 2011) were reported.

Aerosol Type Classification

Better characterization of aerosol properties can be done using both AOD and $\alpha$ as both are functions of wavelength. This can be done using scatter plots of AOD versus $\alpha$ from which different aerosol types can be obtained for a specific location through determination of physically interpretable cluster regions of the diagram (Kaskaoutis et al., 2007). This technique has been used by many authors (e.g., Eck et al., 1999; Pac et al., 2006; Kaskaoutis et al., 2007; Kalapureddy et al., 2009; Kaskaoutis et al., 2011; Pathak et al., 2012) for the discrimination between different aerosol types.

The scatter plot diagram of AOD08 versus $\alpha$ (Fig. 2(b)) has been divided into physically interpretable clusters, in which each cluster represents the different aerosol type. For defining the background aerosol type the continental average model given by Hess et al. (1998) is assumed. According to this aerosol model, AOD at 550 nm is 0.151 for background aerosols and $\alpha$ in the spectral range 350–500 nm is 1.11 while in the range 500–800 nm is 1.42. The average AOD sub over the present study location is ~0.58 while $\alpha$ is found to be 1.11 for 500–870 nm. The threshold values of continental average (CA) types are taken as AOD sub < 0.3; $\alpha$ < 0.9. Most of the data points are located in the cluster region AOD sub > 0.35, $\alpha$ > 1, which corresponds to the particles of urban/industrial and biomass burning (UB). Cluster with higher AOD sub (> 0.40) and $\alpha$ < 0.7
indicates the presence of Desert Dust (DD). The remaining points are scattered corresponding to a variety of AOD500 values ranging from ~0.3 to ~0.9 and a wide range of $\alpha$ (~0.3 to ~1.5). These are categorized as the underdetermined or mixed type (MT) aerosols (Cachorro et al., 2001). This mixed or undetermined aerosol type is formed possibly by the mixture of anthropogenic and natural aerosols.

The seasonal distribution of the percentage contributions of the different aerosol types calculated using the scatter plot diagram of AOD500 versus $\alpha$ is presented in Fig. 3. During the post monsoon and winter, dominant aerosol type is UB followed by the undetermined or mixed type (MT). The presence of small amounts of Desert Dust (DD) and continental average (CA) type aerosols in PoMS and winter respectively is observed. During winter season, the anthropogenic emissions (fossil-fuel combustion, black carbon emissions) are found to be large over India (Ramachandran and Rajesh, 2007; Pathak et al., 2010). During PMS, UB and DD aerosol, types dominate and during SMS dominant aerosol type is MT followed by UB and DD respectively.

MODIS detected fire locations: In India, 55% of the total forest cover is prone to fires annually (Gubbi, 2003), which are mainly attributed to anthropogenic factors, like slash and burn agricultural practices, controlled burning, deforestation, fire-wood burning and others. Vadrevu et al. (2013) done a detailed study of these forest fires in India they attributed, fires in Punjab region and Indo-Ganges region, to agricultural residue burning and burning of closed broad leaf deciduous forests. In southern India, the fires are attributed to slash and burn agriculture, locally known as “Podu”. In central India (in and around measurement location) are attributed to biomass burning of crop residues, mostly Soybean and Wheat and forest burning due to intentional fires of tropical dry deciduous forests. The forests are burnt for clearing of land for agriculture, facilitating growth of grass for cattle grazing, in addition to management fires by the local forest department. In the northeast region, large amount of fires in the region is attributed to slash and burn agriculture also known as Jhum, practiced by the local people.

Fig. 4 shows MODIS sensor detected fire locations for different seasons. During PMS, there is a large amount of biomass burning in distinct parts of India. During other seasons, the biomass burning is observed to be low except in the Punjab region during post monsoon, south west and north east regions during winter.

Role of Aerosol transport: Source apportionment: Fig. 4 shows the locations of sources of air masses reaching at the measurement site for different seasons namely, PMS, SMS, PoMS and winter. During PMS, the air masses were originated from the biomass burning regions (see Fig. 4), desert regions and also from marine regions. During SMS, because of the sustained south westerly flow of the monsoon winds, the air masses were mostly of marine origin. During the post monsoon season, the dominant air masses were originated from north India, including transport of air masses from biomass burning, Punjab region. During winter, the origins of air masses were located in eastern India and IGP region.

