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Analysis and interpretation of particulate matter – PM_{10} , $PM_{2.5}$ and PM_1 emissions from the heterogeneous traffic near an urban roadway

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ABSTRACT

This paper presents analysis and interpretation of diurnal, weekly and seasonal cycles of 1–h average particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) concentrations measured near an urban roadway in Chennai city, India, between November 2007 and May 2008. The PM data analysis showed clear diurnal, weekly and seasonal cycles at the study site. In diurnal cycle, highest PM concentrations were observed during weekday's peak hour traffic and lowest PM concentrations were found during trickle traffic (afternoon and nighttime). The seasonal PM data analysis showed highest concentrations during post monsoon season (PM_{10} = 189, $PM_{2.5}$ = 84, PM_1 = 66 μg/m^3) compared to winter (PM_{10} = 135, $PM_{2.5}$ = 73, PM_1 = 59 μg/m^3) and summer (PM_{10} = 102, $PM_{2.5}$ = 50, PM_1 = 34 μg/m^3) seasons. The particle size distribution during post-monsoon, winter and summer seasons showed two distinct modes viz. accumulation (mean diameter, d = 2.2 μm; distribution = 40%) and coarse (d = 7.1 μm, distribution = 60%).

The frequency distribution of PM_{10} concentrations during post–monsoon and winter seasons indicated that the PM_{10} values at the study site fall under moderate to poor categories. During post–monsoon and winter seasons, it was found that more than 50% of the time the 24–h average PM_{10} concentrations were violating the Indian national ambient air quality standards (NAAQS) (100 μg/m^3) and world health organization (WHO) standard (50 μg/m^3). The 24–h average $PM_{2.5}$ concentrations were also exceeding the NAAQS (60 μg/m^3) and WHO standards (25 μg/m^3) by 75% of time, irrespective of seasons.

Keywords:
Particulate matter
Exhaust emissions
Heterogeneous traffic
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1. Introduction

The issue of urban air quality in particular particulate matter (PM) concentrations receiving more attention as an increasing share of the world's population lives in urban centers (UN, 2004). The traffic–generated emissions are accounting more than 50% of the total PM emissions in the urban areas (Wrobel et al., 2000). It is reported that, in London, UK, more than 80% of PM emission is from the road traffic (DoT, 2002) and in Athens, Greece, 66.5% is from the road traffic (Economopoulou and Economopoulos, 2002). At present, over 600 million people living in urban areas worldwide are being exposed to dangerous levels of traffic–generated air pollutants (Cacciola et al., 2002). About 30% of the respiratory diseases are related to personal exposure to high level ambient PM concentrations (WHO, 2000). At global scale, more than 0.5 million deaths per year are due to exposure to ambient PM concentrations (AQEG, 2005). In developed countries, PM emissions are mainly responsible for respiratory health problems (Yang, 2002; Shendell and Naeher, 2002; Wang et al., 2003). The main sources for ambient PM concentrations at urban roadways are vehicle exhausts, emissions from tyre and brake wear and re–suspension of road dust.

During recent years, India is experiencing unprecedented economy growth rate and rapid urbanization. The number of urban centers increased from 1 827 in the year 1901 to 5 161 in the year 2001 (UN, 2004). This resulted in expansion of city, increase in urban population, vehicular population, vehicle kilometer travelled (VKT), traffic congestion, large scale construction activity and unsystematic land usage (Datta, 2006). Brandon and Hommann (1995) have reported that the ambient air pollution levels in 36 major Indian cities were exceeding WHO standards. This study also revealed that 40 350 premature deaths, 19.8x10^6 hospital admissions and 1.20x10^6 incidences of minor sickness were related to exposure to high levels of air pollutant concentrations.

Recently, Chennai city has also been experiencing rapid urbanization and industrialization. In the year 1991, the total population of the city was 5.42 million which was increased to 6.42 million in the year 2001. The population density of the city in the year 2001 was 24 231 persons/km^2 (DoES, 2007). Vehicles are the major source of air pollution in city. It is estimated that, vehicular emissions contribute more than 300 tons/day of pollution load into the city atmosphere (CRRI, 2006). In recognition of the severity of the air pollution problem, Chennai has been designated as a non–attainment area by Central Pollution Control Board (CPCB), India. In particular, the PM levels in the city are increasing at an alarming rate. Therefore, there is an urgent need to prepare strategies to control the PM emissions in Chennai city.

