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Assessments of PM_1, $PM_{2.5}$ and PM_{10} concentrations in Delhi at different mean cycles

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Daily, monthly, seasonal and annual moving means of PM_1, $PM_{2.5}$ and PM_{10} concentrations from August, 2007 to October, 2008 at Delhi (28º 35' N; 77º 12' E), the seventh populous megacity in the world are presented. PM_1, $PM_{2.5}$ and PM_{10} concentrations varied seasonally with atmospheric processes and the anthropogenic activities. PM_{10} decreases during monsoon by ~25–80 μg m^{-3} and PM_1 and $PM_{2.5}$ by ~10–15 μg m^{-3} from their pre-monsoon levels. Emissions from fireworks during Deepawali in the post-monsoon season increases PM_1, $PM_{2.5}$ and PM_{10} levels by 300, 350 and 400 μg m^{-3}, respectively over their monsoon levels. Seasonal variation of mixing heights, temperatures, winds and rainfall, accounts for the inter-annual variability of PM_1, $PM_{2.5}$, and PM_{10}. Accordingly, wintertime PM_1, $PM_{2.5}$ and PM_{10} components contribute by ~30–33% to annual levels. PM_{10} in summer is higher by 8% to that of $PM_{2.5}$ and by 9% to that of PM_1. PM_{10} components in post-monsoon are lower by 5% to that of $PM_{2.5}$ and by 7% to that of PM_1. Also, PM_1, $PM_{2.5}$ and PM_{10} levels were higher during October, 2008 than those in 2007, but their levels were almost remain the same in August and September of 2007 and 2008. Moving means of PM_1, $PM_{2.5}$ and PM_{10} and their concentrations in different seasons are useful in policy making decisions thereupon aiming to improve the air quality in Delhi.

Keywords: running mean cycles, air-quality, residence time, particulate matter, wet removal

1. Introduction

Particles with aerodynamic diameters < 10 μm (PM_{10}) are of concern for environmental problems (Seinfeld and Pandis, 2006). Aerosols with aerodynamic diameters < 2.5 μm ($PM_{2.5}$) are responsible for health hazards and with aerodynamic diameters < 1.0 μm (PM_1) contributes to visibility degradation (Jin et al., 2006) and radiative effects (Berico et al., 1997). Also, the PM_1 particles can penetrate deeper into the respiratory system (Hind, 1999; Salma et al., 2002). As $PM_{2.5}$ and PM_1 particles have relatively large surface to volume ratio and longer residence times in the atmosphere, they posses persistently high proportion of organic compounds than larger particles (Jaenicke, 1984). PM_1 and $PM_{2.5}$ levels much beyond permissible limit of world health organization (WHO) have significant impact on mortality and morbidity caused by respiratory and cardiovascular diseases (Chen et al., 2005; Dominici, et al., 2005; Schwartz et al., 2001). Thus PM_1, $PM_{2.5}$, and PM_{10} levels are considered in difining air-quality standards (WHO, 2000, 2006).

Furthermore, particulate matter (PM) has wider impact on climate, causing direct (absorbing, reflecting and scattering), indirect (clouds formation, clouds albedo and life time) and semi-direct (heating and cooling) effects on the Global radiative budget (IPCC, 2007). Impacts are also known on ecosystems (Bytnerowicz et al., 2007, Chate and Devara, 2009). All these environmental, climatic and health aspects of aerosol pollutants have motivated researchers to focus on aerosol research in recent years (Pope et al., 2004; Brunekreef and Forsberg, 2005; Dockery and Stone, 2007; Pérez et al. 2008; Murugvel and Chate, 2009; Chate, 2011; Srivastava et al., 2011, 2012a).

In developing countries, industrial growth, increased transportation, fossil fuel burning, fast urbanization, population growth and migrations are inevitable, which consequently resulted in adverse air-quality. India is the world's seventh largest country and second to China in its population. Rapid growth in megacities (e.g. Delhi, Mumbai etc.) is a cause of concern for air-quality. Delhi is the forth most polluted and the seventh most populous metropolis in the world. The transport sector of Delhi shares ~72% to total airborne pollutants (Goyal and Sindhanta, 2003, Kathuria, 2005). Air quality in Delhi has exceeded prescribed standards of World Health Organization (Gurjar et al., 2004). However, these are not issues only in Delhi, but in several megacities, of the entire world. Air quality assessment in Delhi, has been carried out for PM emissions, effect of CNG regulations, air toxicity, air quality index etc. (Goyal and Sindhanta, 2003; Srivastava et al., 2005; Parashar et al., 2005; Kumar and Foster, 2007; Bishoi et al., 2009; Bhati et al., 2009).

Assessment of PM_1, $PM_{2.5}$, and PM_{10} concentrations over daily, monthly, seasonal and data points ensembles mean cycles, assumes significance in environmental, health and climatic perspective. Results of such assessments in terms of running means on analyzing data of airborne PM_1, $PM_{2.5}$, and PM_{10} from August 2007 to October, 2008, at Delhi are presented here. In order to interpret effective variability of PM_1, $PM_{2.5}$, and PM_{10} levels, the relative humidity, temperature and particle concentrations are analyzed over daily, seasonal and data points ensemble running mean and also by simply averaging the entire data of aerosols over these ensembles. The PM_1, $PM_{2.5}$, and PM_{10} components in different seasons in Delhi are interpreted in terms of physical processes, which in general control the ambient PM concentrations.

2. Observational site

Srivastava et al. (2005) have emphasized the role of annual wind rose in interpreting air quality in Delhi. Strong wind prevails from summer to monsoon and frequent low winds in winter. The average wind speed at Delhi is ~2.1 m s^{-1} and low winds (< 1 m s^{-1}) frequency is ~35.52%. The prevailing continental airflow leads to dry condition from post-monsoon to winter and extremely hot summer. Mean temperature ranges from 14.3 ºC in January (lowest 3 ºC) to 34.5 ºC in June (highest 47 ºC) with annual mean of 25.3 ºC (Srivastava et al., 2005).