Validation of MODIS Aerosol and Water Vapor Products
Seasonal variability of AOD over India: Fig. 5 shows seasonal average MODIS Terra AOD$_{500}$ over the Indian subcontinent and surrounding regions. Seasonal variations in AOD are found to be significant (AOD > 0.7) over northwest during SMS, IGP during PoMS and North east during winter. Southern part of India shows relatively less AOD (<0.45) compared to north India during all the seasons. Consistently high AOD in IGP region during all the seasons and inability to capture significant AOD seasonal changes in south India, indicate that there may be a significant bias in MODIS retrieval algorithm. This is due to adjusting of its algorithm based on AERONET station...
(IIT Kanpur: 26.28°N, 80.24°E) data and in this process, the AOD’s retrieved over other parts of India may be significantly under/over estimated. It is this point we would like to explore further by validating AOD over Nagpur located in central India.

**Validation of MODIS Aerosol Optical Thickness**

The purpose of validating any satellite-based geophysical parameter is to understand the errors involved in retrieval of such parameters and later correct the retrieval algorithm accordingly. Moreover, increase in the number of validated regions will lead to better comparison of the parameters on a global scale. For this purpose, detailed validation of MODIS AOD products of different versions with distinct spatial resolutions by using the ground-based multi wavelength radiometer and MICROTOPS sun photometer has been performed by several authors over the Indian subcontinent (e.g., Tripathi et al., 2005; Prasad et al., 2007; Mishra et al., 2008; Vinoj et al., 2008; Guleria et al., 2012). The studies found MODIS overestimating the AOD values during the summer and underestimating during winter. The present study attempts to validate the latest MODIS aerosol product version C005 over the central Indian region where there is no validation exercise done so far.

It is seen from the Fig. 6 that the MODIS AOD values were relatively lower than the sun photometer AOD values. The scatter plot (Fig. 6(a)) of sun photometer AOD versus MODIS AOD showed good agreement for daily observations. The linear regression line between AOD derived from MODIS and sun photometer was found to be

\[
\text{MODIS AOD} = 0.65 \times \text{sun photometer AOD} - 0.03, \quad (R = 0.75)
\]

A high correlation of 0.75 observed indicates that the MODIS can capture the seasonal variability well, and a slope of 0.65 implies an underestimation of 35% lower AOD compared to sun photometer. The absolute errors in retrieval of MODIS AOD show a linear relationship with its AOD and were found to be given as follows:

\[
\text{Absolute error} = -0.13 \times \text{MODIS AOD} + 0.26,
\]

Fig. 6(d) shows that the absolute error in estimation of AOD by MODIS decreases for an increase in aerosol loading. We see that the MODIS–sun photometer AOD correlation line has a small negative offset and a slope less than one (Levy et al., 2005; Tripathi et al., 2005). The y-axis offsets imply errors induced by assuming inappropriate surface reflectance. On the other hand, the less-than-one slope implies errors in the aerosol models (Levy et al., 2005). A similar deviation of the slope from unity was observed by several authors (e.g., Tripathi et al., 2005; Mishra et al., 2008; Gloria et al., 2012), which they attributed to error in aerosol model assumptions. Below we discuss possible error sources.

To understand the results, linear regression lines were fitted season wise as shown in Table 1. In the MODIS
Fig. 4. MODIS active fire data (red color symbols) and locations of sources of air masses (filled yellow color circles) reaching at the measurement site and overlaid on ESRI (http://www.esri.com) world image layer for different seasons PMS, SMS, PoMS and winter.

AOD retrieval algorithm, by default neutral aerosol model (Single Scattering Albedo (SSA) ~0.9) was set for a major part of Asia (Remer et al., 2005; Levy et al., 2007) for different seasons throughout a year. Absorbing (SSA ~0.85) or non-absorbing (SSA ~0.95) models were applied in other parts around the world. This is based on the aerosol types observed in AERONET sites located at different parts around the world and based on the condition that if either the non-absorbing or the absorbing aerosol occupied more than 40% of the pie, and the other occupied less than 20%, then the site was designated as the dominant aerosol type. In India, there is only one AERONET site (IIT Kanpur: 26.28°N, 80.24°E) located within the IGP region and aerosol types derived there is used in the retrieval of AOD for other locations.

