

Aerosol Classification and Identification of Source Region over Bhopal from Satellite Remote Sensing

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ABSTRACT: 9 years long-term, remote sensing satellite data on aerosol optical properties from MODIS and OMI sensors are analysed to infer on the major aerosol types present over the study location, Bhopal situated in central part of peninsular India. Aerosol Optical Depths (AODs), Angstrom exponent (α) and Aerosol Index (AI) examined for the purpose of type identification. Aerosol parameters exhibited significant seasonal variations. Seasonal air mass back trajectories are computed to explain nature of source region and to infer on the transport component over the study region. By assigning proper thresholds (depending on the nature of the location and transport pathways) on AOD and α value, aerosols are discriminated into their major types viz., marine influenced, desert dust, urban/industrialized and mixed types. Further sub-categorization of the aerosols has been done on an annual scale taking into account of their absorptance information in terms of the OMI-AI values. Mixed type aerosols contributed the most during all the seasons. Over BPL, ~45.5% marine influenced aerosols found during winter and this amount is almost equal to amount of mixed type aerosols. During summer, this study region dominated by ~31.64% marine influenced aerosols next to mixed type. ~7.26% of Urban/industrial influenced aerosols found over this study location inferred local activity apart from air mass transport.

KEYWORDS: MODIS, Aerosol Optical Depth (AOD), Classification, Air mass back trajectories, Mixed aerosols.

I. INTRODUCTION

Aerosols play an important role in our climate system by means of their direct and indirect impacts yet, they are still one of the least understood components of the global climate system (Charlson et al., 1987; Ramanathan et al., 2001; Intergovernmental Panel on Climate Change, 2007). Classification of aerosols is a process which groups homogeneous aerosol constituents together based on a decision rule. Accurate assessment of the aerosol impact on radiative transfer is a complex task, since various aerosol types cause different effects on the solar radiation spectral distribution (Kaskaoutis and Kambezidis, 2008). The types of aerosols depend on their sources and can be categorized broadly as mineral dust, sea salt, volcanic, carbonaceous, and sulfate aerosols coming from various natural and anthropogenic sources (Giannakaki et al., 2010). There are numerous studies on the classification of aerosol types over the globe based on (i) influence of air-mass transport (Estelles et al., 2007; Kaskaoutis et al., 2010); (ii) Raman/elastic backscatter lidar observations (Giannakaki et al., 2010); (iii) ground based Aerosol Optical Depth (AOD) measurements and Angstrom exponent (α) (Kaskaoutis et al., 2007; Garcia et al., 2012); (iv) satellite derived aerosol optical properties (Kim et al., 2007). Scaling down to Indian subcontinent and surrounding oceanic regions, several studies have been performed to classify the aerosol types using ground based spectral AOD measurements (Kalapureddy et al., 2009; Sinha et al., 2012; Srivastava et al., 2012; sreekanth 2013). In the present study aerosol type classification has been attempted over metropolitan city Bhopal (BPL, 23.25° N, 77.41° E), India utilizing satellite database. This attempt has been first of its kinds in terms of the selected study location and in choosing the two

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supplementary methodologies to classify the major aerosol types. The major urban geographical location chosen for classification was shown in Fig.1