In this paper, an attempt has been made to analyze and interpret the diurnal, weekly and seasonal cycles of coarse (PM_{10}) and fine particulate matter ($PM_{2.5}$ and PM_1) concentrations measured at an urban roadway having heterogeneous traffic flow-different categories of vehicles such as two–wheeler, three–wheeler, four–wheeler light–duty, four–wheeler heavy–duty, and slow moving vehicles are moving in the same lane constituting mixed traffic conditions. The impact of meteorology on diurnal, weekly and seasonal cycles of PM_{10}, $PM_{2.5}$ and PM_1 concentrations is also discussed.

2. Materials and Methodology

2.1. Site description

Figure 1 shows the sampling location at the study area. The monitoring station is located at Sardar Patel road (SP road), which is one of the busiest roads in the Chennai city. The city is located on a flat eastern coastal plain (13°5′24″ North and 80°16′12″ East) having an average elevation of 6.7 m. It stretches (25.6 km length) over an area of 176 km^2 along the coast of Bay of Bengal. The monitoring site is surrounded by a number of primer educational and research institutes (Indian Institute of Technology Madras, Central Leather Research Institute, Central Polytechnic and Anna University, central and state government schools), cancer hospitals, tourist spots, residential areas, and commercial centers. As a result, this region is subjected to intense human activity and vehicular traffic.

2.2. Traffic data

A traffic census was conducted at the study region at 15–minute intervals for a period of 24–h on both weekday (Monday) and weekends (Saturday and Sunday). The vehicles were classified into seven groups viz., two–wheelers, three–wheelers (auto), cars, buses, carriers, mini carriages (MC) and lorries (Figure 2). Monday to Friday (weekdays) being the working days of the week, therefore, the traffic pattern is expected to be the same for working days and as such traffic volume count (TVC) was done on Monday only, which was assumed to be representative for the rest of the weekday TVCs. Since, most of the government, private offices located at the study region, Saturday and Sunday being holidays and some schools and colleges which are off only on Sundays. Therefore, TVCs were conducted for both Saturday and Sunday. Figure 2 shows the hourly variations of traffic flow at the study site. From the analysis it was found that during the weekdays (working days) traffic is dominated by the 2–wheelers (59%) followed by the cars (28%), autos (6%), buses (3%), carriers (2%), lorries (1%) and mini carriages (1%). During weekends, the use of cars at the study region has increased from 28 to 31% and 35% respectively, for Saturday and Sunday. Similarly, the use of auto's (3–wheelers) was also increased from 6% to 9% and 8%, respectively for Saturday and Sunday. The total number of vehicles plying on Monday, Saturday and Sunday were 169 254, 169 296, and 104 363, respectively. Further, we observed a marginal variation between the daily average traffic flow at SP road on Monday and Saturday.

2.3. PM measurements

The PM_{10}, $PM_{2.5}$, and PM_1 mass concentrations at the study site were monitored using environmental dusts monitor (GRIMM–107) for the three season's viz., post-monsoon (14–days during November to December 2007), winter (35–days during January to February 2008) and summer (90–days during March to May 2008). The Grimm dust monitor is a portable instrument designed to provide continuous concentrations of particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) suspended in the ambient air. The dust particles are measured by the physical principle of orthogonal light scattering. It is designed to measure particle size distribution and particle mass based on a light scattering measurement of individual particles in the sampled air. Each single particle is illuminated by a defined laser light and each scattering signal is detected at an angle of 90° by a photo diode. In accordance with Mie theory, each measured pulse height is directly proportional to the particle size. The particle diameter data are first converted to particle volume using the mean particle diameter between the thresholds of the 31 different channels (complete size distribution 0.25 to 32 µm) and assuming spherical particles. Then these volume data are converted to a mass distribution using density factor corresponding to the Grimm established "urban environment" factor. This factor has been verified with the EPA FRM results of several urban environments.