During PMS main aerosol types observed over Nagpur location, were UB and DD, but MODIS algorithm assumes neutral aerosol while there is a good percentage of UB is present, which is of absorbing type of aerosol. The absolute error between AOD measured by the sun photometer to that of MODIS retrieved AOD is maximum (0.29) for this season. A good number of MODIS fire locations over central India and back trajectory analysis also indicate that there is a transport from such locations. This will lead to underestimation of AOD, as for absorbing aerosols if the algorithm considers the scattering nature of aerosols, it will wrongly assign a smaller value of AOD to match calculated radiance with observed radiance leading to underestimation of the retrieved AOD. The SSA for black carbon aerosols due to biomass burning is significantly lower than that of dust aerosols (Myhre et al., 2005). This may be the reason, while other authors reported overestimation of MODIS AOD compared to ground based AOD, over this region, we had observed the underestimation because of the significant amount of black carbon.

Similarly, during PoMS and winter seasons also presence of substantial amounts of UB leads to underestimation, while the variation in percentage of underestimation may be due to the presence of another type of aerosol such as mixed type of aerosol. During SMS, it is difficult to interpret because of the dominating presence of mixed type of aerosol and also presence of cloud contamination and less no of data points.

It is observed from Table 1 that the PoMS and winter season were having lower negative offset compared to PMS and SMS, while negative offset implies the overestimation.
of surface reflectance. Again this is because the surface type assumed, for India is based upon the AERONET site located at Kanpur. MODIS algorithm assumes that many of the AERONET sites in the tropics are in savanna or grassland regions, where the landscape is not as green, and hence the reds to SWIR ratios are also lower. Significant y-offset observed during different seasons also indicate that there is an inadequacy in surface reflectance assumption for the heterogeneous surfaces consisting of several land features (Water bodies, settlements, vegetated surface etc.). So Land surface features also need to be included in the pixel level (may be by using high resolution land imagery products), in order to reduce the offset and seasonal dependence of surface type needs to be taken into the retrieval model. Overall, the validation results show that the MODIS AOD retrievals do not represent, accurately, true observations in central India, and thus cannot be well applied there. This can be attributed to a complexity of surface conditions and aerosol types and seasonal changes of surface reflectance and aerosol models over different ecological and geographic regions. Hence we suggest a higher absorbing type of model and also include seasonally changing land use/land cover features in central India for an accurate retrieval.

Seasonal variation and Validation of columnar water vapour: Columnar water vapor (CWC) amount measured using a sun photometer over this region is typically in the 0.4–4 cm range. A seasonal variation of CWC values during the year 2011 is shown in Fig. 7(c). There exists a well-defined seasonal variation in CWC, with the maximum value during the monsoon months and minimum during winter months. Similar variations in CWC have been observed from other locations in India (e.g., Moorthy et al., 1999; Balakrishnaiah et al., 2011). The validation of gridded products (MODIS) is important as they are used for assimilation in numerical weather prediction and global climate models (Prasad et al., 2009). For this purpose, detailed validation of MODIS water vapor product is attempted.

It is seen from the Fig. 7 that the MODIS water vapor (WV) values were relatively higher than the water vapor values measured by the sun photometer. The scatter plot (see Fig. 7(a)) of sun photometer WV versus MODIS WV showed good agreement for daily observations. The linear regression line between WV derived from MODIS and sun photometer was found to be:

\[
\text{MODIS WV (NIR)} = 1.2 \times \text{(sun photometer WV)} - 0.3, \quad (R = 0.89)
\]

The absolute errors in retrieval of MODIS WV show a linear relationship with its WV and were found to be given as follows:

\[
\text{Absolute error} = 0.3 \times \text{(MODIS WV (NIR))} - 0.1, \quad (R = 0.89)
\]

Fig. 7(d) shows that the absolute error in estimation of WV by MODIS increases with an increase in water vapour content. In the case of SMS this may be the reason for high absolute error because of high rainfall.
Fig. 6. (a) A scatter plot between AOD derived from MODIS and Sun photometer: linear regression line and 1:1 line is shown. Variations in (b) monthly and (c) seasonal-averaged AOD$_{550}$ retrieved from MODIS and sun photometer; the error bars in panels (b) and (c) represent the standard deviation of AOD. (d) A scatter plot of the absolute error in MODIS AOD retrieval and MODIS AOD.