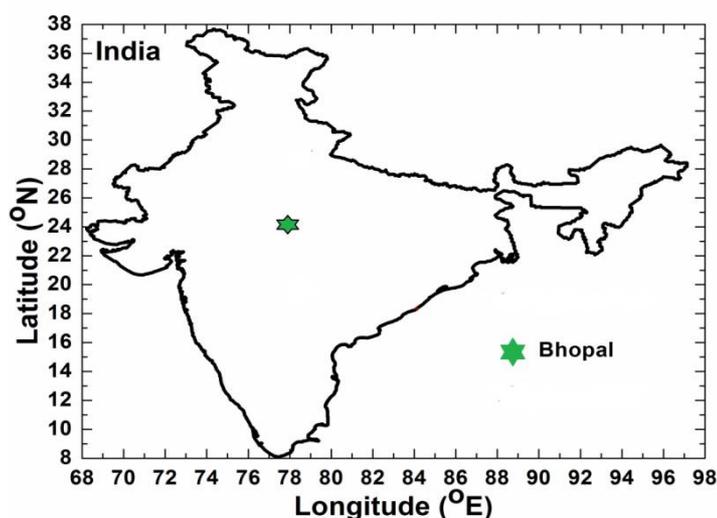


Fig.1. Map of India showing geographical locations of metro sites chosen for aerosol classification studies.

II. STUDY AREA

Bhopal (BPL) is the capital of the Indian state of Madhya Pradesh and the administrative headquarters of Bhopal district with area of 648.24 km². Bhopal is known as the City of Lakes. Bhopal is the 14th largest city in India with a population of 2,795,648. Bhopal houses various institutions and installations of national importance. Some of these include ISRO's Master Control Facility, AIIMS Bhopal (Established in 2012). The city attracted international attention in December 1984 after the Bhopal disaster, when a Union Carbide India Limited (UCIL) pesticide manufacturing plant leaked a mixture of deadly gases, leading to one of the worst industrial disasters in the world's history. It is suspected that the disaster was mainly due to leakage of methyl isocyanate (MIC). The Bhopal disaster continues to be a part of the socio-political debate and a logistical challenge for the people of Bhopal. The city has a national domestic airport, 4 railway stations, and 5 major bus stations. In addition; around 600 mini-buses are run by private operators. They constitute a major source of anthropogenic emissions. The city has more than 150 small medium and big industries. It has a mean altitude of 527 m above sea level and lies on the Deccan plateau of Indian Peninsula. It has a tropical wet and dry climate, with dry conditions prevailing for most of the year as it is located far from Bay of Bengal and Arabian Sea. The onset of monsoon is June and it extends up to September.

III. DATA SETS AND METHODOLOGY

Classification of aerosol types over study region becomes complex and a single instrument or sensor data cannot accurately discriminate aerosols. Simultaneous datasets from MODIS (Aqua) and OMI sensors have been utilized in the present study for the classification of aerosol key types over study locations. Long term data for 9 years (January 2005 to December 2013) has been analyzed for the same purpose. The length of the study period is constrained based on the availability of the OMI data. MODIS Aqua data has been chosen due to the near matching in the equator crossing time of both satellites. Level 3 1° × 1° daily gridded MODIS AODs (at 550 nm), Angstrom exponent ($\alpha_{470/660}$), and OMI UV Aerosol Index (AI) for the study period are acquired from the website <http://gdata1.sci.gsfc.nasa.gov>. AOD values give information on the columnar aerosol load, gives qualitative information on

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the aerosol size and AI values tell us about the columnar UV absorbing aerosol load. More details of MODIS and OMI sensors are available in (Remer et al. 2005) and (Levelt et al. 2006) respectively. OMI AI is a measure of how much the wavelength dependence of backscattered UV radiation from an atmosphere containing aerosols (Mie scattering, Rayleigh scattering, and absorption) differs from that of a pure molecular atmosphere (pure Rayleigh scattering).

$$AI = 100[\log_{10}(1360/1331)_{measured} - \log_{10}(1360/1331)_{calculated}]$$

AI is positive for absorbing aerosols (e.g., dust and smoke particles) and negative for non-absorbing aerosols (e.g., sulphates) (Herman et al., 1997). In the current study, daily mean AOD₅₅₀ and $\alpha_{470/660}$ values from MODIS Aqua are utilized in a first order classification of seasonal aerosol types. Then the OMI AI values have been introduced to subcategorize the aerosols into absorbing and non-absorbing classes. In the current classification based on AOD and α value, methodology suggested by Kaskaoutis et al. (2009) for the metropolitan Hyderabad has been adopted. The AOD and α threshold are re-iterated based on their absolute values and the geographical nature of the study region. The modified values are as follows (i) values of AODs < 0.3 with $\alpha < 0.9$ represent background conditions with marine influence type (M); (ii) AODs > 0.5 and $\alpha > 1.0$ represent urban/industrial aerosol type (I); (iii) AODs > 0.6 and $\alpha < 0.7$ are indicative desert/mineral dust (D). Remaining cases not belonging to any of the above groups, are characterized as mixed type or undetermined aerosols (U).

