Original scientific paper

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

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Abstract

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 μg m^{-3}, 350 μg m^{-3} 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 atmospheric, 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 ~218m 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. 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 in used. 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.

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

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.

4. Results and discussion

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

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 $\mu g\ m^{-3}$ for PM_{10} and ~10-15 $\mu g\ m^{-3}$ 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 350 μg m^{-3} and PM_1 by 300 μg m^{-3} from their monsoon levels) as evident from Fig. 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 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 increases 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 μg m^{-3} in post-monsoon. During monsoon, simple mean for PM_{10} was ~100 μg m^{-3} for PM_{10} in 2007 and 2008, whereas running mean was ~ 200-300 μg m^{-3}. Simple mean column for PM_1, and $PM_{2.5}$, shows ~37-50 μg m^{-3} during monsoon and running mean shows ~ 100-200 μg 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 μg m^{-3} in 2001-02 to 239.8±10.9 μg 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 μg m^{-3} for PM_{10} and ~10-15 μg 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, PM_{10} contribution to post-monsoon is significantly lower than those of $PM_{2.5}$ and PM_1. Bursting of fire-crackers during Deepawali, quick gravitational settling of PM_{10} as against longer residence time of PM_1 and $PM_{2.5}$ 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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References

Berico, M., Luciani, A. and Formignani, M. (1997): Atmospheric aerosol in urban area-measurements of TSP and PM10 standards and pulmonary deposition assessments, *Atmos. Environ.*, **31**, 3659-3665.

Bhati, S., Manju M. and Archana R. (2009): Application of air dispersion modeling for exposure assessment from particulate matter pollution in mega city Delhi, *The seventh Intern. Conf. on Urban Climate: 29 June - 3 July 2009, Yokohama, Japan.*

Bishoi, B., Amit, P. and Jain V. K. (2009): A Comparative Study of Air Quality Index Based on Factor Analysis and US-EPA Methods for an Urban Environment, *Aerosol Air Qual. Research,* **9**, 1-17.

Bytnerowicz, A. Omasa, K. and Paoletti, E. (2007): Integrated effects of air pollution and climate change on forests: A northern hemisphere perspective. *Environ. Pollut.* **147**, 438–445.

Brunekreef, B. and Forsberg, B. (2005): Epidemiological evidence of effects of coarse airborne particles on health, *European Respiratory Journal,* **26**, 309–318.

Chate, D. M. and Devara, P. C. S. (2009): Acidity of raindrop by uptake of gases and aerosol pollutants, *Atmos. Environ.*, **43**, 1571-1577.

Chate, D. M. (2011): Below-thunderstorm rain scavenging of urban aerosols in the health hazardous modes, *Nat. Hazards,* **56**, 81–91.

Chen, L. H., Knutsen, S. F. Beeson, L. Ghamsary, M. Shavlik, D. Petersen, F. and Abbey, D. (2005): 'The Association between Ambient Particulate Air Pollution and Fatal Coronary Heart Disease among Persons with Respiratory Symptoms/Disease', *Annals of Epidemiology*, **15**, 642-42.

Dominici, F., McDermott, A., Daniels, M., Zeger, S. L. and Samet, J. M. (2005): 'Revised Analyses of the National Morbidity, Mortality, and Air Pollution Study: Mortality among Residents\ of 90 Cities', *Journal of Toxicology and Environmental Health-Part a-Current Issues*, **68**, 1071-92.

Dockery, D. W. and Stone, P. H. (2007): Cardiovascular Risks from Fine Particulate Air Pollution, *NEJM,* **356**, 511–513.

Goyal, P. and Sidhartha (2003): Present Scenario of Air Quality in Delhi: a case study of CNG implementation, *Atmos. Environ.,* **37**, 5423-5431.

Gurjar, B. R., Van Aardenne, J. A., Lelieveld, J., Mohan, M. (2004): Emission estimates and trends (1990–2000) for megacity Delhi and implications, *Atmos. Environ.*, **38**, 5663-5681.

Hind, W. C. (1999): Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, John Wiley and Sons: New York, 111-170 pp.

IPCC, (2007): Climate Change 2007, the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC (ISBN 978 0521 88009-1 Hardback; 978- 0521 70596-7 Paperback).

Jaenicke, R. (1984): Physical aspects of atmospheric aerosol. In: Gerbard, H.E., Deepak, A. (Eds.), Aerosols and their Climatic Effects, Deepak Publishing, Hampton, Virginia, USA, 7 – 34 pp.

Jin, X., Dubois, D., Pitchford, M., Green, M. and Etyemezian, V. (2006): Attribution of sulfate aerosols in Federal Class I areas of the western United States based on trajectory regression analysis, *Atmos. Environ*., **40**, 3433–3447.

Kathuria, V. (2005): 'Impact of CNG on Delhi's Air Pollution', *Economic and Political Weekly*, **40**, 1907-1916.

Kumar, A. and Foster, T.C. (2007): Shift in Induction Mechanisms Underlies an Age- Dependent Increase in DHPG-Induced Synaptic Depression at CA3–CA1 Synapses, *J. Neurophysiol,* **98**, 2729–2736.

Murugavel, P. and Chate, D. M. (2009): Generation and Growth of aerosols over Pune, India, *Atmos. Environ*., **43**, 820-828,

NAAQMS (2001): National Ambient Air Quality Monitoring Station: Air Quality in Delhi (1989-2000), NAAQMS /17/ 2000-2001, *Central Pollution Control Board, Parivesh Bhawan, Delhi, India*.

Parasharar, D. C., Gadib, R., Mandala, T. K. and Mitraa A. P. (2005): Carbonaceous aerosol emissions from India, *Atmos. Environ.,* **39**, 7861–7871.

Pope, C. A., Burnett, R. T., Thurston, G. D., Thun, M. J,. Calle, E. E., Krewski, D., Godleski, J. J. (2004): Cardiovascular mortality and long-term exposure to particulate air pollution, *Circulation,* **109**, 71–77.

Pérez, N., Castillo, S., Pey, J., Alastuey, A., Viana, M. and Querol, X. (2008): Interpretation of the variability of regional background aerosols in the Western Mediterranean. *Sci. Total Environ.,* **407**, 527–540.

Salma, I., Balashazy, I., Hofmann, W. and Zaray, G. (2002): Effect of physical exertion on the deposition of urban aerosols in the human respiratory system, *J. Aerosol Sci.,* **33**, 983-997.

Seinfeld, J. H. and Pandis, S. N. (2006): Atmospheric chemistry and physics: from air pollution to climate change. Wiley, the University of Michigan, ISBN: 0471720186, 9780471720188.

Schwartz, J., Laden, F., Zanobetti, A. and Dockery, D. W. (2001): 'Is There a Threshold in the Association of PM2.5 with Daily Deaths?', *Epidemiology*, **12**(4), S65-S65.

Soni, K., Singh, S., Bano, T., Tanwar, R. S., Nath, S. and Arya, B. C. (2010): Variations in single scattering albedo and Angstrom absorption exponent during different seasons at Delhi, India, *Atmos. Environ.,* **44**, 4355-4363.

Srivastava, A., Anjali, A,. Josepha, E., Patila, S., Morea, A., Dixitb, R.C. and Prakash, M. (2005): Air toxics in ambient air of Delhi, *Atmos. Environ*., **39**, 59–71.

Srivastava, A. K., Tiwari, S., Devara, P. C. S., Bisht, D. S., Srivastava, M. K., Tripathi, S. N., Goloub, P. and Holben, B. N. (2011): Pre-monsoon aerosol characteristics over the Indo-Gangetic Basin: Implications to climatic impact, *Ann. Geophy.,* **29**, 789–804.