The observational site IITM, Delhi (28º 35' N; 77º 12' E) is located in central urbanized part at ~218 m above mean sea level. The dispersion and transport of pollutants, particularly those in lower levels of the atmosphere, are governed by circulation patterns in Delhi region. The megacity is affected by severe cold winter. The prevailing winds are northeasterly during winter and southwesterly during summer monsoon. The continental air-mass rich in pollutants pass over Delhi during post-monsoon and winter when the entire northern part of India especially the Indo-Gangetic plain, experiences a thick foggy weather and lower boundary layer heights. Such conditions are unfavorable for dispersion or mixing of pollutants in free troposphere. As a result, poor visibility and moderate to higher level of various pollutants prevail in Delhi. In recent studies, Soni et al. (2010) and Srivastava et al. (2012b) have demonstrated that the absorption at Delhi by aerosols is mainly due to the abundance of black carbon (mostly in fine-mode) from fossil fuel emissions.

3. Method

3.1. Measurements

The sampling of aerosols was carried out at about 15 m above the ground level, on the rooftop of an IITM Building (Delhi). The area is primarily a residential area and no large pollutant source is nearby to influence directly the sampling site. A portable particle analyzer, known as optical particle counter (OPC, Model 1.108, GRIMM Inc.), specifically designed for PM_{10}, $PM_{2.5}$ and PM_1 for ambient air sampling by optical techniques is used in the present study. This technology enables the Model 1.108 to make precise cut off diameters for all three PM sizes. This system allows collecting all three PM fractions simultaneously. Coarse particles (PM_{10}) and fine particulates ($PM_{2.5}$ and PM_1) have been monitored using the GRIMM particles sampler. The GRIMM particle counter was operated continuously during August, 2007 to October, 2008. A constant flow rate ~1.2 liter per minute was maintained. The GRIMM particles measuring system is equipped with GRIMM-1174 Software-Package for data acquisitions. Simultaneously, relative humidity and ambient temperature were recorded with an automatic weather station. The equipment was set to record data at one minute intervals and stores them in memory to be downloaded to a PC and analyzed later.

3.2. Data analysis

The mean at each point is found along a time-series of entire raw data of PM_{10}, $PM_{2.5}$ and PM_1 mass concentrations for daily, monthly, seasonally, etc. during August, 2007 to October, 2008. For example, the daily running mean is obtained with a time constant of 1440 minutes, or 1440 data points calculating the mean of the first 1440 points, then subtracting the value of first point, and adding the value of 1441st point for the next mean value. Similarly the moving monthly, seasonal and annual means or data point ensembles mean of PM_{10}, $PM_{2.5}$ and PM_1 mass concentrations is worked out by subtracting the value of first point from the running mean, and adding the value of next point for taking successive means. The Eq. (1) below, which is built in the Matlab package, computes running means in time-series data of PM_{10}, $PM_{2.5}$ and PM_1 mass concentrations over several days on data point ensembles.

$$y_{j+1} = y_j + \frac{(x_{j+1} - y_j)}{j+1} \tag{1}$$

where x – data point in original time series, y – is the variable data point in running mean time series and j – position of the data point in the time-series.

a)

b)

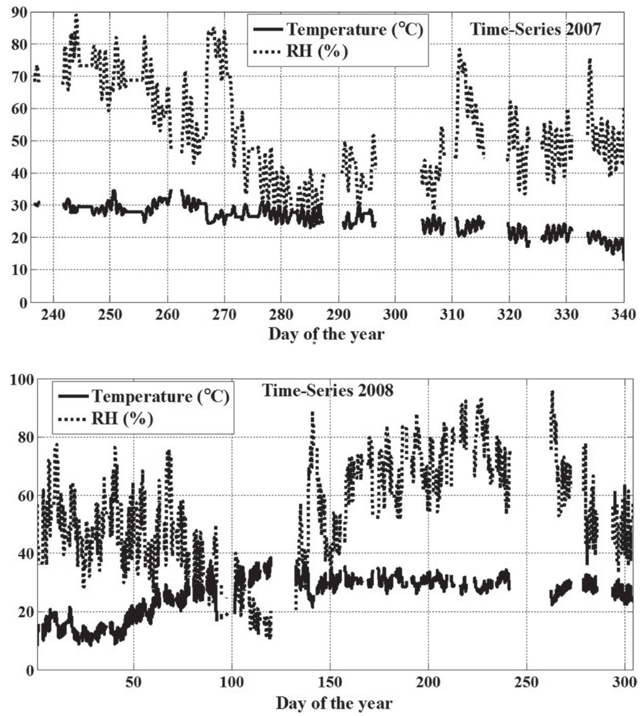
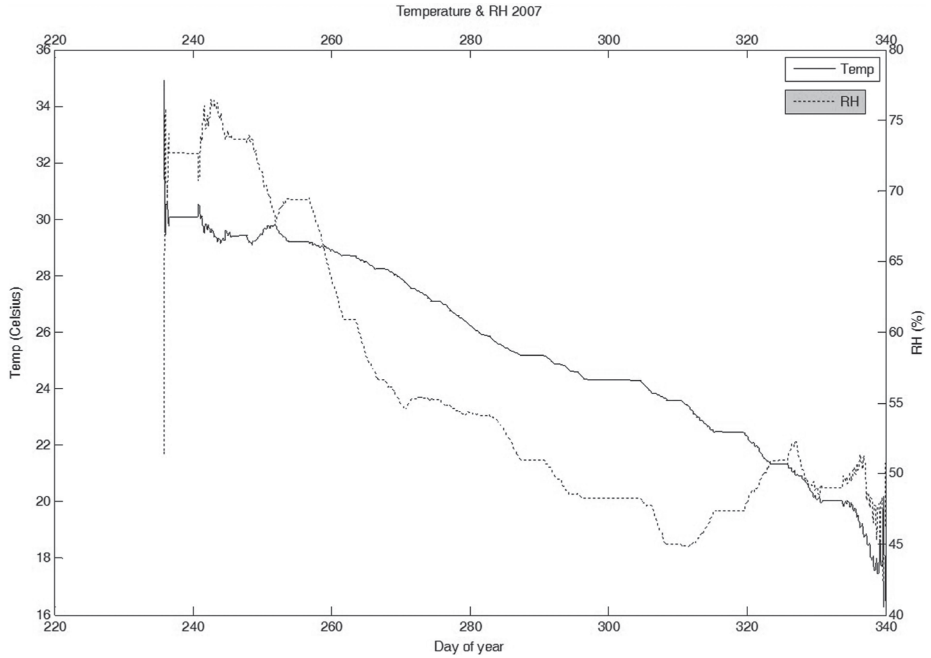