The dust monitor samples air at the rate of 1.2 liters/min with a lower cut–off at 0.25 µm. The instrument kept at a distance of about 6.5 meters from the SP road and the sampling inlet was placed at 1.2 m above the ground level. The PTFE–Teflon filter, 47 mm diameter, 0.2 micron size was used for PM sampling. Filters were changed once in 7–days. During the monitoring, the 1–minute average concentrations of PM_{10}, $PM_{2.5}$ and PM_1 were recorded on a data storage card. The 1–h and 24–h average concentrations were subsequently calculated from the 1–minute readings.

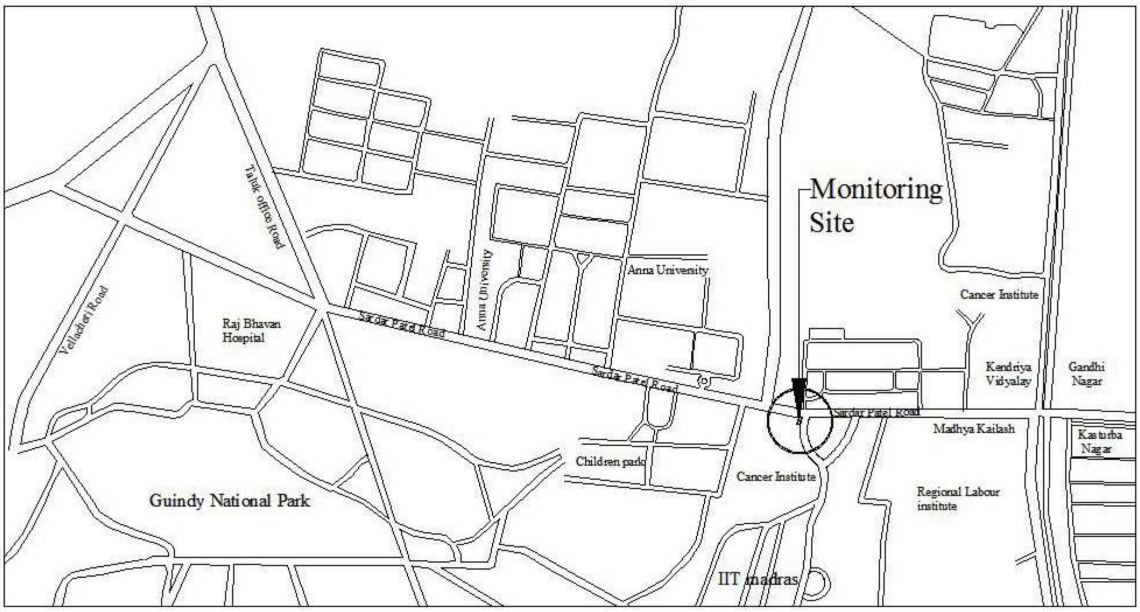

Figure 1. *Details of the study site in Chennai city.*

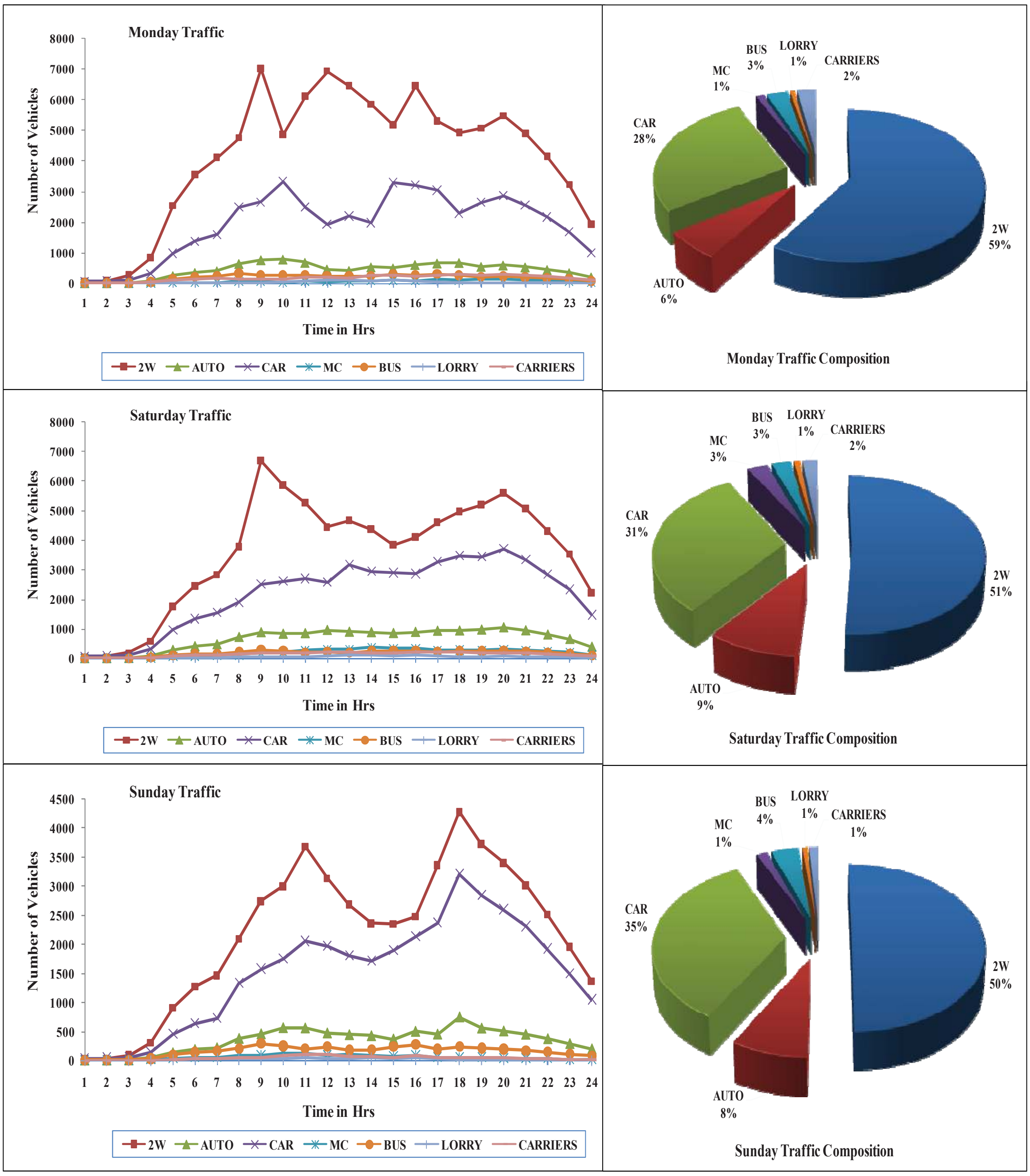

Figure 2. *Hourly variation of traffic count and traffic composition during weekday (Monday) and weekend (Saturday and Sunday) at the study site.*

2.4. Meteorological data

In order to study the impact of local meteorology on PM levels, meteorological parameters such as temperature, humidity, pressure, wind speed, and wind direction at the study region were collected from the Indian meteorological department, Chennai for the same study period (November 2007–May 2008), for which the PM concentrations were measured. The impact of meteorology on the particulate matter emissions is discussed in Section 3.4.