Srivastava, A. K., Tripathi, S. N., Dey, S., Kanawade, V. P. and Tiwari, S. (2012a): Inferring aerosol types over the Indo-Gangetic Basin from ground based sunphotometer measurements, *Atmos. Res.,* **109-110**, 64–75.

Srivastava, A. K., Singh, S., Pant, P. and Dumka, U. C. (2012b): Characteristics of black carbon over Delhi and Manora Peak-a comparative study, *Atmospheric Science Letters,* doi: 10.1002/asl.386 (In Press).

WHO (2000): "Guidelines for Air Quality" World Health Organization, Geneva.

WHO (2006): World Health Organization: Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulphur Dioxide – Global Update 2005 – *Summary of Risk Assessment,* Geneva.

Legends

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.

Figure 2: Varitions 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.

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

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

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

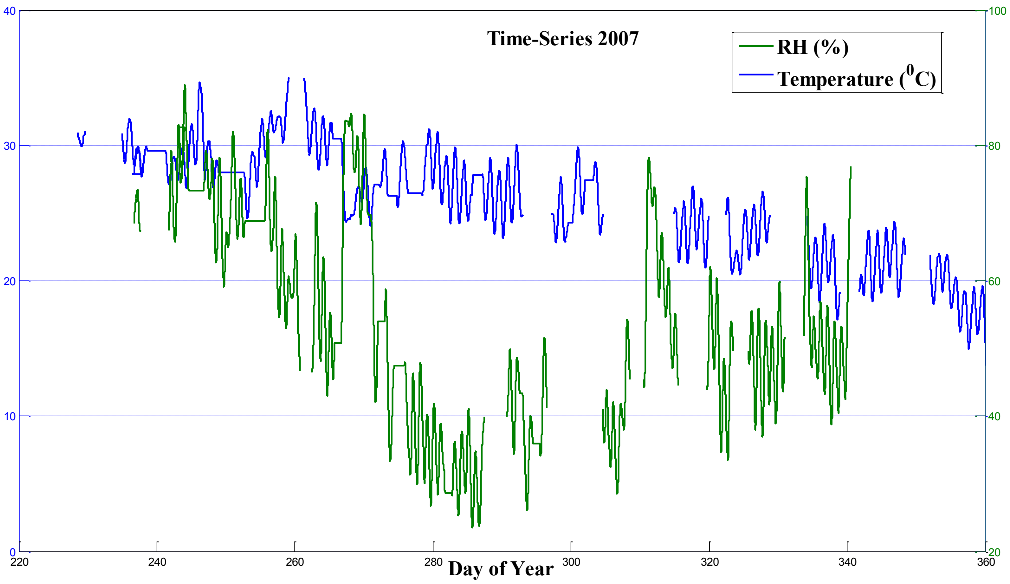
Figure 6: The averages of PM_1, $PM_{2.5}$ and PM_{10} portions to each season. Note the rapid decrease in the percentage contributions during monsoon.

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.

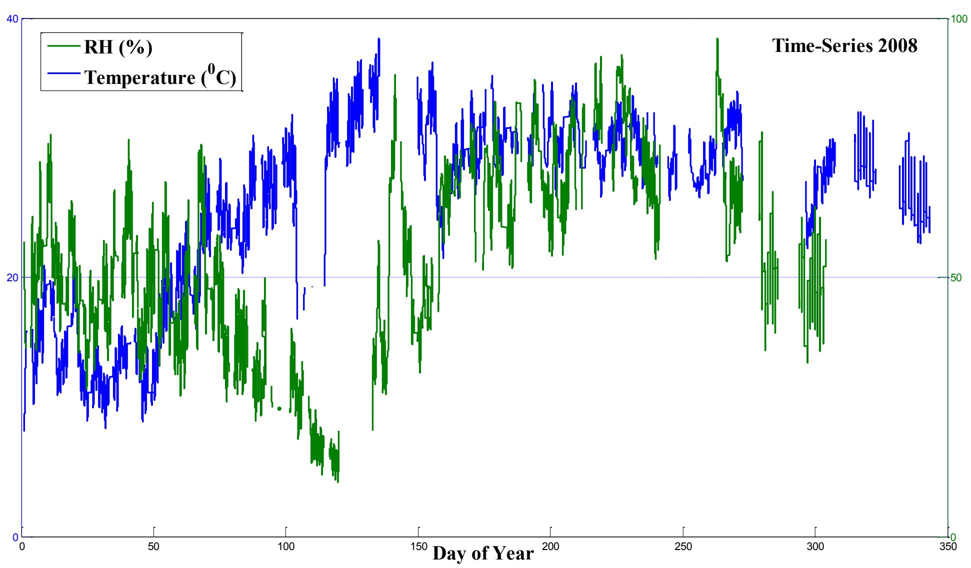
Figure 8: Time-series variations in PM_1, $PM_{2.5}$ and PM_{10} concnetrations during August-December 2007 with running mean on (a) daily and (b) data points ensembles cycle.

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.

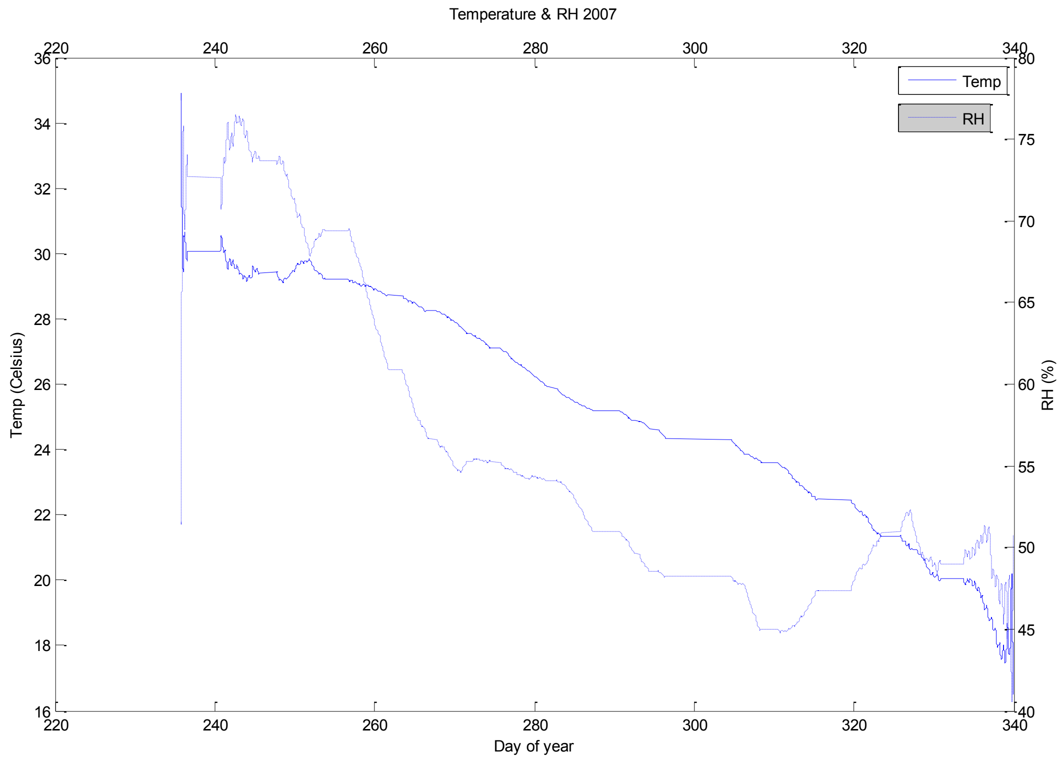
Figure 1 (a)