Figure 1. Temperature and RH (a) during 2007 daily (August–December) and (b) 2008 (January–October) and (c) during 2007 and (d) 2008 time scale cycles of observation with running mean.

c)



d)

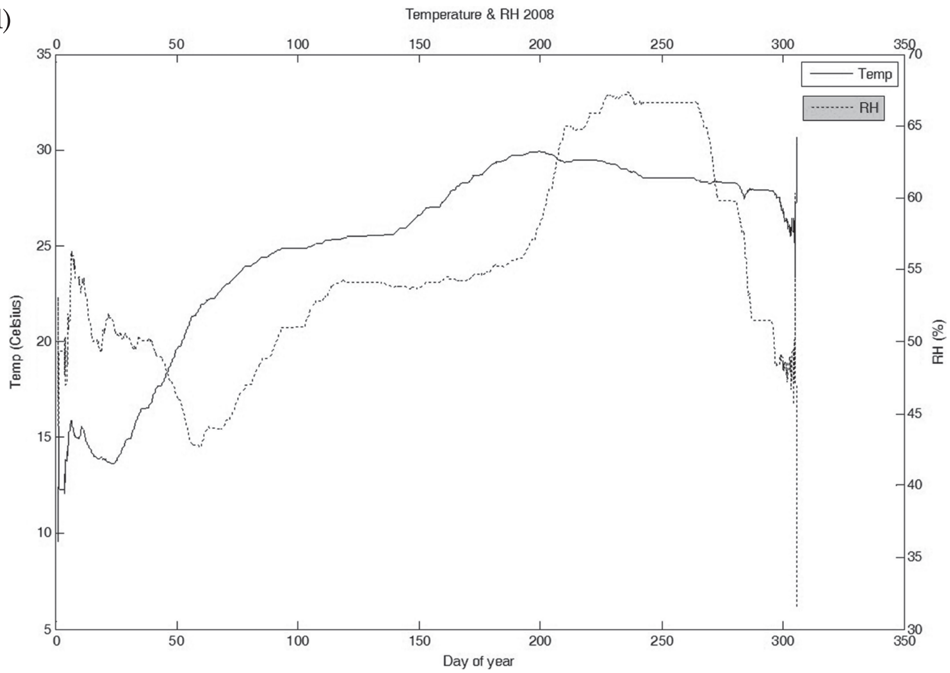


Figure 1. Continued.

4. Results and discussion

According to the India Meteorological Department, climatically, Delhi is divided into four seasons (CPCB, 2001); winter (December–March), pre-monsoon or summer (April–June), monsoon (July–September) and post-monsoon (Octo-

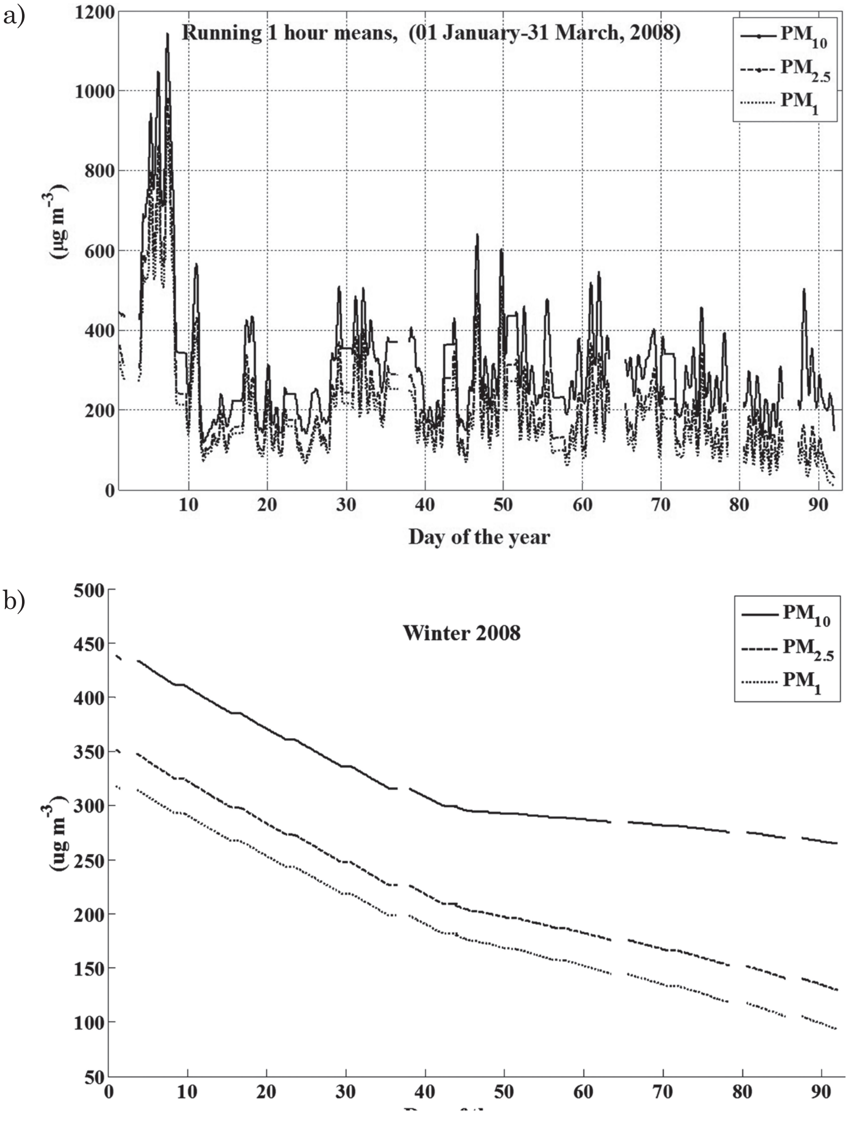


Figure 2. Variations in PM_1, $PM_{2.5}$ and PM_{10} concnetrations during winter 2008 (January–March) with running mean on (a) daily and (b) seasonal cycles.