3. Results and Discussion

3.1. Diurnal variations of PM_{10}, $PM_{2.5}$ and PM_1 concentrations

Figure 3 provides the diurnal variations of PM_{10}, $PM_{2.5}$ and PM_1 concentrations versus the total vehicle count during weekdays and weekends at the study site for post–monsoon, winter and summer seasons, respectively. In the diurnal cycle, the 1–h PM concentration showed two peaks– one corresponding to the morning peak traffic flow i.e. between 8:00 am to 11:00 am; and another corresponding to evening peak traffic flow i.e. between 5:00 pm – 9:00 pm. The PM levels were considerably lower between 12:00 noon to 4:00 pm for all the three seasons because of low traffic volumes (and consequently low emission rates) and favorable dispersion conditions (increase in the mixing height). During nighttime, i.e. after 10:00 pm, the PM concentrations were significantly decreased because of trickle traffic flow (low emission rate). However, noticeable increases in PM_{10}, $PM_{2.5}$ and PM_1 concentrations were observed after 1:00 am (after midnight). The probable reason for this may be the built–up of particles under inversion conditions. Further, it was found that the nighttime PM concentrations were 0.5 times of morning peak hour PM concentrations. Gomiscek et al. (2004) have also reported a similar trend for three urban sites in Austria.