IV. METEOROLOGY OF STUDY AREA

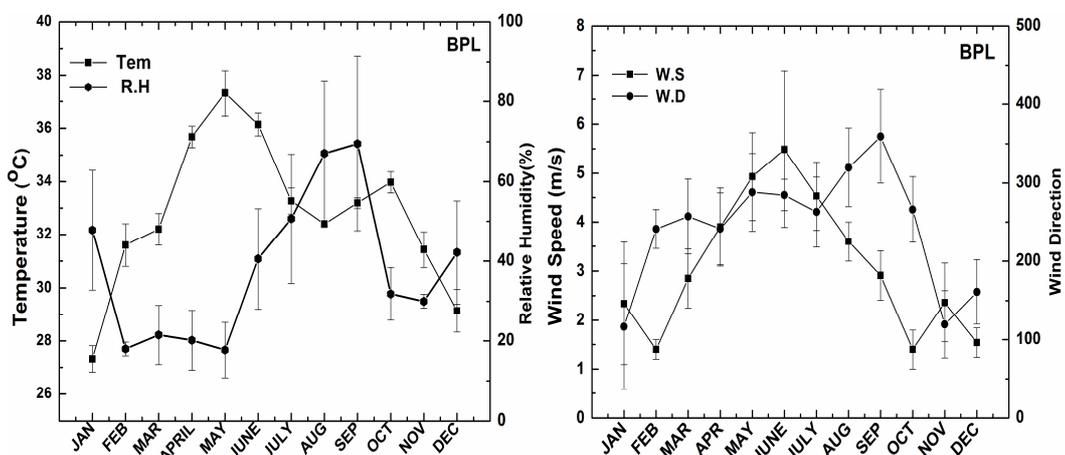


Fig.2 Temperature (°C), Relative humidity (%), Wind speed (m/s), Wind direction (deg, 360° scale) over study location.

The highest temperature and the lowest temperature found to be $\sim 37.31 \pm 0.86$ (May), $\sim 27.32 \pm 0.5$ (Jan), over Bhopal. RH value found maximum ($\sim 69.51 \pm 7.52$), during monsoon season and minimum value found to be ($\sim 18 \pm 1.73$), over study location. Over Bhopal, it was noticed that the wind during winter is South east direction. The prevailing winds are mostly from west and south west direction during summer and monsoon. Prevailing winds are mostly from South east direction during post monsoon season. Meteorological parameter trends over study region shown in Fig.2.

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V. AEROSOL OPTICAL PARAMETER TRENDS

Annual, Seasonal variations of AOD over study locations during 2005-2013 shown in Fig.3. Over study area, AOD values found to be less in during winter season. It was noticed that the AOD values showed increase in summer peaking monsoon and further decreased in post monsoon season. It was observed that ~0.43 (2013) is the highest annual mean AOD over BPL while ~0.33 (2005) is the lowest. During summer ~0.45 (2012) observed as the maximum and ~0.36 (2005) observed as minimum mean AOD. The mean monsoon AOD value observed to be maximum ~0.6 (2013) while minimum~0.42(2010). During study period the mean Post monsoon AOD found to be maximum in 2013 with its value ~0.42 and post monsoon mean AOD found lowest in 2005(~0.24).