ber–November). Measurements of PM_{10}, $PM_{2.5}$ and PM_1 concentrations were made in-situ under prevailing ambient relative humidity (RH) and temperature conditions. The variation in temperature and RH would have their effect on PM_{10}, $PM_{2.5}$ and PM_1 concentrations. Therefore the variation in ambient RH and corresponding changes in temperature from August to December, 2007 and from

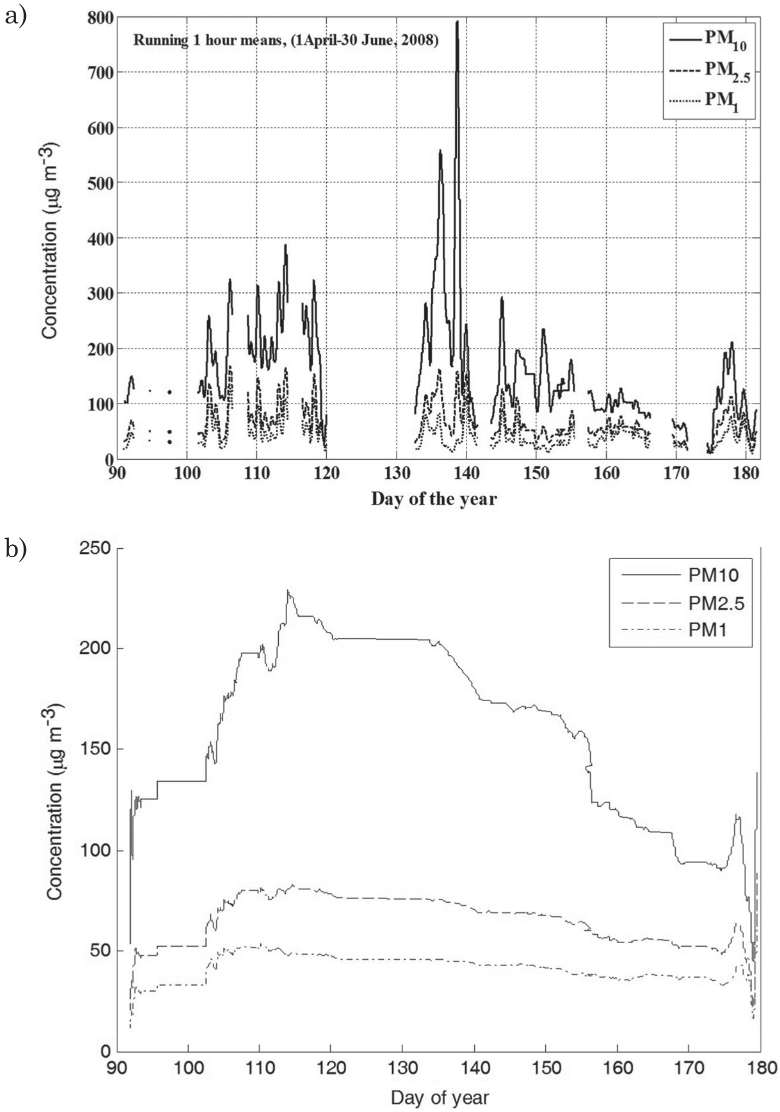


Figure 3. Variations in PM_1, $PM_{2.5}$ and PM_{10} concnetrations during pre-monsoon/summer (April–June 2008) with running mean on (a) daily and (b) seasonal cycles.

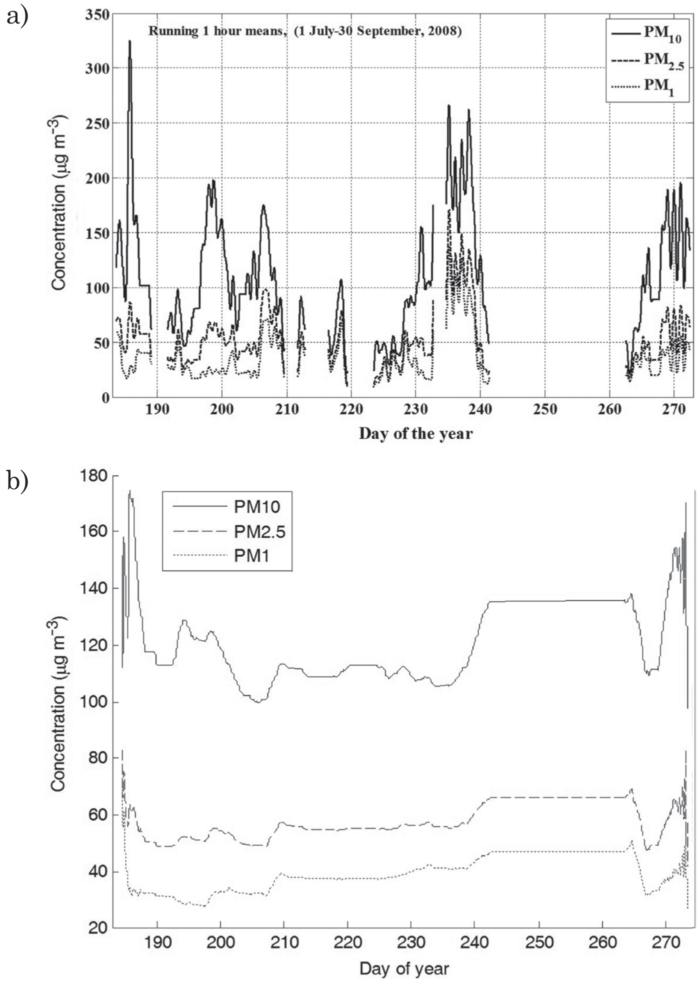


Figure 4. Variations in PM_1, $PM_{2.5}$ and PM_{10} concnetrations during monsoon (July–September 2008) with running mean on (a) daily (b) seasonal cycles.

