Inter and Intra-Annual Variability in Aerosol Characteristics over Northwestern Indo-Gangetic Plain

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ABSTRACT

This study reports the temporal characteristics of aerosols mass concentration (PM10, PM2.5, PM1), size distribution and optical depth from December 2011 to November 2013 over Patiala (30.33°N, 76.40°E, 249 a.s.l.), a site located in Indo-Gangetic Plain (IGP) in northwestern India, a region with the highest population density in the world. PM10, PM2.5, and PM1 varied from 71 to 221, 27 to 92, and 17 to 75 µg/m3, respectively, with the highest concentration of PM10 during summer of 2012, and PM2.5 and PM1 during autumn of 2013. These mass concentrations were significantly higher than National Ambient Air Quality (NAAQ) standards (PM10 = 60 and PM2.5 = 40 µg/m3), suggesting poor quality of air over IGP. Both natural and anthropogenic sources were found to be responsible for poor air quality of IGP with more contribution from the latter source as inferred from Ångström exponent ($\alpha_{580-870}$) and fine mode fraction (FMF: PM2.5/PM10) of aerosols, which have shown large temporal variability. The particle size distribution is skewed towards particles with size less than 1.00 µm and very few particles are having the size greater than 6.25 µm. Aerosol optical depth at 500 nm (AOD500) ranged from 0.36 to 0.64 and shows the highest value during summer of 2012 (0.64 ± 0.09) and autumn of 2013 (0.64 ± 0.25) and minimum (0.36 ± 0.05) in spring of 2013, further reflecting the different effects of aerosols on climate during different seasons. The relation between AOD500 and PM mass has also been investigated, which has exhibited significant seasonality and AOD500 is more sensitive towards the concentration of PM1 rather than PM2.5 and PM10. These results give insight to the relative contribution of natural as well as anthropogenic aerosol sources to their total atmospheric abundances and their possible effect on ambient air quality and Earth’s radiation balance.

Keywords: Particulate matter (PM); Fine mode fraction (FMF); Aerosol optical depth (AOD); Ångström exponent.

INTRODUCTION

Aerosols are important constituent of the atmosphere due to their impact on air quality, human health, precipitation pattern and radiation budget (Poschal, 2005). Aerosols are emitted naturally (e.g., dust, sea-salt, biogenic emissions) as well as anthropogenically (industrial emissions, vehicular emissions, biomass and fossil fuel burning). These are also produced and modified by chemical reactions in the atmosphere and constantly cycled among the Earth's oceans, atmosphere and biosphere. In climate studies, the atmospheric aerosols have drawn greater significance recently because of their potential to perturb the radiation balance of Earth at regional and global scales (Charlson et al., 1992). These effects are direct and indirect. The direct aerosol effect consists of direct interaction of radiation with atmospheric aerosols, such as absorption or scattering, and the indirect effect results from the modification of microphysical properties of clouds by aerosols i.e., act as cloud condensation nuclei (CCN) which in turn can affect the cloud albedo, cloud life time and precipitation rate. In addition to optical and radiative interactions, which affect the geosphere and biosphere, atmospheric aerosols are also having a direct bearing on Earth’s environment and human health. The increases in ambient particulates mass concentration are associated with adverse health effects, ranging from least adverse (increase in symptoms of respiratory irritation) to the most adverse, mortality (Chen et al., 2005; Dominici et al., 2005). Past studies have shown that lung function related problem in children increases due to rise in PM10 (particulate matter with aerodynamic diameter < 10 µm) mass concentration (Pope and Dockery, 1992). PM2.5 causes about 3%, 5% and 1% of mortality in children below 5 yr, worldwide from cardiopulmonary disease, from cancer of the trachea, bronchus and lung and from acute respiratory infections respectively, which amounts to about 0.8 million premature deaths and 6.4 million years of life lost (Cohen et al., 2005). Although significance of PM relevant to

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environmental & health studies is well known, it is poorly studied over developing countries, where PM is expected to affect larger population. PM_{10} and PM_{2.5} are of concern for environmental problems, responsible for health hazard, and PM_{1} contributes to visibility degradation and radiative impact (Berico et al., 1997; Jin et al., 2006; Seinfeld and Pandis, 2006). Also, the PM_{1} particles have been documented to be responsible for causing the respiratory problems (Salma et al., 2002).