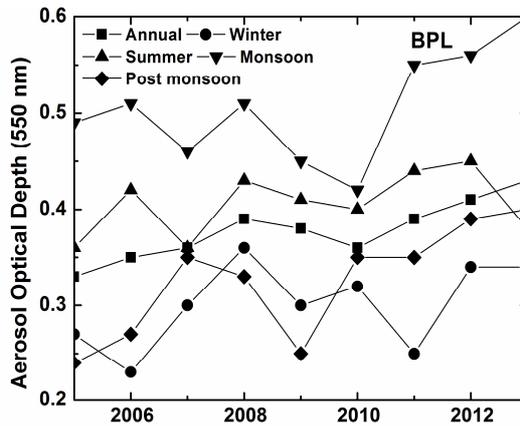


Fig.3 Annual, Seasonal variations of AOD over study locations during 2005-2013.

Over BPL, the mean AOD values found to be minimum ($\sim 0.31 \pm 0.24$). The mean AOD increases in summer ($\sim 0.41 \pm 0.19$) and reaches peak value in monsoon ($\sim 0.50 \pm 0.28$). It was observed that maximum “ α ” value ($\sim 1.01 \pm 0.47$) during monsoon and ($\sim 0.61 \pm 0.07$) during summer. Higher length of the box for AE in monsoon indicates that the aerosols during a particular season can be from different sources and mechanisms. The AI values found maximum ($\sim 1.21 \pm 0.46$) during summer and minimum ($\sim 0.81 \pm 0.26$) during winter season. Seasonal variation of MODIS AODs (550 nm), Angstrom Exponent ($\alpha_{470/660}$) and OMI Aerosol Index over study area shown in Fig.4.

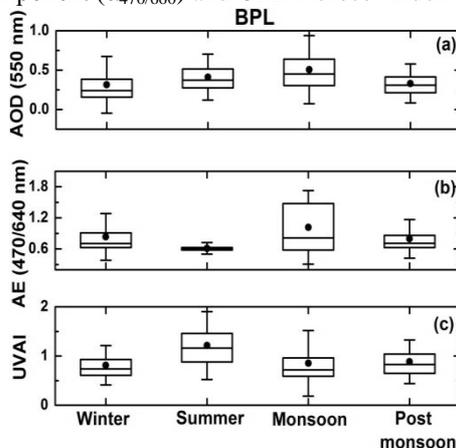


Fig.4 Seasonal variation of MODIS AODs (550 nm), Angstrom Exponent ($\alpha_{470/660}$) and OMI Aerosol Index.

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VI. IDENTIFICATION OF SOURCE REGION

The aerosol load and types at any location are generally influenced by the meteorological conditions (primarily wind and convection) and hence affect the air mass transport over the region for a particular period. Figure shows the 5-day isentropic back trajectories of NOAA-HYSPLIT (National Oceanic and Atmospheric Administration Hybrid Single-Particle Lagrangian Integrated Trajectory) version 4 [Draxler and Rolph, 2003] model, where different types of air masses that influence AOD over study locations are revealed in each season.