January to October, 2008 on daily and entire data cycles running mean are plotted in Fig. 1 (a, b, c, d). From August to September, 2007 the ambient temperature was less variable, while RH has registered higher values. Later, temperature gradually decreased at the end of 2007, while RH increased from October end, 2007 and subsequent increasing trend till middle of the February, 2008. While temperature registered gradual increasing trend up to middle of the July, 2008, RH was lower during this period. During monsoon, RH registered its maximum and temperature was almost constant. RH registered lowest and a slight variation in temperature was observed during October, 2008.

a) b)

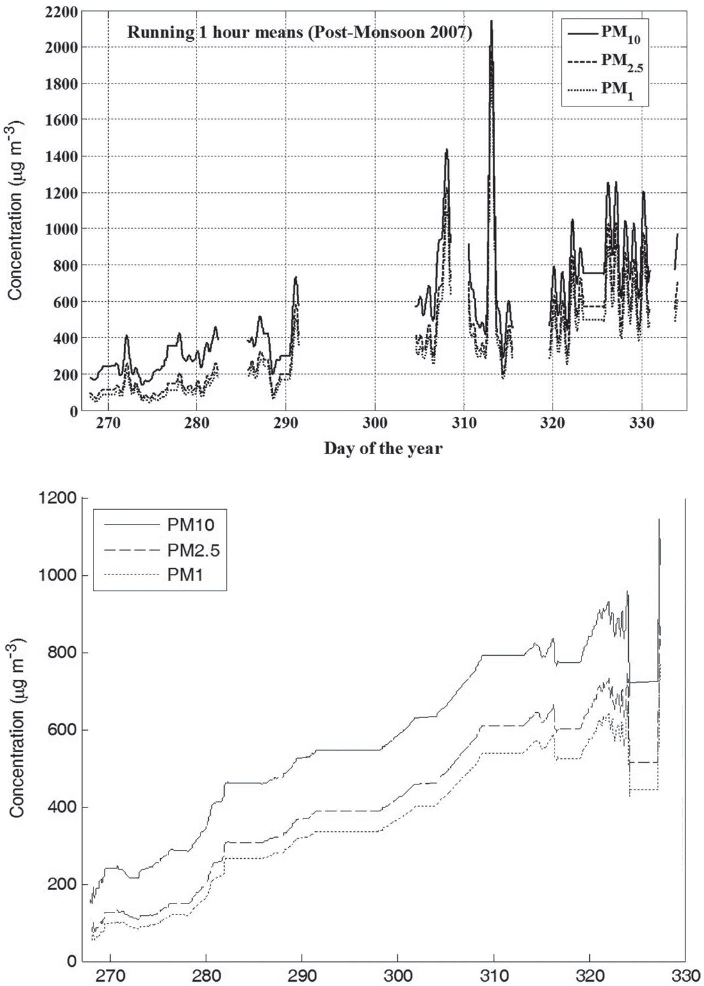


Figure 5. Variations in PM_1, $PM_{2.5}$ and PM_{10} concnetrations during Post-monsoon (October–November 2007) with running mean on (a) daily and (b) seasonal cycle.

The pre-monsoon (summer), monsoon data (PM_1, $PM_{2.5}$, and PM_{10} concentrations) of 2008, post-monsoon data of 2007 and winter data from January to March, 2008 were analyzed. Running means over daily and each seasonal ensemble, the variability in PM_1, $PM_{2.5}$, and PM_{10} concentrations was computer and presented in Figs. 2–5 for the winter, pre-monsoon, monsoon and post-monsoon periods, respectively. The PM_1, $PM_{2.5}$, and PM_{10} concentrations decrease in pre-monsoon and attains its minimum in the monsoon (decreases by ~25–80 µg m^{-3} for PM_{10} and ~10–15 µg m^{-3} for PM_1 and $PM_{2.5}$ from pre-monsoon) before increasing again during the post-monsoon (PM_{10} increases by 400 µg m^{-3}, $PM_{2.5}$ by

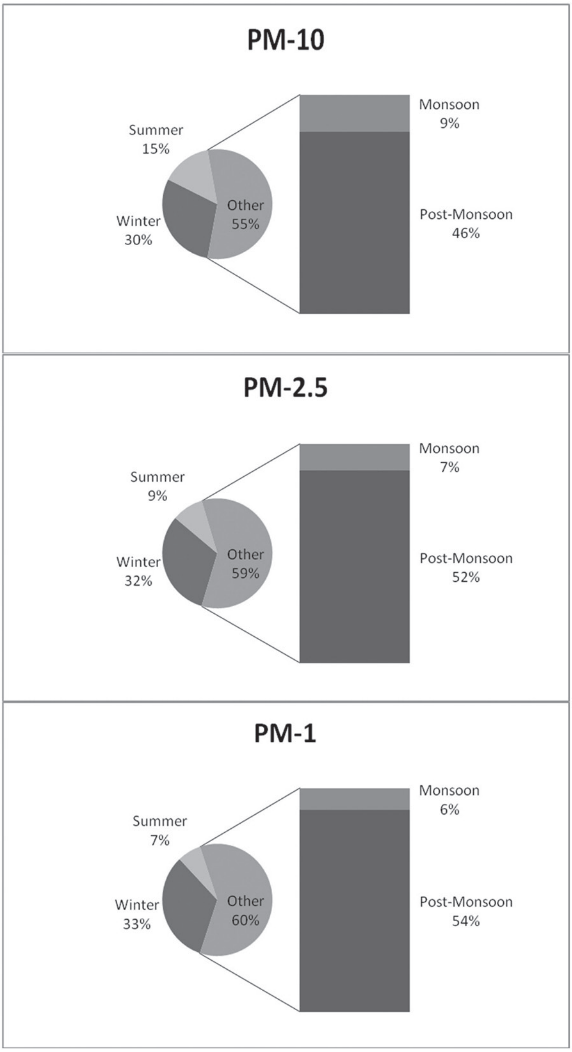


Figure 6. The averages of PM_1, $PM_{2.5}$ and PM_{10} portions to each season. Note the rapid decrease in the percentage contributions during monsoon.