Further, aerosol optical depth (AOD) is a key parameter that represents the extinction of incoming solar radiation due to atmospheric aerosols; hence its long term quantification is of utmost importance for climate studies. Modifications to weather and climate would result in modification of natural aerosols cycles. The change in the spectral AOD trend over any region reflects the variation of anthropogenic activities and therefore, information associated with AOD is necessary for policy makers towards mitigation strategies. There are many studies on the long term trends in AOD over the globe based on satellite data but most of these studies focused only on the oceanic region and there is a lack in the ground based measurements (Massie et al., 2004; Mishchenko et al., 2007; Zhang and Reid, 2010; Hsu et al., 2012). Over the South and Southeast Asian regions, Wild et al. (2005) has reported the global dimming due to aerosols.

In the present paper, we have studied the temporal characteristics of aerosols mass concentration (a measure of ground level air quality) and optical depth (measure the extinction of incoming solar radiation by aerosols in vertical column) over Patiala, a sub-tropical site located in IGP (northwestern India), a region with highest population density in the world, during the years 2012 and 2013. The study region faces diverse meteorological conditions and emission sources which make aerosols over the region highly complex in nature.

**SITE DESCRIPTION AND METEOROLOGY**

The sampling site is at the rooftop of the Physics department, Punjabi University, Patiala (30.33°N, 76.40°E, 249 a.s.l.), located in northwestern India (Fig. 1). The sampling site is part of fertile IGP, close to Shivalik Hills in the east and Thar Desert in the southwest. The industrial cities like Ludhiana, Mandi Gobindgarh located in the northwest direction of the sampling site affect the aerosol characteristics over the study region. For further detail related to the site description, reference is made to our earlier publications (Rajput et al., 2011; Sharma et al., 2012; Singh et al., 2014). This site represents a region where both anthropogenic and natural aerosols show distinct seasonal characteristics and mixing.

We have classified the data into five seasons named as winter (December–February), spring (March–April), summer (May–June), rainy (July–September) and autumn (October–November), depending upon the dominance of different emission sources and meteorological conditions. The climate of the study region is semi-arid with total annual rainfall of ~750 mm occurring mostly in the rainy season. Due to anthropogenic activities and low temperature during winter season, the study region suffers from severe fog, haze and smog. In autumn, the large scale post harvest paddy residue burning in and around the city is a major source of pollutants (Mittal et al., 2009). During spring and summer, the region experiences occasional dust storms (Sikka, 1997; Sharma et al., 2012). In May during summer, wheat residue burning also contributes significantly to ambient PM (Rajput et al., 2011).

The variation of various meteorological parameters such as temperature (Temp), relative humidity (RH), and rain fall (RF) has been measured by automatic weather station of the Indian Meteorological Department (IMD) observatory,
located in the university campus. During autumn, the winds are north-westerly, changing to westerly during winter and south-westerly during seasons of spring and summer. The south-easterly and easterly winds are dominant during rainy season. The seasonal average values of these meteorological parameters are shown in Table 1.

**RESULTS AND DISCUSSION**

**Variability in Particulate Mass and Particle Size Distribution**

In broader sense, PM$_1$ can be considered as secondary aerosols if the contribution of black carbon (BC) and primary organic carbon (POC) is excluded; PM$_{2.5}$ can be both primary and aged secondary whereas PM$_{1.5-10}$ are mainly primary particles from natural sources.

Seasonal variations in PM$_{10}$, PM$_{2.5}$ and PM$_1$ concentrations during 2012 and 2013 are shown in Fig. 2. In 2012, mass concentration of PM$_{10}$ was highest in summer followed by autumn, spring, winter and minimum in rainy season whereas during 2013, it was found to be highest in autumn followed by summer, winter, rainy and minimum in spring.