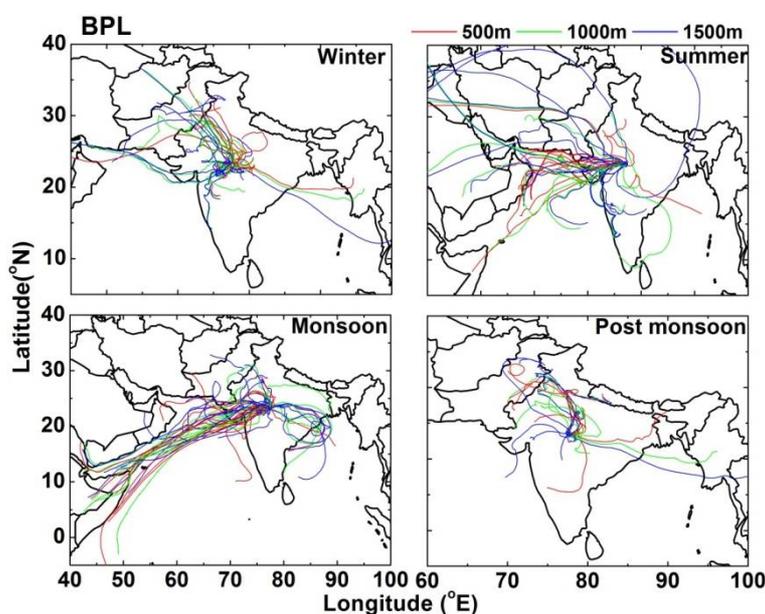


Fig.5 Five-day back trajectories ending at Bhopal, in each season at 500 m (red), 1000 m (green), and 1500m (blue). The trajectories were taken from the HYSPLIT model and refer to 1000 UTC.

At 500 m the air masses come from northern/northeastern directions originating from Bangladesh and traversing the eastern Indian coast, where densely populated areas and industries are situated. Some of the trajectories are originating from the east-Asian countries. These air masses can bring in continental aerosols via oceanic environment of Bay of Bengal. These aerosols can exhibit complex physical properties due to the interaction of the continental and marine air masses, which can finally result as mixed type aerosols. (Niranjan et al. (2005) have shown how the transported (via oceanic regions of Bay of Bengal) polluted air mass from north India enhanced the accumulation mode aerosols over southern latitudes. At 1500 m the air masses are of continental origin, northern India and IGP, where often intense fog and pollution-haze conditions occur (Badarinath et al., 2007a). Over Bhopal, at 500m the air masses come from the north and northeast traversed through east coast bringing marine and continental aerosols. During winter, at 1000m and 1500m most of the trajectories show air masses travelling from west, North Westerly which is originated at Thar Desert. These air masses can bring, soil dust, minerals dust and marine aerosols originated from Arabian ocean.

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VII. RESULTS AND DISCUSSION

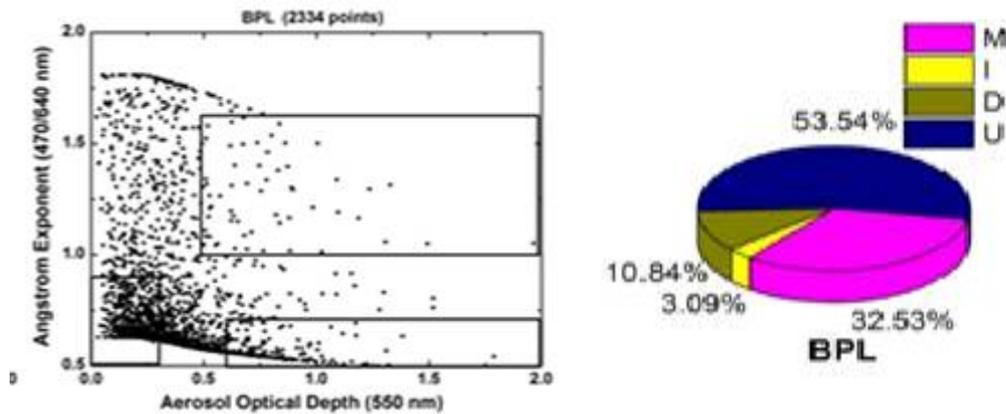


Fig.6 (a) Scatter plots between AODs and Angstrom exponent (α) Solid boxes represent various aerosol types (b) Percentage contribution of different aerosol types inferred from method-1

This study found ~1965 AOD values over Bhopal during whole study period. In this study method-1, segregates AODs into 4 groups based on fixing threshold conditions between AOD and α value. If the values of $AOD < 0.3$ and $\alpha < 0.9$, AODs represent marine influenced type, values $AOD > 0.5$ and $\alpha > 1$ represent urban industrial dust finally $AOD > 0.6$ and $\alpha < 0.7$ represent desert dust. The scatter plot between AOD and α value showed in 4.6. The total study period points classified over the study location using method-1 and percentage contribution of different aerosol types showed in Fig.6.