Table 1. Linear regression parameters for different seasons.

<table>
<thead>
<tr>
<th>Season</th>
<th>Linear regression line</th>
<th>R</th>
<th>No. of samples</th>
</tr>
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<tbody>
<tr>
<td>PMS</td>
<td>MODIS AOD = 0.76 (Sun photometer AOD) − 0.13</td>
<td>0.62</td>
<td>38</td>
</tr>
<tr>
<td>SMS</td>
<td>MODIS AOD = 1.45 (Sun photometer AOD) − 0.35</td>
<td>0.85</td>
<td>7</td>
</tr>
<tr>
<td>PoMS</td>
<td>MODIS AOD = 0.79 (Sun photometer AOD) − 0.06</td>
<td>0.77</td>
<td>20</td>
</tr>
<tr>
<td>Winter</td>
<td>MODIS AOD = 0.67 (Sun photometer AOD) − 0.03</td>
<td>0.88</td>
<td>37</td>
</tr>
</tbody>
</table>

Over this location, it is seen that the turbidity parameter is maximum during PMS and SMS seasons and minimum during PoMS and winter seasons. This may be the reason for observed errors. This is in accordance with the observation that under hazy conditions (with visibilities less than 10 km) or when the surface reflectance near 1 µm is small (less than about 0.1), errors can be 10% or slightly greater in our retrieved water vapor values using the atmospheric transmittance model (Gao and Kaufman, 2003). Their result was according to the validation performed using the microwave radiometer but in our case, we used a sun photometer for the validation. The discrepancy during the SMS may be due to the least number of data points.

CONCLUSIONS

This paper presents seasonal variability of Aerosol optical depth, Angstrom parameters, aerosol types and water vapour over Nagpur, central India. The role of forest and biomass burning fires and transport of air masses was also analyzed. Seasonal variability of AOD over India is analyzed using MODIS C005 Aerosol data products and validation of MODIS AOD and water vapour is performed.

The main conclusions of the study are summarized as follows:

1. Four different aerosol types have been classified from the relation between AOD$_{500}$ and $\alpha$, applying appropriate
threshold values. The percentage contribution of each type varies seasonally. UB aerosol type dominates all the seasons except summer monsoon season. The significant contribution of desert dust during Pre monsoon and summer monsoon is present.

2. MODIS active fire data suggest there is a large amount of biomass burning during the pre monsoon season, which may be the reason for the observed high contribution of UB aerosol type observed during this season. Air mass back trajectory analysis suggests that the sources were located in biomass burning, desert and marine regions. During the post monsoon season, the dominant air masses were originated from north India and in winter, the origins of air masses were located in eastern India and IGP region.

3. Seasonal variations in MODIS retrieved AOD\textsubscript{550} over India suggests high AOD over northwest during SMS, IGP region during PoMS and North east during winter. Southern part of India shows relatively less AOD compared to north India during all seasons.

4. Validation of MODIS TERRA retrieved AOD\textsubscript{550} with Sun photometer suggests underestimation by MODIS, which has been attributed to errors in aerosol model and surface reflectance assumptions. Instead of the neutral aerosol model assumed in the MODIS retrieval algorithm, we recommend more absorbing type of model in view of the sizeable contribution of biomass burning aerosols in the central Indian region and India at large.

5. There exists a well-defined seasonal variation in the columnar water vapor, with the maximum value during the monsoon months and minimum during the winter months. Validation of MODIS TERRA retrieved water vapor (NIR) with Sun photometer suggests overestimation by MODIS, which has been attributed to errors due to turbidity or haze in the atmosphere.

Aside from the above conclusions, it is confirmed that the MODIS aerosol and water vapor products cannot be used all over the globe with same accuracy. Users should validate the products before the use, for reliable conclusions. This caution is applicable for MODIS data derived air pollution studies etc also. This also points out at the need for new kind of technique such as polarizing airborne
instrument for spatial studies of the Aerosols in India.

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