### Table 1. The seasonal average temperature (Avg ± SD), relative humidity (Avg ± SD), and rain fall (total) during five major seasons of year 2012 and 2013.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>2012 Temp (°C) (Avg ± SD)</th>
<th>2012 RH (%) (Avg ± SD)</th>
<th>2012 RF (mm) (Total)</th>
<th>2013 Temp (°C) (Avg ± SD)</th>
<th>2013 RH (%) (Avg ± SD)</th>
<th>2013 RF (mm) (Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>18 ± 3</td>
<td>61 ± 15</td>
<td>18</td>
<td>17 ± 4</td>
<td>71 ± 15</td>
<td>140</td>
</tr>
<tr>
<td>Spring</td>
<td>29 ± 3</td>
<td>42 ± 10</td>
<td>25</td>
<td>30 ± 3</td>
<td>49 ± 11</td>
<td>25</td>
</tr>
<tr>
<td>Summer</td>
<td>39 ± 3</td>
<td>34 ± 09</td>
<td>31</td>
<td>38 ± 3</td>
<td>54 ± 13</td>
<td>148</td>
</tr>
<tr>
<td>Rainy</td>
<td>32 ± 3</td>
<td>72 ± 12</td>
<td>406</td>
<td>34 ± 2</td>
<td>76 ± 09</td>
<td>597</td>
</tr>
<tr>
<td>Autumn</td>
<td>27 ± 3</td>
<td>56 ± 10</td>
<td>4</td>
<td>27 ± 3</td>
<td>54 ± 13</td>
<td>11</td>
</tr>
</tbody>
</table>
season. On annual scale, the mass concentrations of PM$_{10}$ in spring and summer of 2012 were higher than that during 2013. The significant difference in the magnitude of mass concentration during season of spring is mainly due to occurrence of unusual severe dust storm in the third week of March, 2012 (Srivastava et al., 2014). It is referred as unusual because the major dust storms are generally observed during the months of April–June over the northwest Indian region. The same sources are dominant during season of summer but this noticeable difference in seasonal average may be due to wash out of aerosols by frequent rain during year of 2013 (145 mm) as compared to year of 2012 (27 mm) in June. The mass concentrations of PM$_{2.5}$ and PM$_{1}$ were recorded highest in autumn season of both years, suggesting the dominance of submicron aerosols in the atmosphere during that time. In year 2012, the mass concentrations of PM$_{2.5}$ and PM$_{1}$ were found to be lowest during rainy and summer season, respectively, whereas in the year of 2013, the mass concentration of PM$_{2.5}$ and PM$_{1}$ exhibited minimum concentration in spring season. The lower values of fine fraction of particulates during seasons of summer and spring are attributed to larger abundances of primary aerosols (dust) over the study region. The aerosol loading in autumn is mainly due to large scale paddy residue burning in the open fields by the farmers. During winter, high aerosol loading is due to prevalence of agricultural waste burning, fossil fuel combustion and wood-fuel burning for domestic heating (Badarinath et al., 2006; Rajput et al., 2011; Rastogi et al., 2014; Singh et al., 2014). Over the study region, Rastogi et al. (2014) reported that the PM$_{2.5}$ composition was dominated by organic matter followed by the salts of ammonium and potassium with sulfate and nitrate, and the ratio of organic (OC) to elemental carbon (EC) was high during the season of autumn and winter, suggesting the dominance of biomass burning emissions. Occasional dust storms during spring and summer season are responsible for high aerosol loading (Sikka, 1997; Sharma et al., 2012). During the pre-monsoon period (April–June) of year 2010, Sharma et al., (2012) observed high value of AOD (> 1), aerosol index (2.1–6.7) and atmospheric aerosol radiative forcing (~40–80 W/m²) due to occurrence of six dust storms over the Patiala region. Thus, over the study location both anthropogenic (emissions from biomass burning) and natural (dust particles) aerosols show distinct seasonal characteristics.