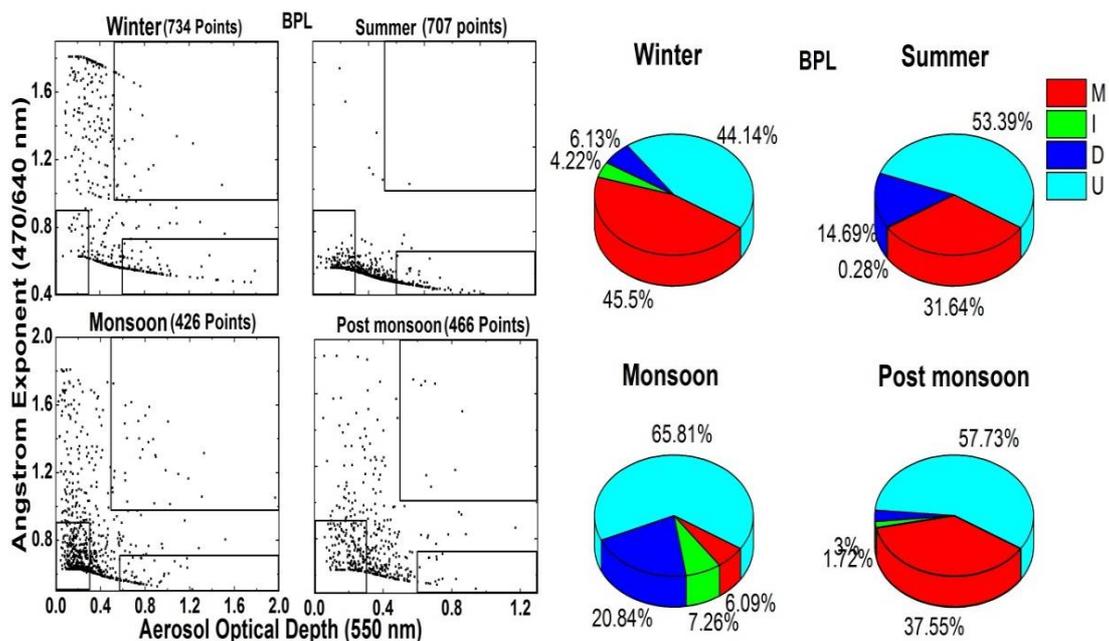


Fig.7. (a) Scatter plots between AODs and Angstrom exponent (α) in each season Solid boxes represent various aerosol types (b).Percentage contribution of different aerosol types in each season inferred from method.

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It was noticed that the desert dust found over Bhopal ~10.84% and marine influenced aerosols found ~32.53%. Un-classified aerosols using method-1 found maximum over Bhopal ~53.54%. Season-wise scatter plots between AODs (550 nm) and $\alpha_{470/660}$ are shown in various panels of Fig. 4.8. During monsoon and post-monsoon seasons the data points are comparatively less due to the frequent rainfall and cloudy conditions. Also, only two months fall under the category of post-monsoon. A large dispersion in the points has been observed during all the seasons. Solid vertical and horizontal lines in each of the panels in the Fig.7 Separate out different aerosol types. Threshold values for aerosol type classification using MODIS–OMI algorithm shown table 1. Over BPL, It was noticed that points associated with $AOD > 0.5$ and $\alpha > 1.0$ are very less~4.5% indicating less very small urban industrial aerosol type dominance during winter. Over BPL, higher AODs associated with low α values and lower AODs associated with lower α found indicating dominance of dust and marine type of aerosols during monsoon and post monsoon season. During all the seasons, mixed (or undetermined) type aerosols dominated. Mixed type aerosols are a result of mixing between different sized particles belonging to different sources. Mixed aerosols represent higher aerosol loading which was not associated with dust. During monsoon and post-monsoon seasons, the high relative humidity conditions can lead to coagulation and hygroscopic growth of water soluble urban aerosols leading the mixed type aerosol class. The percentage contribution of each of the type is given in Fig.8 as a pie diagram, for all the seasons. The relative seasonal contribution of each aerosol type highly depends on the synoptically changing source and sink strengths, transport component, its pathways, local meteorology and aerosol mixing processes in the column. The larger RH values close associated with the lower $\alpha_{470-660}$ in monsoon may be an evidence of coagulation and hygroscopic growth of the water-soluble urban aerosols, since the higher growth factor includes the hygroscopic and water-soluble particles (Day and Malm, 2001). The dominance of the desert dust (after mixed type) during monsoon and urban/industrial aerosol type during post-monsoon reported by (Kaskaoutis et al. 2009) for Hyderabad is very much line with present study. In a similar study over Dibrugarh, (Pathak et al. 2012) also reported significant contribution of transported desert dust and urban aerosol type during pre-monsoon. Based on multi-year ground based sun/sky radiometer measured aerosol products, Srivastava et al. (2012) have found high dust enriched aerosols (polluted dust) to contribute more during pre-monsoon over Kanpur in the central Indo-Gangetic plains. Using a similar methodology based on AOD and α values, Kalapureddy et al. (2009) found coastal Arabian Sea dominated by urban and industrial aerosol; mid Arabian Sea by desert dust aerosols; far Arabian Sea by clean marine aerosols.