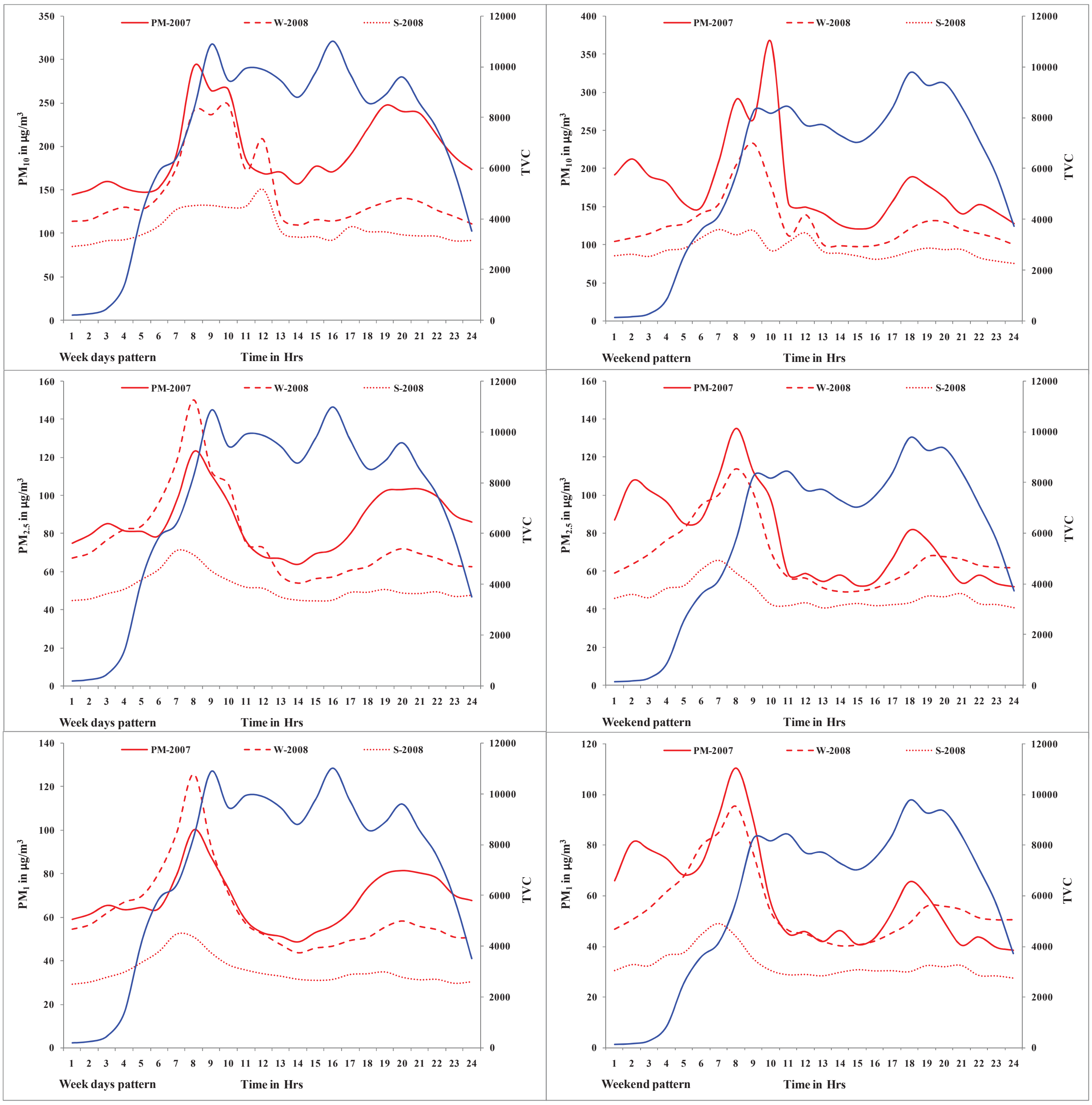

Figure 3. *Diurnal variation of traffic vehicle count and corresponding PM variations during weekdays and weekends at study site.*