350 µg m^{-3} and PM_1 by 300 µg m^{-3} from their monsoon levels) as evident from Figs. 2–5. However, seasonal variability was more pronounced for PM_1 and $PM_{2.5}$ as compared to PM_{10}. Seasonally the concentration is highest in post-monsoon for PM_1, $PM_{2.5}$, and PM_{10} due to prevailing winds, lower RH (Fig. 1) and local effect of Deepawali festival. In India, during Deepawali, fireworks on large scale especially in urban areas, add significant amount of anthropogenic pollutants into local environments. During 8 to 11 November, 2007 (Deepawali day was on

9th November) and during 27 to 30 October, 2008 (Deepawali day was on 28th October), the occurrence of high PM_1, $PM_{2.5}$, and PM_{10} concentration between 100 and 1400 µg m^{-3} in the daily running mean and between 100 and 800 µg m^{-3} in the seasonal running mean during the post-monsoon, 2007, which were attributed to bursting of crackers on Deepawali days. Also, low winds, mixing height ~300 m, low temperature ~20 °C and high RH (Fig. 1) contributed to these PM levels. RSPM levels over Delhi during Deepawali, 2007 was reported about 610–1294 µg m^{-3} by the central pollution control board (http://www.cpcb.nic.in/Air-Quality-Delhi.php), which are comparable with PM_1, $PM_{2.5}$, and PM_{10} concentrations during post-monsoon season of 2007 (Figs. 2–5).

The averages of PM_1, $PM_{2.5}$, and PM_{10} portions in each season in Delhi are shown in Fig. 6. The percentage for each slice of pie and rectangular charts indicates PM_1, $PM_{2.5}$, and PM_{10} portion to each season. The PM_1, $PM_{2.5}$, and PM_{10} components in winter are 30 to 33%. PM_{10} portion to summer is higher by 8% to that of $PM_{2.5}$ and by 9% to that of PM_1. The emissions of coarser particles to the ambient air by wind blown dust during summer period caused the increased

a)
b)

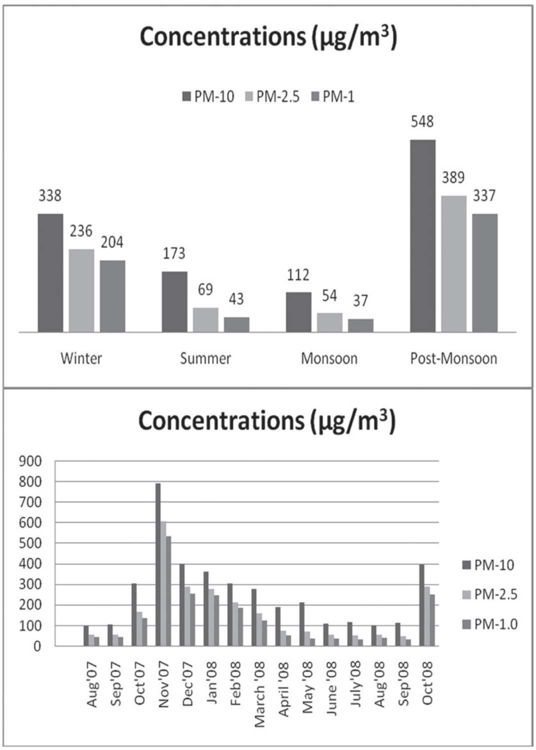


Figure 7. Simple (a) seasonal averages of PM_1, $PM_{2.5}$ and PM_{10} and (b) monthly averages of entire data from August, 2007 to October, 2008.

a)

b)

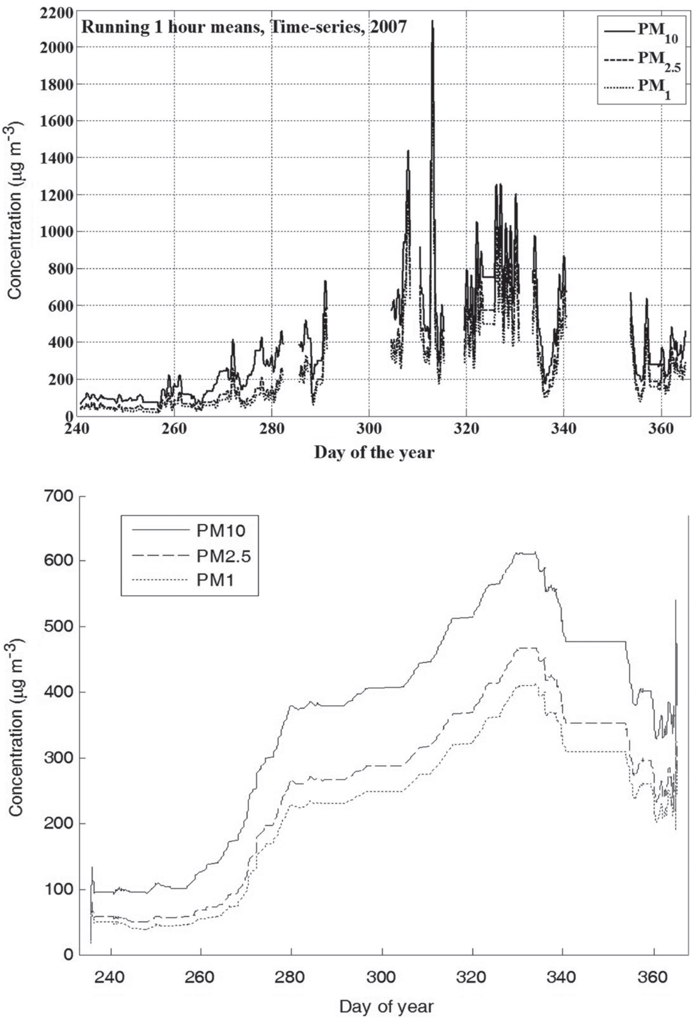


Figure 8. Time-series variations in PM_1, $PM_{2.5}$ and PM_{10} concnetrations during August–December 2007 with running mean on (a) daily and (b) data points ensembles cycle.