Time-Series 2007
RH (%)
Temperature (^{0}C)
Day of Year
40
30
20
10
0
100
80
60
40
20
220
240
260
280
300
320
340
360

(b)

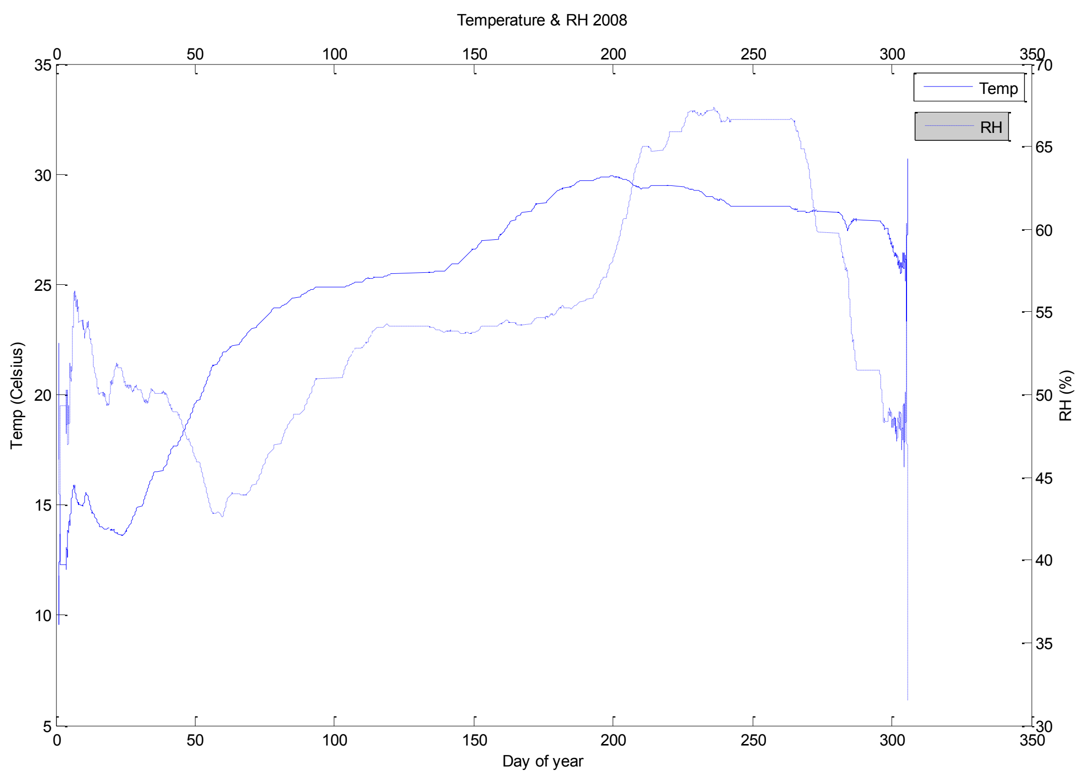

RH (%)
Temperature (^{0}C)
Time-Series 2008
Day of Year
40
20
0
100
50
0
0
50
100
150
200
250
300
350

(c)



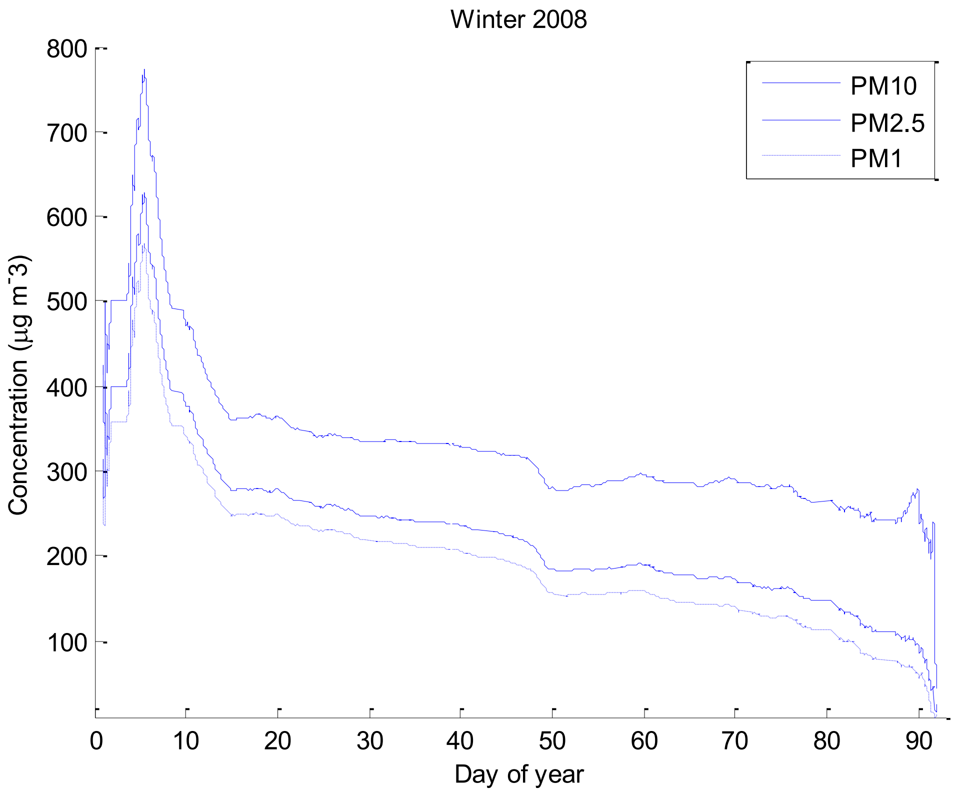
Temperature & RH 2007
Temp
RH
Temp (Celsius)
RH (%)
Day of year
220
240
260
280
300
320
340
36
34
32
30
28
26
24
22
20
18
16
80
75
70
65
60
55
50
45
40

(d)



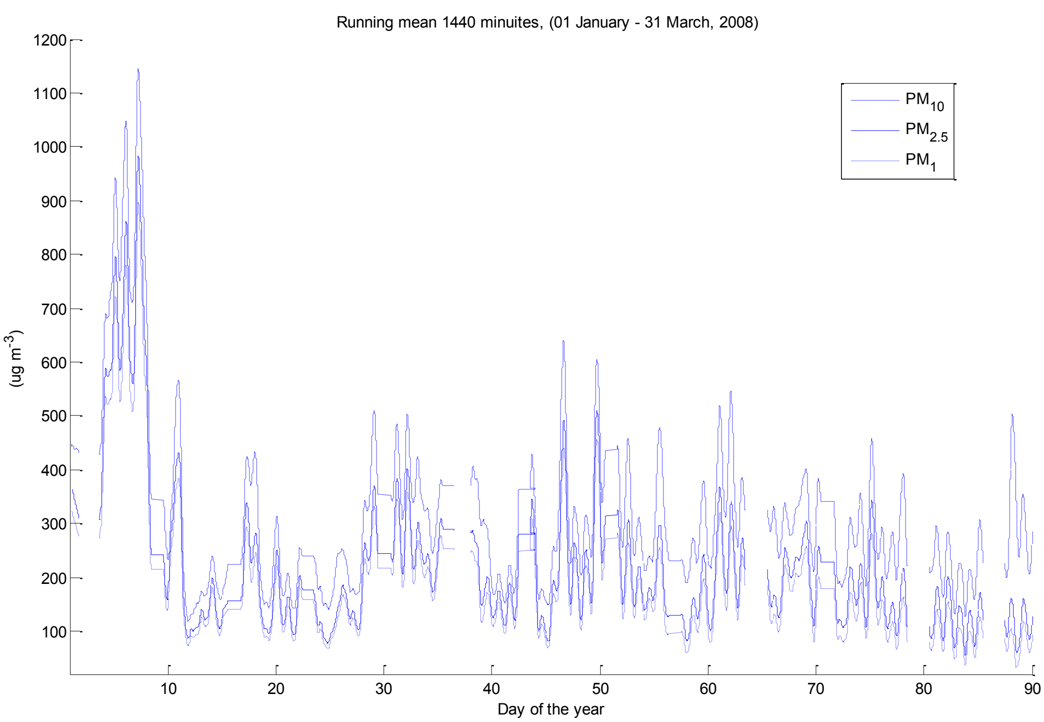
Temperature & RH 2008
Temp
RH
Temp (Celsius)
RH (%)
Day of year
0
50
100
150
200
250
300
350
35
30
25
20
15
10
5
70
65
60
55
50
45
40
35
30