Table 1 shows the correlation between PM_{10} with $PM_{2.5}$ and PM_1 concentrations during daytime (i.e., traffic flow hours, 6:00 am–10:00 pm) and nighttime (i.e., lean/trickle traffic flow hours, 10:00 pm–6:00 am) for post–monsoon, summer, and winter seasons. During traffic flow hours, the relationship between PM_{10} with $PM_{2.5}$ and PM_1 concentrations showed moderate correlation between coarse (PM_{10}) and fine particulates ($PM_{2.5}$ and PM_1) for post–monsoon season (R^2 = 0.56 for PM_{10} vs. $PM_{2.5}$; R^2 = 0.42 for PM_{10} vs. PM_1). However, for the lean traffic period of the same season, better correlations were observed between PM_{10} with $PM_{2.5}$ and PM_1 (R^2 = 0.77 for PM_{10} vs. $PM_{2.5}$; R^2 = 0.69 for PM_{10} vs. PM_1). The low R^2 value was found for the correlation between PM_{10} and PM_1 concentrations during traffic flow hours in the summer period. This might be because of frequent changes in meteorological conditions (i.e. dispersion conditions) and variations in emission rates during that period. High R^2 value has been found for the correlation between PM_{10} and PM_1 concentrations measured during 10:00 pm to 6:00 am (lean traffic flow hours) for all the three seasons.

3.2. Weekly variations of PM_{10}, $PM_{2.5}$ and PM_1 concentrations

The weekly variations of PM_{10}, $PM_{2.5}$ and PM_1 concentrations at the study region were shown in Figures 4 (a), (b) and (c), respectively for post–monsoon, summer and winter seasons. During post–monsoon season, the weekdays (corresponding to morning peak traffic flow), hourly average PM_{10}, $PM_{2.5}$ and PM_1 concentrations were varied between 148–292, 81–122 and 64–100 µg/m^3, while for weekend these values ranged between 150–290, 85–134 and 68–110 µg/m^3. In winter season, the weekday hourly average PM_{10}, $PM_{2.5}$ and PM_1 concentrations corresponding to the peak hour traffic varied between 127–248, 84–150 and 69–125 µg/m^3, respectively. The hourly average PM_{10}, $PM_{2.5}$ and PM_1 values for the weekend were between 127–232, 70–113 and 53–95 µg/m^3, respectively. It was observed that the difference between maximum and minimum PM concentrations of weekday and weekends were marginal. During the summer season, the weekday (PM_{10} = 98–132, $PM_{2.5}$ = 55–71 and PM_1 = 38–50 µg/m^3) and weekend (PM_{10} = 95–120, $PM_{2.5}$ = 42–65 and PM_1= 30–48 µg/m^3) PM concentrations were comparatively lower than those measured in other two seasons. This is mainly because of improved dispersion conditions (mixing height and wind speed) during that period. The low R^2 value for PM_{10} vs. $PM_{2.5}$ and PM_1 (Table 1) also indicates the improved dispersion conditions during summer season.

Further, it was observed that the hourly variation of average PM_{10} concentration between weekdays and weekends during post–monsoon and winter seasons was not significant when compared to summer season. The hourly $PM_{2.5}$ and PM_1 concentrations showed minimum values during weekends (Sunday) and maximum values during the middle of the week (Wednesday and Thursday). The variations of fine PM fractions ($PM_{2.5}$ and PM_1) during weekdays were significantly higher than weekends. This was probably because of the weekdays traffic movement at the study site that was significantly higher compared to weekends (Sunday) traffic. This is also typical for air pollutant concentrations influenced by vehicular emissions from urban roadways.