The dominance of natural vis-à-vis anthropogenic sources can be identified through temporal variability in fine mode fraction (FMF; PM$_{2.5}$/PM$_{10}$; PM$_{1}$/PM$_{10}$) of aerosols (Fig. 3). The FMF varied from 0.23 to 0.64 (PM$_{2.5}$/PM$_{10}$) and 0.08 to 0.53 (PM$_{1}$/PM$_{10}$) with highest values (50 to 70% of PM$_{10}$) during winter and autumn, and lowest values during spring and summer (5 to 25% of PM$_{10}$) for both years. Higher FMF values are attributed to the anthropogenic emissions from biomass burning and fossil fuel combustion during seasons of winter and autumn. Fine primary aerosols and precursors of secondary aerosols are emitted from biomass burning and fossil fuel combustion, and Rastogi et al. (2014) has documented that there is significant amount of secondary aerosols formation during these seasons over the study region. On the other hand, lowest FMF during spring and summer is ascribed to large abundances of primary aerosols (mainly dust) in the atmosphere. During these seasons, weather is mainly dry and southwesterly winds bring the mineral dust from Thar Desert and southwest Asia to the study region which contributes to the major fraction of total aerosol loading (Sharma et al., 2012).
During the observation period, the annual average concentration of PM10 and PM2.5 was well above the National Ambient Air Quality (NAAQ) standards, set up by Central Pollution Control Board (CPCB), India. The NAAQ standards at annual average scale are 60 µg/m³ and 40 µg/m³ for PM10 and PM2.5, respectively. PM10 concentration was 2.5 and 2.0 times higher than the NAAQ standards in year 2012 and 2013, respectively. On the other hand, PM2.5 was 1.5 times higher than the NAAQ standards during both years. The observations implicate that emission from natural sources (mineral dust) during spring and summer and anthropogenic sources (biomass and fossil fuel burning) during autumn and winter play significant role in degradation of air quality over study region. The dominance of secondary aerosols during winter and autumn could also be responsible for the formation of fog and haze which further cause visibility degradation over the study region.

The diurnal variation of PM1 in time interval of 09:00–17:00 hrs (IST) during five major seasons (winter, spring, summer, rainy and autumn) of years 2012 and 2013 is shown in Fig. 4. The detailed examination of diurnal pattern is useful to develop the local and regional strategies to minimize air pollution for health and climatic reasons. In diurnal cycles, the two local maxima (during morning and evening hours) and one local minima (during afternoon) occur during autumn and winter but not much prominent during spring and summer. Particulates show high value in the morning time between 09:00–11:00hrs; thereafter slowly decrease to reach minimum value in the afternoon around 14:00 hrs. There is again increment in mass concentrations during evening hours. These diurnal cycles were mainly due to variation in local anthropogenic activity and meteorological parameters. The morning hour’s peak value can be attributed to intense emissions from vehicles during rush hours. The stable atmospheric conditions during morning time also favor the high concentrations of aerosols near the surface. However during afternoon, the boundary layer height maximizes due to strong surface heating and as a result, there is an increase in vertical diffusion of aerosols and a
decrease in aerosol concentrations near the surface. The evening peak can also be attributed to the increased traffic activity and shallow boundary layer. During season of spring and summer, the morning and evening maxima are not easily distinguished because the weather is mainly dry, hot and the primary aerosols (dust aerosols) are significant fraction of the total aerosol loading. On the other hand, during autumn, the evening peak is too much prominent in comparison to other seasons. It was mainly altered by the large scale post harvest paddy residue burning in the open fields by the farmers mostly in the afternoon hours which emit the large amount of precursor’s gases for the formation of secondary aerosol.

The seasonal average particle size distribution at 15 different channels (0.35–22.50 µm) during year 2012 and 2013 is summarized in Fig. 5. The particle size distribution is dominated by particles of size less than 1.00 µm and becomes very low at size greater than 6.25 µm throughout the observation period. The ratio of particle size distribution at fine to coarser size mode decreases during spring and summer as compared to winter and autumn. It is due to occurrence of occasional dust storms resulting in enhancement of coarse mode particles over the study region. It is further observed that the particle counts as well as mass of coarser particles is higher in spring of year 2012 as compared to year 2013 which is due to the occurrence of unusual severe dust storm in March 2012.