Figure 2 (a)



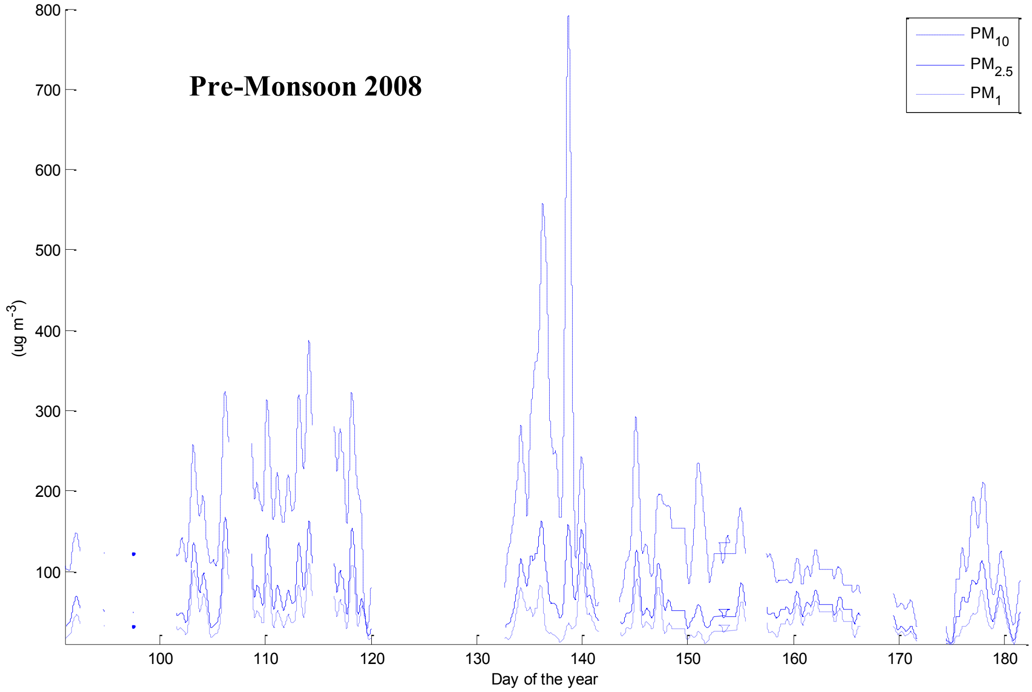
Winter 2008
800
700
600
500
400
300
200
100
Concentration (µg m^-3)
0
10
20
30
40
50
60
70
80
90
Day of year
PM10
PM2.5
PM1

(b)



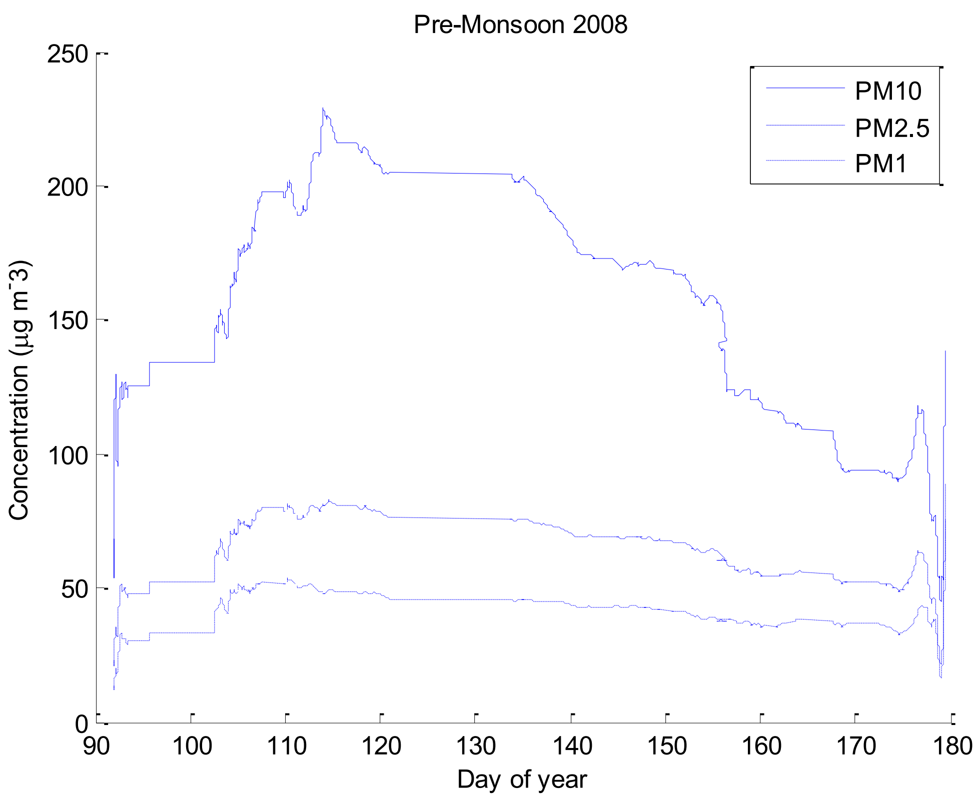
Running mean 1440 minuites, (01 January - 31 March, 2008)
1200
1100
1000
900
800
700
600
500
400
300
200
100
(ug m-3)
10
20
30
40
50
60
70
80
90
Day of the year
PM10
PM2.5
PM1

Figure 3 (a)