Table 1. *Correlation between PM_{10}, $PM_{2.5}$ and PM_1 concentrations*

Description	Seasonal	Best-fit equation	R^2	Diurnal Cycle	Best-fit equation	R^2
$PM_{2.5}$ vs. PM_{10}	Post Monsoon	Y=0.343x+19.17	0.54	Day Hours	Y=0.300x+24.40	0.56
				Night Hours	Y=0.676x-27.65	0.77
	Winter	Y=0.532x+1.28	0.76	Day Hours	Y=0.515x+0.86	0.75
				Night Hours	Y=0.300x-9.12	0.88
	Summer	Y=0.416x+7.48	0.74	Day Hours	Y=0.396x+8.44	0.72
				Night Hours	Y=0.553x-2.02	0.88
PM_1 vs. PM_{10}	Post Monsoon	Y=0.264x+15.88	0.43	Day Hours	Y=0.224x+21.70	0.42
				Night Hours	Y=0.554x-26.20	0.69
	Winter	Y=0.398x-5.44	0.68	Day Hours	Y=0.372x+6.94	0.66
				Night Hours	Y=0.573x-9.97	0.84
	Summer	Y=0.284x+5.38	0.59	Day Hours	Y=0.268x+6.56	0.56
				Night Hours	Y=0.383x-2.24	0.77
PM_1 vs. $PM_{2.5}$	Post Monsoon	Y=0.849x-5.44	0.97	Day Hours	Y=0.843x-4.74	0.97
				Night Hours	Y=0.856x-6.61	0.98
	Winter	Y=1.212x+1.40	0.92	Day Hours	Y=1.235x+0.20	0.906
				Night Hours	Y=1.153x+4.42	0.99
	Summer	Y=0.736x+2.426	0.93	Day Hours	Y=0.741x-2.44	0.93
				Night Hours	Y=0.717x-2.07	0.93