**Temporal and Seasonal Variation of AOD**

During the study period, the day to day AOD values range between 0.30–0.80 most of the time but occasionally go beyond or close to one as shown in Fig. 6 (AOD data during rainy season of 2013 was not available). The values of AOD are found to be higher during those months when the mass concentrations of PM were on higher side, suggesting the enhancement in concentration of particulates play key role in Earth’s radiation budget by changing the magnitude of AOD values. The relation between AOD and PM mass exhibit significant seasonality (discussed later).

Seasonal variability of AOD at 500nm (AOD\(_{500}\)) during both years is shown in Fig. 7. During study period, seasonal AOD\(_{500}\) shows highest value of 0.64 ± 0.09 and 0.64 ± 0.25 during summer of 2012 and autumn of 2013, respectively, whereas it exhibited minimum value (0.36 ± 0.05) in spring season of 2013. During rainy season of year 2013, no data has been recorded for AOD due to non availability of clear days. These observations are justified with the conjunction of mass concentration of particulates. The seasonal variation of AOD during study period at five representative wavelengths (380, 440, 500, 675 and 870 nm) is shown in Fig. 8. Higher or lower values of AOD at a given wavelength indicate higher or lower abundance of particles having diameter similar to the wavelength of interest. The AOD at longer wavelengths was higher in spring and summer season (March–June) in comparison to other seasons, suggesting coarse particles (mineral dust) driven by westerly and south-westerly winds dominate aerosol abundance, a conclusion similar to that derived using FMF and particle size distribution. AOD at shorter wavelengths is high in comparison to other wavelengths during all the seasons but are more significant during autumn, suggesting fine particles are always abundant with greater particle counts of fine mode particles and FMF during autumn. During autumn north-west region of India comprising Punjab, Haryana and Uttar Pradesh is dominated by paddy residue burning in the open fields by farmers injecting large amount of trace gases as well as sub-micron particles into atmosphere (Badarinath et al., 2006; Schuster et al., 2006). AOD pattern is found to be similar in winter as in the autumn but with lower value of AOD. On annual scale, the magnitude of AOD is almost similar in all respective seasons of both years except significant difference at all wavelengths during spring season of 2012 and 2013. This is also seen in the case of particulates loading. This observation is attributed to

![Fig. 5. Seasonal average particle size distribution at 15 different channels (0.35–22.50 µm) during year 2012 and 2013.](image-url)
Fig. 6. Temporal variation of AOD at 500 nm during five major seasons (winter ‘w’, spring ‘Sp’, summer ‘Su’, rainy ‘R’, and autumn ‘A’) of year 2012 and 2013.

Fig. 7. Seasonal mean AOD at 500 nm during five major seasons of year 2012 and 2013.

occurrence of unusual dust event storm in 2012 as discussed earlier. In the case of summer season, difference has been found at longer wavelength which is also reflected in the coarse mode mass fraction and particle counts of coarser particles during both years of study. Here the frequent rain is responsible for effective wash out of coarse mode particles.