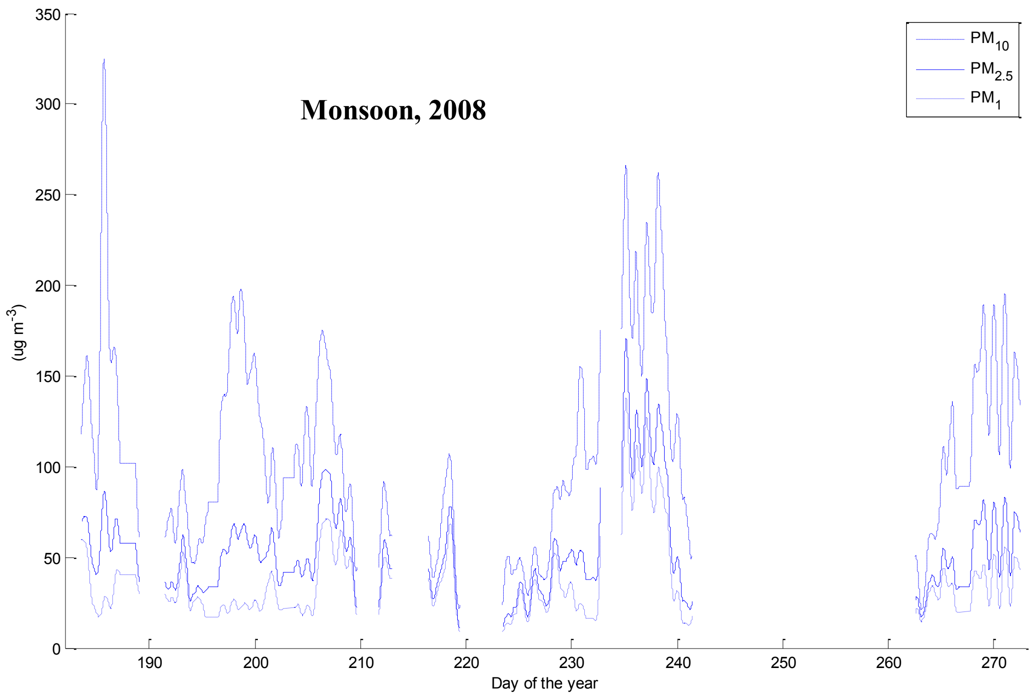
Pre-Monsoon 2008
PM10
PM2.5
PM1
(ug m-3)
Day of the year
800
700
600
500
400
300
200
100
100
110
120
130
140
150
160
170
180

(b)



Pre-Monsoon 2008
PM10
PM2.5
PM1
Concentration (µg m-3)
Day of year
250
200
150
100
50
0
90
100
110
120
130
140
150
160
170
180

Figure 4 (a)


Monsoon, 2008
PM10
PM2.5
PM1
(ug m-3)
350
300
250
200
150
100
50
0
190
200
210
220
230
240
250
260
270
Day of the year

(b)

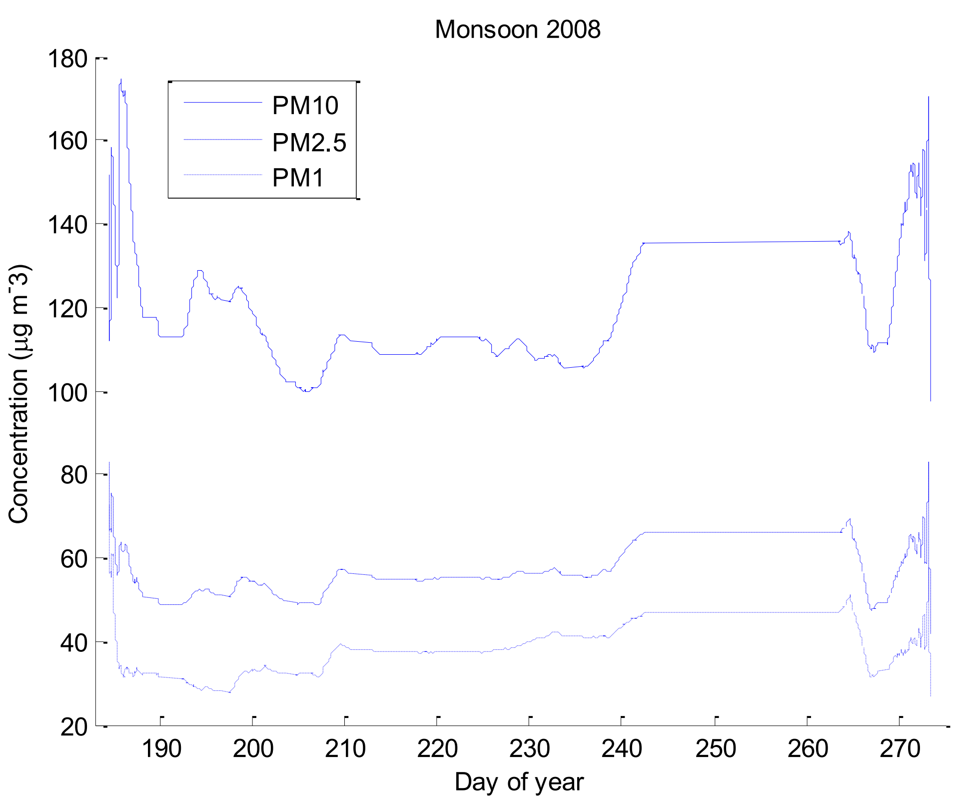
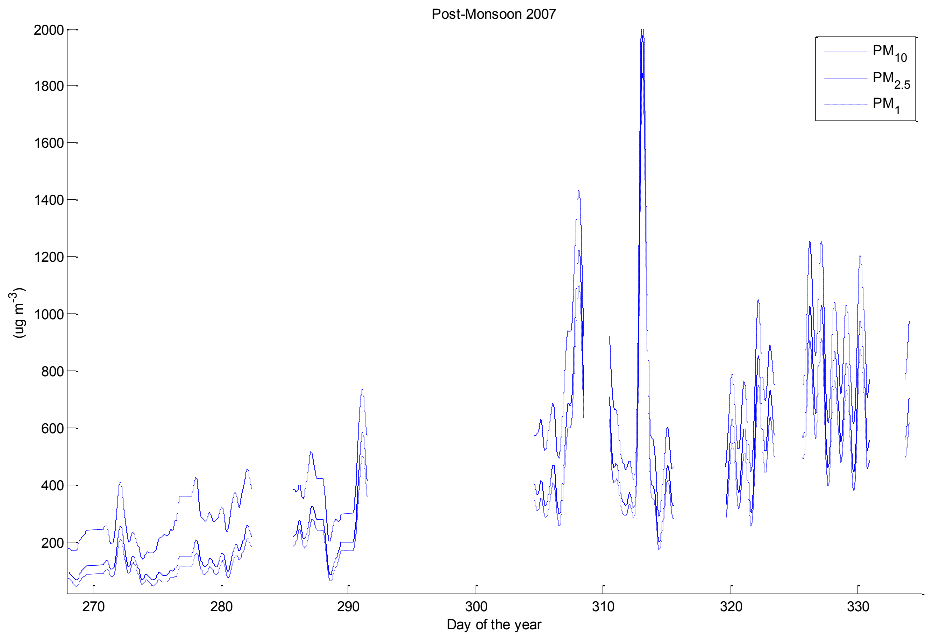
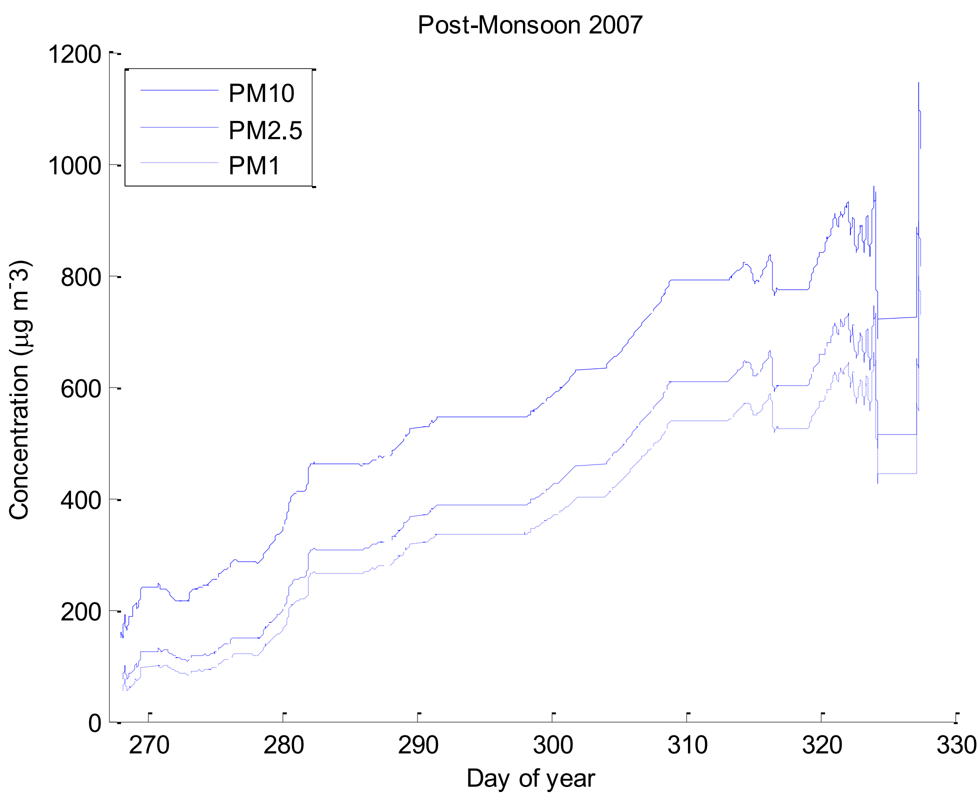