α	AI	
	$AI \leq 0.7$	$AI > 0.7$
$\alpha < 0.8$	Sea salt, Sea salt + Sulphate (if $AOD > 0.2$)	
$\alpha < 0.7$		Dust Sea salt +Dust (if $AOD \leq 0.2$)
$\alpha > 1.0$	Sulphate	
$\alpha > 1.2$		Carbonaceous
$0.8 < \alpha < 1.0$	Sea salt + Sulphate	
$0.7 < \alpha < 1.2$		Dust + Carbonaceous Sea salt + Carbonaceous (if $AOD \leq 0.2$)

Table 1 Threshold values for aerosol type classification using MODIS–OMI algorithm.

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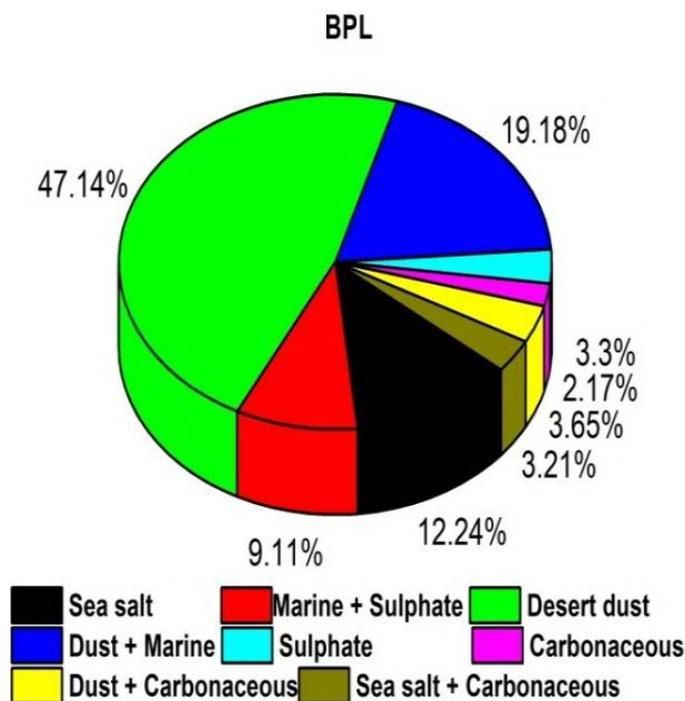


Fig.8. Percentage contribution of different aerosol types inferred from method 2.