PM_{10} portion than those of $PM_{2.5}$ and PM_1. Also, PM_{10} portion to monsoon increases by 2% to that of $PM_{2.5}$ and 3% to that of PM_1. However, PM_{10} share to post-monsoon reduces by 5% to that of $PM_{2.5}$ and by 7% to that PM_1. The dispersion mechanisms and atmospheric residence time of aerosols play major role in seasonal variability of PM_1, $PM_{2.5}$, and PM_{10} levels and their shares in each season. PM_{10} particles settle more quickly on ground due to their higher deposition velocity. PM_1 and $PM_{2.5}$ particles remain airborne for longer time and in turn transported to longer distances. Bursting of crackers during Deepawali increas-

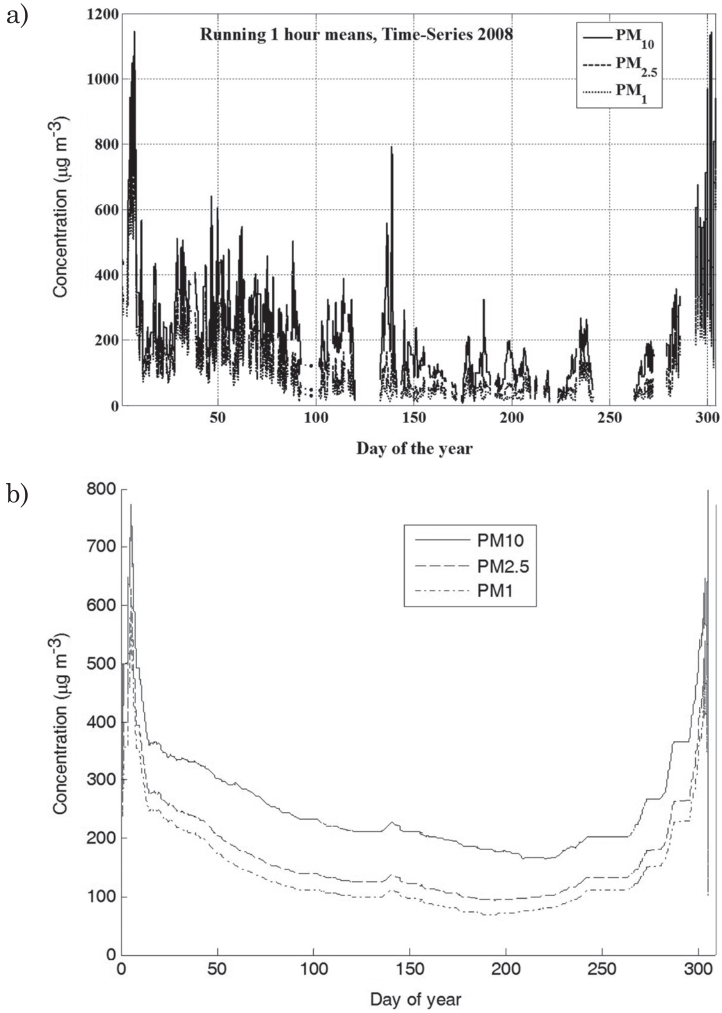


Figure 9. Time-series variations in PM_1, $PM_{2.5}$ and PM_{10} concnetrations during January–October 2008 with running mean on (a) daily and (b) data point ensembles cycle.

es levels of smaller particles in post-monsoon. Consequently, PM_{10} share to post-monsoon is significantly less than that of $PM_{2.5}$ and PM_1.

By averaging the data in each seasonal ensemble, the absolute seasonal mean for PM_1, $PM_{2.5}$ and PM_{10} are shown in Fig. 7 (a). Also, the inter-annual variability in entire data during 2007 and 2008 are shown in Fig. 7(b). Each column in these figures represents seasonal and monthly means of PM_1, $PM_{2.5}$ and PM_{10}. Seasonal patterns were similar to Figs. 2–5 for PM_1, $PM_{2.5}$ and PM_{10}, with lower levels during monsoon. Higher levels were common during post-monsoon, when continental air-mass prevails. Also, bursting of crackers on Deepawali days in October, have added additional load of aerosols on pre-existing levels. In inter-annual variability, PM_1, $PM_{2.5}$, and PM_{10} levels in October, 2008 were higher than those in October, 2007. This variability was observed only in October, whereas mass concentrations in August and September, 2007 were same as in the August and September, 2008.

In order to compare variability of PM_1, $PM_{2.5}$, and PM_{10} concentrations during August–December 2007 and during January–October 2008 based on moving averages with those of monthly averages, the entire data samples are grouped into ensembles and running means are computed on daily and entire data period cycles and shown in Figs. 8 and 9. Higher concentrations are observed in time-series plots of 2007 and 2008 during post-monsoon followed by winter, summer and monsoon. Monthly mean column of November for PM_{10} show 800 $\mu g\, m^{-3}$ whereas daily running mean shows 1400 $\mu g\, m^{-3}$ and running mean on two month cycles reflects 600 $\mu g\, m^{-3}$ in post-monsoon. During monsoon, simple mean for PM_{10} was ~100 $\mu g\, m^{-3}$ for PM_{10} in 2007 and 2008, whereas running mean was ~200–300 $\mu g\, m^{-3}$. Simple mean column for PM_1, and $PM_{2.5}$ shows ~37–50 $\mu g\, m^{-3}$ during monsoon and running mean shows ~100–200 $\mu g\, m^{-3}$. It is seen from Fig. 8 that during winter, when PM_1, $PM_{2.5}$ and PM_{10} concentrations are at their moderate levels due to prevailing continental air-mass, these curves are less resolved, whereas during monsoon they are well separated, with PM_{10} remaining significantly higher than $PM_{2.5}$ and PM_1. This is due to effective scavenging of PM_{10} aerosols by monsoonal rain and nucleation scavenging of PM_1 and $PM_{2.5}$ particles in the process of cloud formation.