Monsoon 2008
PM10
PM2.5
PM1
Concentration (µg m-3)
180
160
140
120
100
80
60
40
20
190
200
210
220
230
240
250
260
270
Day of year

Figure 5 (a)



Post-Monsoon 2007
2000
1800
1600
1400
1200
1000
800
600
400
200
(ug m-3)
PM10
PM2.5
PM1
270
280
290
300
310
320
330
Day of the year

(b)



Post-Monsoon 2007
1200
1000
800
600
400
200
0
PM10
PM2.5
PM1
Concentration (µg m^-3)
270
280
290
300
310
320
330
Day of year

Figure 6

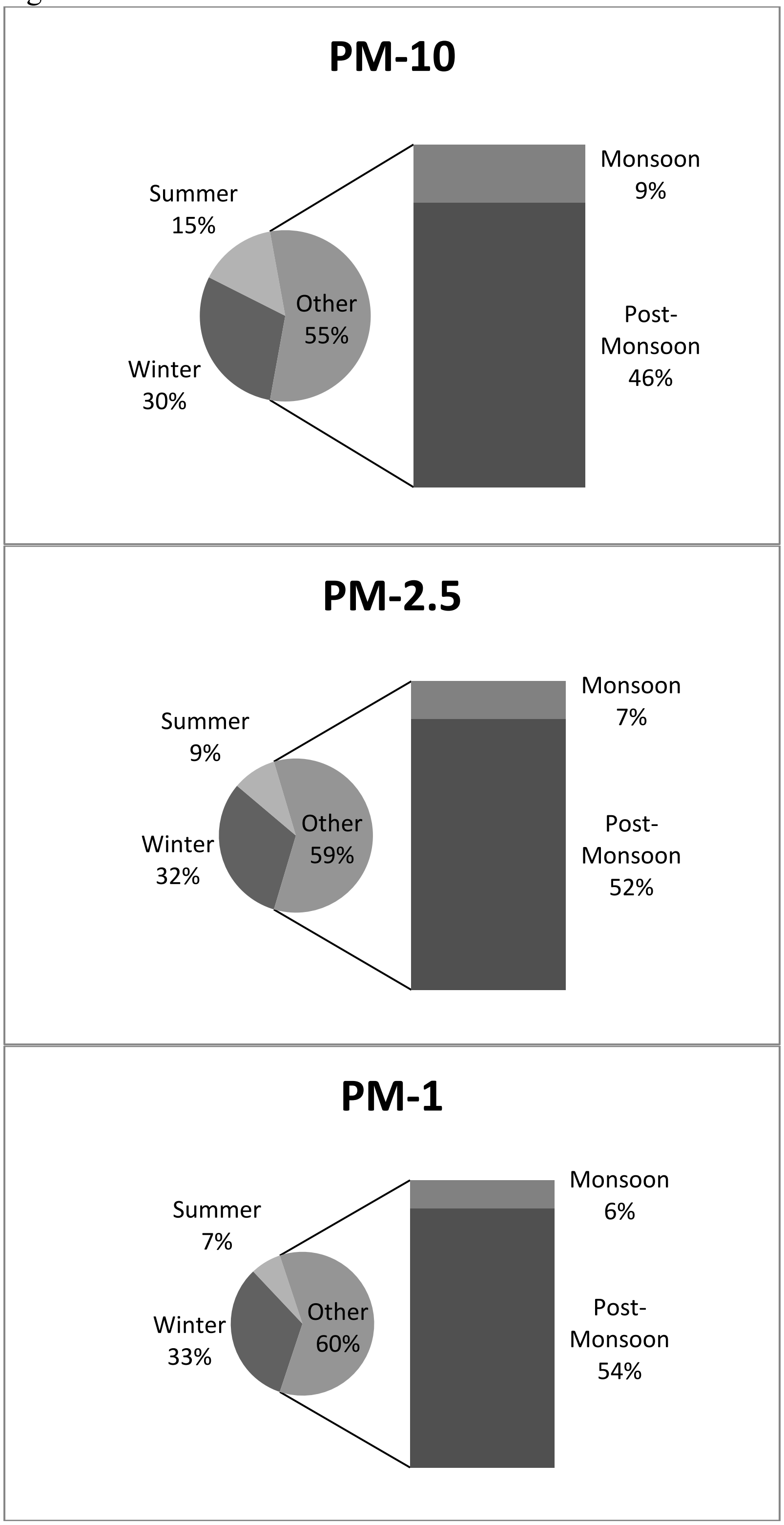
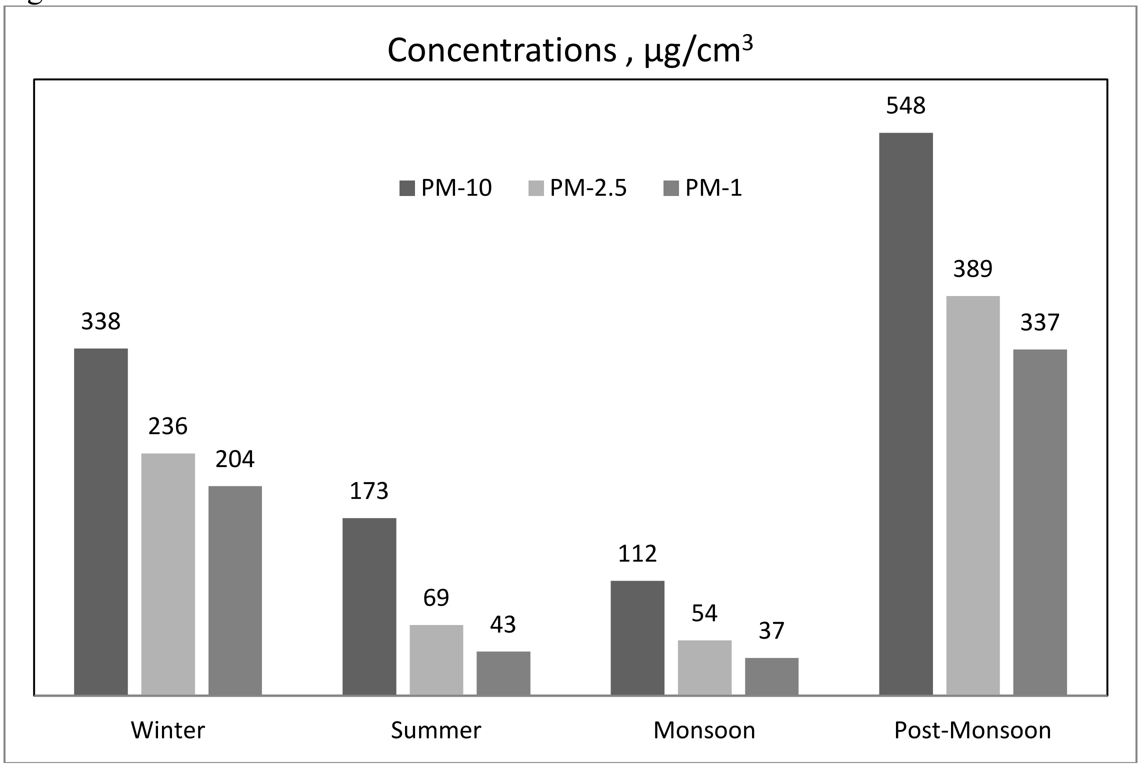