Ångström exponent ($\alpha$) is useful to compare and characterize the wavelength dependence of AOD and columnar aerosol size distribution (Eck et al., 1999). The relative increase in number of large sized particles with respect to the smaller ones results in decreasing the value of $\alpha$ and vice versa (Ganguly et al., 2006). The seasonal variation in Ångström coefficients (380–870 nm) is shown in Table 2. The high values of $\alpha$ were observed during winter and autumn of year 2012 (0.96 ± 0.20 and 1.01 ± 0.21) and 2013 (1.05 ± 0.15 and 0.97 ± 0.18). It was attributed to emission of fine mode particles due to paddy residue burning in the fields during autumn, and due to prevalence of agricultural waste burning, fossil fuel combustion and wood-fuel burning for domestic heating during winter. On the other hand, loading of coarse mode particles due to dust storm events during spring and summer seasons are responsible for low value of $\alpha$ during year 2012 (0.58 ± 0.15 and 0.25 ± 0.11) and 2013 (0.49 ± 0.22 and 0.48 ± 0.32). During rainy season, most of the time sky covered with clouds thus, due to lack of sufficient observation for AOD, we have not drawn any conclusion regarding size distribution of aerosols. The inference drawn with the values of Ångström exponent ($\alpha$) is supported by the conclusion drawn from FMF analysis and size distribution of aerosols over the study region. The high value of turbidity factor ($\beta$) implies the abundances of coarse mode particles in the atmosphere. Thus the Ångström
Fig. 8. Seasonal variation in spectral AOD during five major seasons of year 2012 and 2013.

Table 2. Seasonal mean values of Ångström coefficients ($\alpha_{380-870}$, $\beta_{380-870}$) during five major seasons of year 2012 and 2013.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alpha (Avg ± SD)</td>
<td>Beta (Avg ± SD)</td>
</tr>
<tr>
<td>Winter</td>
<td>0.96 ± 0.20</td>
<td>0.26 ± 0.08</td>
</tr>
<tr>
<td>Spring</td>
<td>0.58 ± 0.15</td>
<td>0.34 ± 0.11</td>
</tr>
<tr>
<td>Summer</td>
<td>0.25 ± 0.11</td>
<td>0.61 ± 0.14</td>
</tr>
<tr>
<td>Rainy</td>
<td>0.87 ± 0.19</td>
<td>0.32 ± 0.12</td>
</tr>
<tr>
<td>Autumn</td>
<td>1.01 ± 0.21</td>
<td>0.31 ± 0.07</td>
</tr>
</tbody>
</table>

Turbidity factor ($\beta$) represents the particle load in atmosphere and it is well established fact that load is determined by coarse particles (Moorthy et al., 1999). In the present study, high magnitude of turbidity factor has been observed during summer season of both years, indicating that loading of coarse mode aerosols in summer as compared to the other seasons of the study period over the site.

Relationship between PM Mass and AOD

AOD is the integration of extinction coefficient in the column from ground to top of the atmosphere and the PM measurement is ground based, it is important to determine the conversion factor to establish a relation between AOD and PM mass. Regionally, some studies found the linear relation between AOD and PM. Chu et al. (2003) has documented a good correlation ($R = 0.82$) between daily average mass of $PM_{10}$ and $AOD_{500}$ over an AERONET site (Holben et al., 1998) in northern Italy. Slater et al. (2004) did an inter comparison between $PM_{2.5}$ and $AOD_{500}$ over a rural site in USA and found a good correlation ($R^2 = 0.66$). In the context of India, Singh et al. (2004) found a poor correlation ($R = 0.24$) between AERONET AOD and $PM_{10}$ mass over the Kanpur. In the present study, a linear relation (based on correlation analysis) between columnar $AOD_{500}$ and in-situ measurements of PM mass fractions ($PM_{10}$, $PM_{2.5}$ and $PM_1$) has been explored (Figs. 9(a), 9(b), and 9(c)), and corresponding statistical parameters are presented in Table 3. At times, the higher value of AOD has been observed corresponding to the low concentration of PM; it may be due to biasing of AOD observation with clouds or some aerosol plumes in vertical column. On the basis of correlation analysis on these data sets; we have established an empirical relation between AOD and PM in different seasons (Table 3). Over the study region, the good correlation between AOD and PM has been found during all the seasons and it has been attributed to the accumulation of aerosol under the stable atmospheric conditions. However during the summer, the decrease in correlation has been observed for all PM mass fractions possibly due to the long range transport of aerosols at higher altitudes. We have found that the $AOD_{500}$ is more sensitive towards the concentration of $PM_1$ rather than $PM_{2.5}$ and $PM_{10}$, as discernible from the slopes of linear relationship between PM and AOD (Table 3). These empirical relations will be very useful to improve the algorithms of aerosol monitoring satellites over the land as there is large uncertainty in the retrieval of satellite data.
over the land. It also has implication in constructing the map of spatial and temporal distribution of aerosol characteristics over the regions where simultaneous measurement of AOD and PM are sparse.