On the annual scale, desert dust influenced type of aerosols dominated with ~47.14%, followed by dust + marine (19.18%), sea salt (12.24%), marine +sulphate (9.11%),dust + carbonaceous , sulphate, Sea-salt + carbonaceous influenced aerosols (~3.5%) and carbonaceous types recorded the lowest (2.46%) percentage occurrence over BPL. Aerosol classification has been done using two methodologies, (i) utilizing MODIS AOD and Angstrom exponent (α) values; (ii) utilizing MODIS AODs, Angstrom exponent (α) and OMI Aerosol Index over all study locations. Method-1 has been implemented on a total study period, seasonal basis, while method 2 has been performed on an annual basis. Method-1 classification has surfaced a major contribution from the mixed type aerosols over the study location along with other key aerosol type's viz., marine influenced, desert dust, and urban/industrial aerosols. In order to have an in-depth investigation on these mixed type aerosols, method 2 has been employed taking into account of the information of aerosol absorptance properties. Aerosol absorptance has been considered in terms of OMI Aerosol Index. Percentage contribution of different aerosol types inferred from method 2 shown in Fig.8. The thresholds in both methods have been re-iterated to keep in mind the geographical locations and nature of the study regions and to maintain consistency between the methods. In method 2, sea-salt + sulfate type aerosols dominated on the annual basis. The sea-salt contribution in method 2 might have encompassed the winter and summer-time dominance of the sea-salt type inferred from method 1. Dust contribution from method 2 seems to cover the summer and monsoon-time dominance of the dust type aerosol from method 1. Clearly method 2 is an over estimate compared to method 1, in case of dust. Carbonaceous type from method 2 can be compared with urban/industrial type of method 1. Clearly both methods underestimated these particular types of aerosols. Quantitatively, the percentage contribution of the mixed type aerosols from method 1 matches with the total contribution of the sea-salt + sulfate, sea-salt + dust, dust + carbonaceous and seasalt + carbonaceous. This indicates that the mixed type aerosol of method-1 can be thought to be comprised of any of the above indicated or a mixture. As the transport pathways and local meteorological conditions change seasonally, the

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mixture and its relative contribution of the aerosol types can be different during different seasons. Keeping in mind the transport pathways (Fig.4) over the study regions and the urban nature of the study locations, the probable mixture contributing to the mixed type aerosols might be (i) sea-salt + carbonaceous and sea-salt + sulphate during winter (ii) dust + carbonaceous, sea-salt + dust and sea-salt + sulfate during summer and (iii) sea-salt + sulfate and sea-salt + carbonaceous during monsoon and post-monsoon. More detailed study is required in order to arrive at a better understanding on the aerosol types and their mixing and transformation mechanisms. Satellite based studies have the limitation on the number of data points due to the availability of only single data point over a particular location per day. Methodology including the combination of two satellite sensors which requires simultaneous datasets will suffer relatively more from data limitation.

VIII CONCLUSIONS

- Seasonal variations in the aerosol optical depth, Angstrom exponent (α), Aerosol Index (AI) over Bhopal analysed during 2005-2013.
- The AI values found maximum ($\sim 1.21 \pm 0.46$) during summer and minimum ($\sim 0.81 \pm 0.26$) during winter season over BPL.
- The seasonal scatter plots between AODs and α have shown distinct patterns. Aerosol types encountered during the study period were classified into four categories using Method-1. Mixed type aerosols contributed the highest throughout all the seasons over all study locations.
- Over BPL, $\sim 45.5\%$ marine influenced aerosols found during winter and this amount is almost equal to amount of mixed type aerosols. During summer, this study region dominated by $\sim 31.64\%$ marine influenced aerosols next to mixed type. $\sim 7.26\%$ of Urban/industrial influenced aerosols found over this study location inferred local activity apart from air mass transport.
- On an annual scale, discriminating methodology using simultaneous AOD, α and AI values revealed that $\sim 19.18\%$ marine + dust influenced aerosols found over BPL.
- The presence of each aerosol type seemed to exhibit strong temporal variability, mainly affected by the season, the long-range transport and the mixing processes in the atmospheric column.

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