PM-10
Summer 15%
Winter 30%
Other 55%
Monsoon 9%
Post-Monsoon 46%
PM-2.5
Summer 9%
Winter 32%
Other 59%
Monsoon 7%
Post-Monsoon 52%
PM-1
Summer 7%
Winter 33%
Other 60%
Monsoon 6%
Post-Monsoon 54%

Figure 7


Concentrations , µg/cm3
PM-10
PM-2.5
PM-1
338
236
204
173
69
43
112
54
37
548
389
337
Winter
Summer
Monsoon
Post-Monsoon

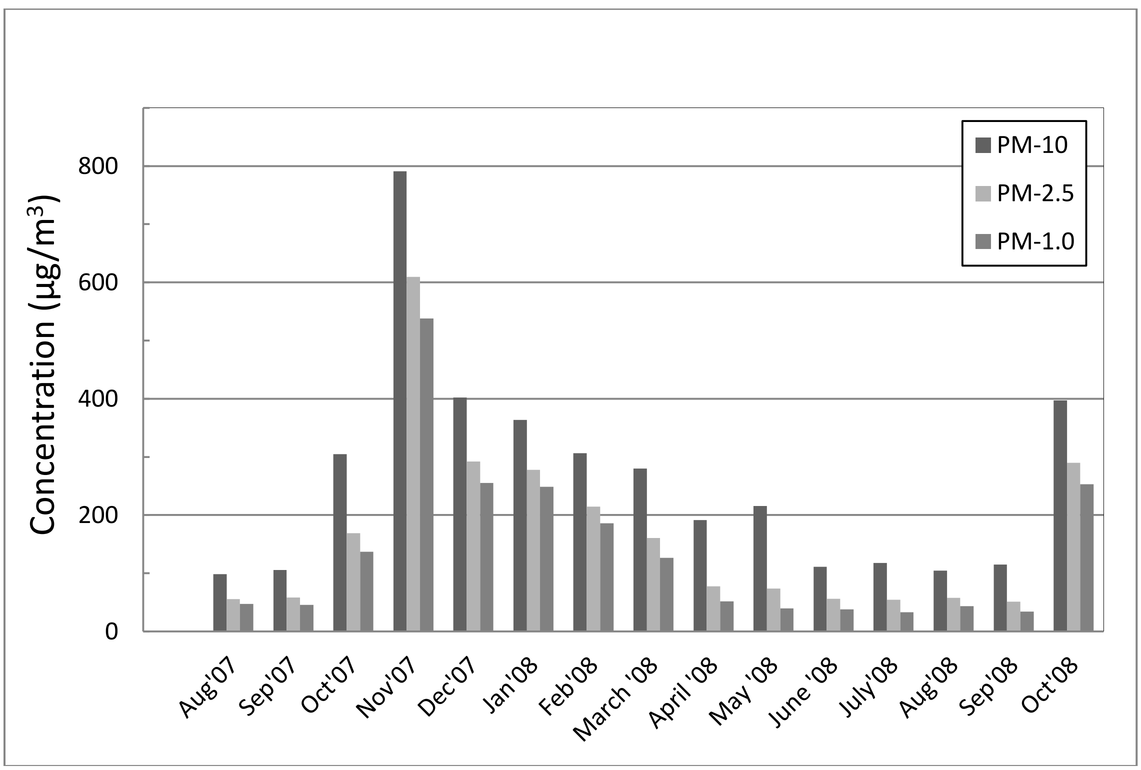
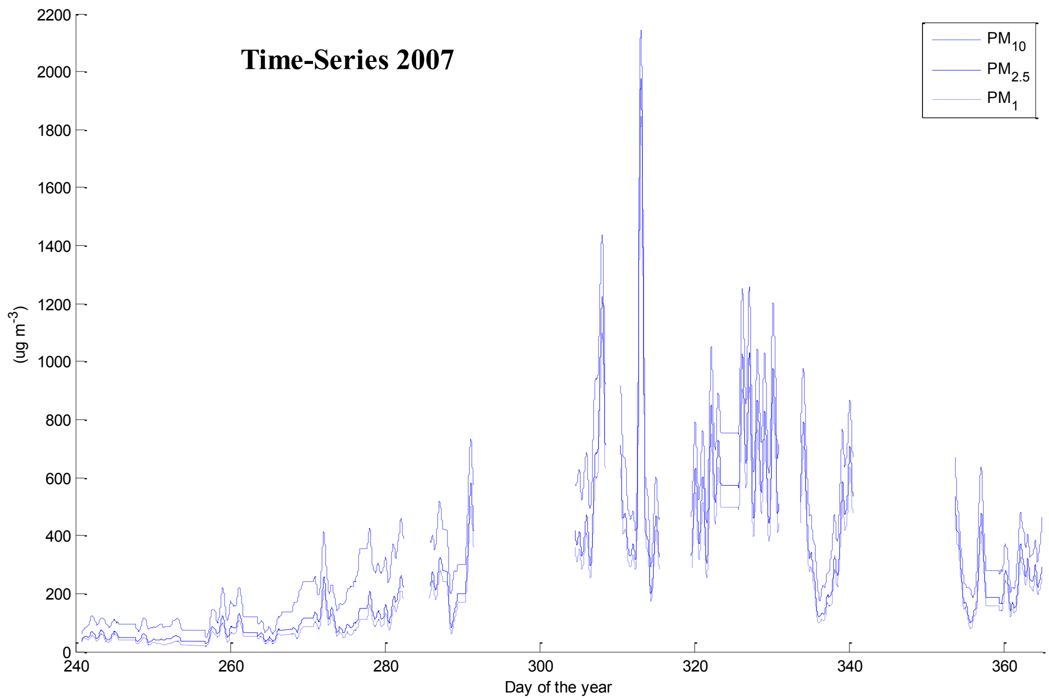

Concentration (µg/m3)
800
600
400
200
0
PM-10
PM-2.5
PM-1.0
Aug'07
Sep'07
Oct'07
Nov'07
Dec'07
Jan'08
Feb'08
March '08
April '08
May '08
June '08
July'08
Aug'08
Sep'08
Oct'08

Figure 8 (a)


Time-Series 2007
PM10
PM2.5
PM1
(ug m-3)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
240
260
280
300
320
340
360
Day of the year

(b)