![Graphs showing AOD dependence on PM for different seasons.](image)

**Fig. 9.** Dependence of AOD<sub>500</sub> on (a) PM<sub>10</sub> (b) PM<sub>2.5</sub> (c) PM<sub>1</sub>.

**Table 3.** Empirical relations between AOD and PM.

<table>
<thead>
<tr>
<th>Particulate Matter</th>
<th>Seasons</th>
<th>Empirical Relations</th>
<th>R-coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td>Winter</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.170 + 0.0026 × PM</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.248 + 0.0014 × PM</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.500 + 0.0009 × PM</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Rainy</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.202 + 0.0018 × PM</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.293 + 0.0024 × PM</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.252 + 0.0027 × PM</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.181 + 0.0062 × PM</td>
<td>0.91</td>
</tr>
<tr>
<td>PM&lt;sub&gt;2.5&lt;/sub&gt;</td>
<td>Summer</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.466 + 0.0050 × PM</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Rainy</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.152 + 0.0074 × PM</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.359 + 0.0037 × PM</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Winter</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.268 + 0.0031 × PM</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.165 + 0.0131 × PM</td>
<td>0.84</td>
</tr>
<tr>
<td>PM&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Summer</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.368 + 0.0182 × PM</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Rainy</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.073 + 0.0188 × PM</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Autumn</td>
<td>AOD&lt;sub&gt;500&lt;/sub&gt; = 0.378 + 0.0044 × PM</td>
<td>0.72</td>
</tr>
</tbody>
</table>
SUMMARY

Aerosol optical depths, particle size distribution and the atmospheric concentration of PM$_{10}$, PM$_{2.5}$ and PM$_1$ have been studied during five major seasons of year 2012–2013 from a sampling site Patiala, located in the north-west region of IGP. These results show how the natural and anthropogenic sources changed throughout the year at sampling site. From the analysis of coarse and fine mode fraction of particulates, an attempt has been made to study the abundances of primary and secondary aerosols over the site. The important facts drawn from our study are:

1. The annual average of PM$_{10}$ and PM$_{2.5}$ concentration is found to be significantly high in comparison to National Ambient Air Quality (NAAQ) standards during both years.
2. A noticeable daily variability in particulate mass concentrations was observed especially during season of autumn and winter due to atmospheric boundary layer dynamics and variation in local anthropogenic activities. Particulate Matter shows significant daily as well as seasonal variation. There is significant increase in mass concentration of PM$_{2.5}$ and PM$_1$ during season of autumn and winter due to biomass and fossil fuel combustion. Occasional dust events are responsible for significant increase in PM$_{10}$ during seasons of spring and summer.
3. AOD at 500 nm shows significant daily as well as seasonal variation, suggesting radiative effects of aerosols will be accordingly different.
4. Emissions from biomass burning and dust storms have significant effects on spectral AOD.
5. Secondary aerosols (fine mode particles) dominated during winter and autumn whereas the primary aerosols (coarse mode particles) are dominant in the summer which is supported by Ångström exponent, particle size distribution and FMF analysis.
6. AOD$_{500}$ is more sensitive towards the concentration of PM$_1$ rather than PM$_{2.5}$ and PM$_{10}$ as discernible from the slopes of linear relationship between PM and AOD.

ACKNOWLEDGEMENT

The present work carried out under the ISRO-GBP program and the authors are grateful to ISRO for financial support. The meteorological data for Patiala station provided by IMD is duly acknowledged. We thank both the anonymous reviewers for their constructive comments and suggestions.

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Charlson, R.J., Schwartz, S.E., Hales, J.M., Cess, R.D., Jr.


Received for review, April 16, 2014
Revised, August 4, 2014
Accepted, August 6, 2014