Kumar and Foster (2007) reported that the average PM_{10} in Delhi declined from 240.2 ± 22.7 $\mu g\, m^{-3}$ in 2001–02 to 239.8 ± 10.9 $\mu g\, m^{-3}$ in 2004–05. They have cautioned against the interpretation of these results in terms of air quality, especially in semi-dry climates where dust is a major contributor of PM_{10} mass. However, running mean cyclic assessments of $PM_{2.5}$ and PM_1 particles during August, 2007 to October, 2008 over daily, monthly, seasonal and annual scale at Delhi, presented in this work can be viewed as indicator of levels for air-quality in Delhi.

5. Conclusions

Assessments of PM_1, $PM_{2.5}$, and PM_{10} particles are presented in this paper on daily, monthly, seasonal and inter-annual time scales over Delhi. Seasonally, concentrations are at their maximum in post-monsoon for PM_1, $PM_{2.5}$ and PM_{10} due to prevailing winds, lower boundary layer height and RH and firecrackers bursting. PM_1, $PM_{2.5}$ and PM_{10} concentrations decrease in pre-monsoon and attain their minimum in the monsoon (decreases by ~25–80 $\mu g\, m^{-3}$ for PM_{10} and ~10–15 $\mu g\, m^{-3}$ for PM_1 and $PM_{2.5}$ from their pre-monsoon levels) before increasing again during the post-monsoon. PM_1, $PM_{2.5}$ and PM_{10} contributions in winter are ~30–

33%. PM_{10} contribution to summer is higher than those of PM_1 and $PM_{2.5}$ due to the loading of wind-blown dust. However, contribution to post-monsoon in number concentration of coarse particles is significantly lower than those of fine particles ($PM_{2.5}$ and PM_1). Bursting of fire-crackers during Deepawali, quick gravitational settling of coarse particles as against longer residence time of fine particles and lower boundary layer height are responsible for such pattern. Higher PM_{10} contribution in monsoon than those of PM_1 and $PM_{2.5}$ is attributed to higher processing rate of smaller aerosols in cloud-formations (in-cloud scavenging) than the removal rate of PM_{10} (below-cloud scavenging).

Increased PM_{10} levels caused by wind blown dust in Delhi due to semi-dry climate are of less concern in view of environmental perspective. However, increased levels of smaller particles (PM_1, $PM_{2.5}$) are the main concern to human being because of their longer atmospheric residence time, higher surface to volume ratio, more pronounced impact on health, visibility, direct, indirect and semi-direct climatic effects and impact on ecosystem, structures, etc. The daily, monthly and seasonal variability of PM_1, $PM_{2.5}$ and PM_{10} levels and their portioning patterns to each season presented in this paper may be useful in policy decision making process aiming to improve the air quality in Delhi.

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SAŽETAK

Procjene koncentracija lebdećih čestica PM_1, $PM_{2.5}$ i PM_{10} u Delhiju, Indija, na različitim vremenskim skalama

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Prikazani su dnevni, mjesečni, sezonski i godišnji klizni srednjaci koncentracija lebdećih čestica PM_1, $PM_{2.5}$ i PM_{10} za razdoblje od kolovoza 2007. do listopada 2008 u Delhiju, Indija (28º 35' N; 77º 12' E), po veličini sedmom velegradu na svijetu. Koncentracije lebdećih čestica PM_1, $PM_{2.5}$ i PM_{10} sezonski se mijenjaju u ovisnosti o atmosferskim procesima i ljudskim aktivnostima. U odnosu na svoje predmonsunske vrijednosti koncentracije PM_{10} se smanjuju tijekom monsunskog razdoblja za ~25–80 $\mu g\,m^{-3}$, a koncentracije PM_1 i $PM_{2.5}$ za ~10–15 $\mu g\,m^{-3}$. Vatrometi tijekom festivala Deepawali podižu razine koncentracija lebdećih čestica PM_1, $PM_{2.5}$ i PM_{10} u post-monsunskoj sezoni za 300, 350, odnosno 400 $\mu g\,m^{-3}$ u odnosu na njihove vrijednosti u monsunskoj sezoni. Sezonska varijacija visine miješanja, temperature, vjetra i oborine doprinosi međugodišnjoj varijabilnosti PM_1, $PM_{2.5}$ i PM_{10}. Zimske razine PM_1, $PM_{2.5}$, i PM_{10} doprinose ~30–33% ukupnim vrijednostima. Koncentracije PM_{10} ljeti su više za 8% od onih za $PM_{2.5}$ i za 9% od onih za PM_1. Koncentracija frakcije PM_{10} u post-monsunskom razdoblju su niže za 5% od onih za $PM_{2.5}$ i za 7% od onih za PM_1. Također, koncentracije PM_1, $PM_{2.5}$ i PM_{10} bile su više tijekom listopada 2008. od onih u 2007., ali su njihove razine ostale gotovo iste u kolovozu i rujnu 2007. i 2008. Klizni srednjaci koncentracija PM_1, $PM_{2.5}$ iPM_{10} te vrijednosti koncentracija u različitim sezonama korisni su za donošenje propisa vezanih uz razine onečišćenja zraka, čiji je cilj poboljšanje kvalitete zraka u Delhiju.

Ključne riječi: ciklusi kliznih srednjaka, kvaliteta zraka, vrijeme boravka u atmosferi, lebdeće čestice, mokro taloženje

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