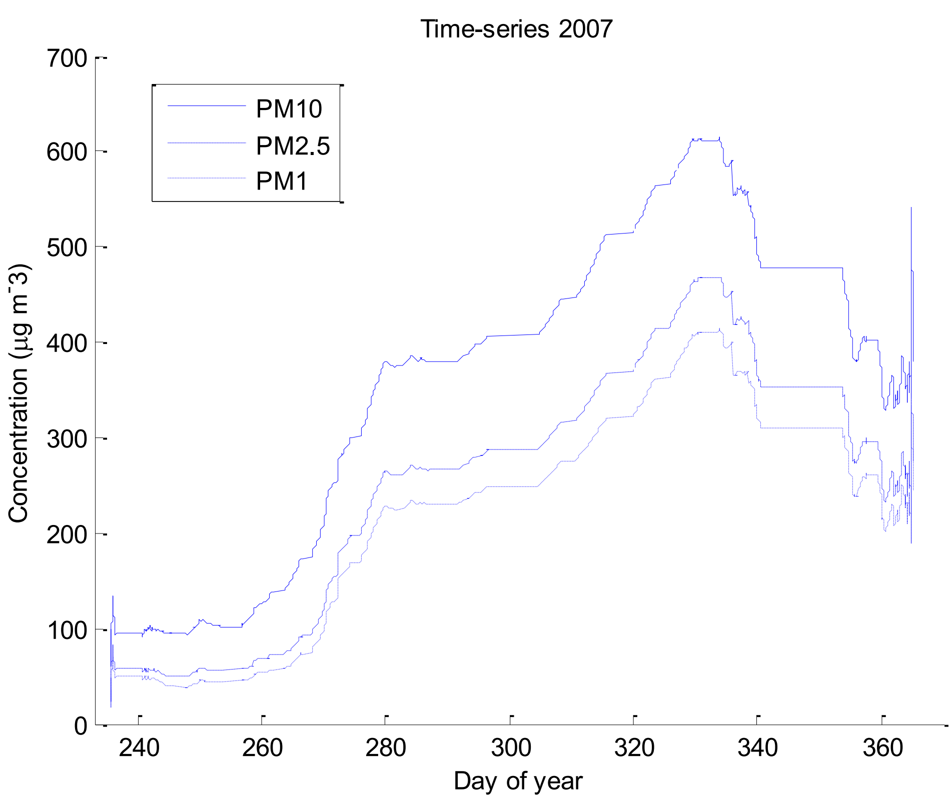
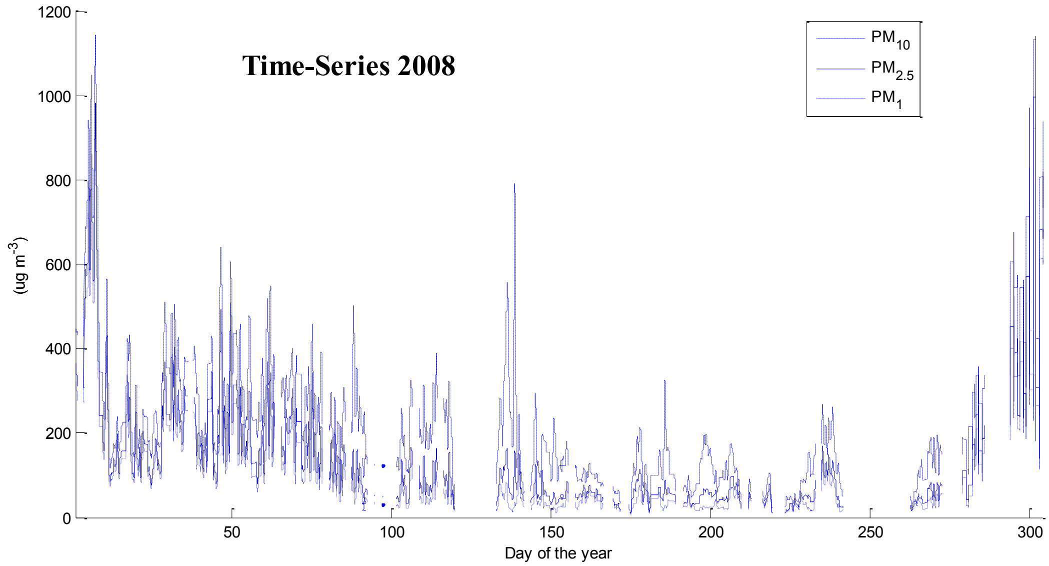
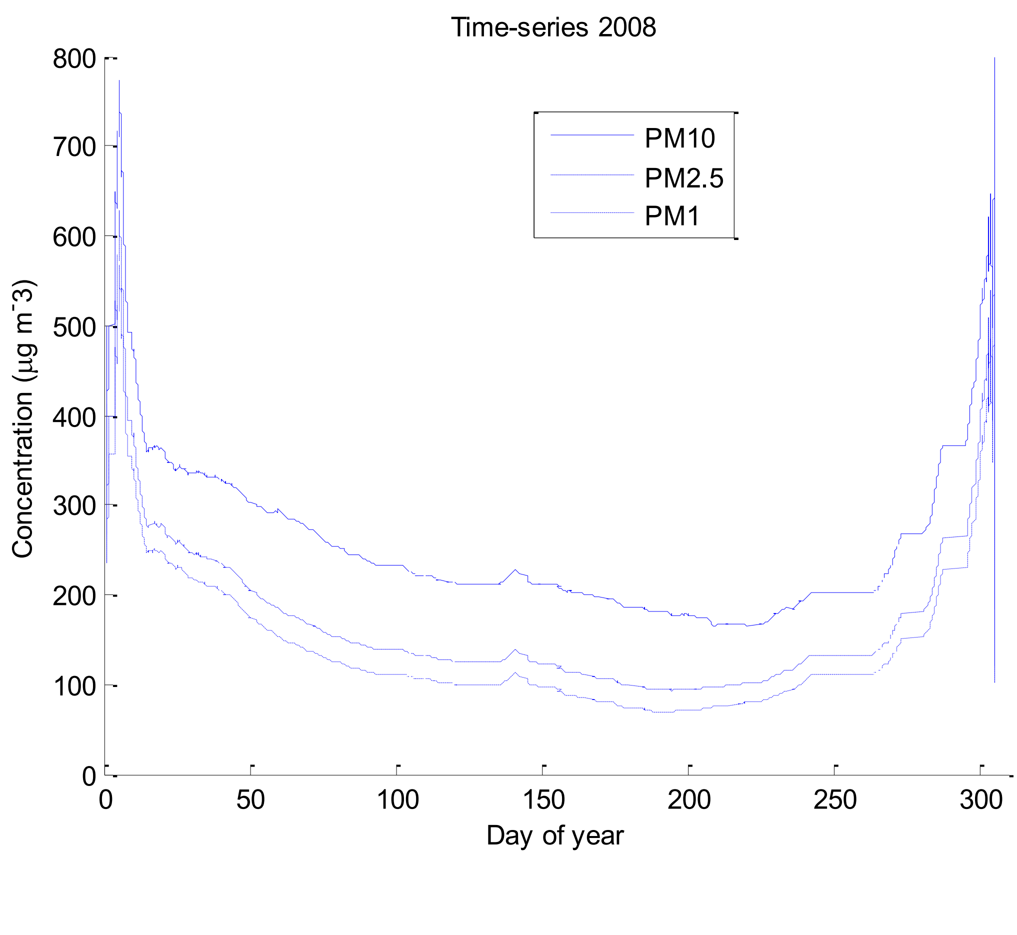

Time-series 2007
PM10
PM2.5
PM1
Concentration (µg m-3)
0
100
200
300
400
500
600
700
240
260
280
300
320
340
360
Day of year

Figure 9 (a)



Time-Series 2008
1200
1000
800
600
400
200
0
(ug m-3)
50
100
150
200
250
300
Day of the year
PM10
PM2.5
PM1

(b)



Time-series 2008
800
700
600
500
400
300
200
100
0
Concentration (µg m-3)
0
50
100
150
200
250
300
Day of year
PM10
PM2.5
PM1