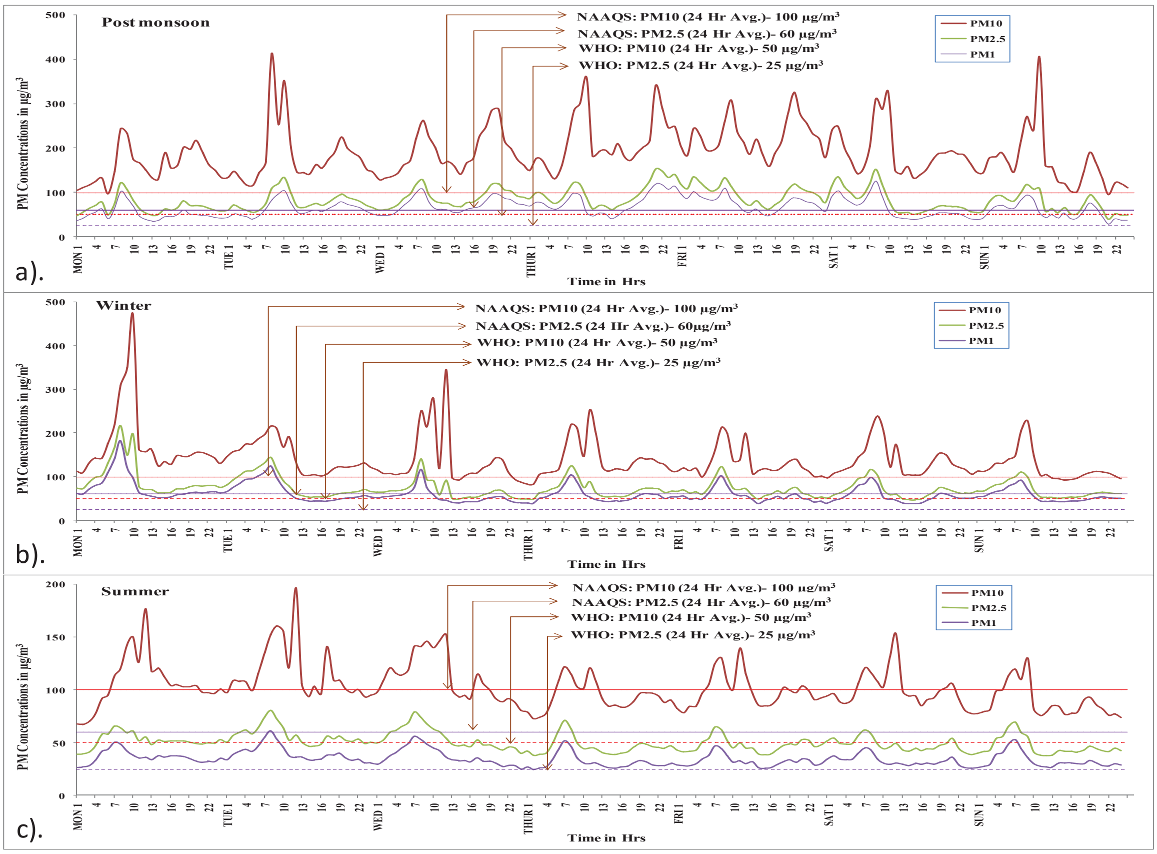

Figure 4. *Weekly cycles of average PM_{10}, $PM_{2.5}$ and PM_1 concentrations during (a) post–monsoon (b) winter and (c) summer seasons.*

The PM_{10}, $PM_{2.5}$ and PM_1 concentrations were typically higher during winter seasons due to prevailing inversion conditions trapping the pollutants. In particular, $PM_{2.5}$ and PM_1 concentrations were significantly higher during winter periods. This is because of poor dispersion conditions and suspension of fine particles in the ambient air for longer hours of the day due to vehicle movement. The variation of $PM_{2.5}$ and PM_1 concentrations during winter period were less pronounced than that of PM_{10} (i.e. the difference between minimum and maximum concentrations was marginal). Similar PM trend was reported in air quality–monitoring network program conducted from 1994 to 1999 at 14 sites in Taiwan (Yang, 2002). Lee et al. (2006) also observed a similar trend at a roadside in Hong Kong. Further, during this season, there were not much significant differences in the weekday or weekend PM concentrations. In summer, the variation in PM concentrations during the weekdays and weekend were significant (Table 1, R^2 = 0.59 for PM_{10} vs. PM_1). During summer, the atmosphere is highly unstable (turbulent) because of increased solar radiation, wind speed and frequent changes in wind directions. This also results in an increase in mixing height and so enhances the dispersion of PM emissions. Pohjola et al. (2002) reported the similar temporal variation of PM_{10} and $PM_{2.5}$ concentrations in the Helsinki metropolitan area. The weekly cycles at the study area were typical for urban areas that are strongly influenced by vehicular traffic.

3.3. Seasonal variations of PM_{10}, $PM_{2.5}$ and PM_1 concentrations

Table 2 summarizes the statistics of hourly average PM concentrations during post–monsoon, winter and summer seasons. The monitored data from November 2007 to May 2008 at the study site reveals a general trend of maximum during post–monsoon (November and December) as well as winter (January and February) periods and minimum during summer periods (March to May). During winter season, the daily average of PM_{10}, $PM_{2.5}$ and PM_1 concentrations were found to be in the ranges of 77–228, 36–148 and 28–109 µg/m^3, respectively. Whereas, it ranged between 147–259, 61–126 and 46–101 µg/m^3 and 29–171, 14–94 and 9–71 µg/m^3 during post–monsoon and summer seasons, respectively. Further, the computed 1–h average PM_{10} concentrations for post–monsoon, winter and summer seasons were found to be 189±71, 135±33 and 102±28 µg/m^3, respectively. These values were comparable with daily average PM concentrations calculated by gravimetric analysis of the particle mass collected on the PTFE filter (i.e. 179±38, 126±46 and 115±29 µg/m^3 for the post–monsoon, winter and summer seasons, respectively).

The standard deviation of the PM_{10}, $PM_{2.5}$ and PM_1 data during summer season was lower when compared to other two seasons. The higher standard deviation values for $PM_{2.5}$ (σ = 39.26) and PM_1 (σ = 31.15) during winter indicates the complex PM dispersion phenomena because of inversion conditions, suspension of fine particulates for longer hours of the day, low wind speed and built–up of particulate matter under favorable inversion conditions.

During post–monsoon season the ratios of $PM_{2.5}/PM_{10}$, PM_1/PM_{10} and $PM_1/PM_{2.5}$ were ranged between 0.17–0.72, 0.11–0.59 and 0.40–0.89, respectively. For winter and summer seasons, the corresponding ratios of $PM_{2.5}/PM_{10}$, PM_1/PM_{10} and $PM_1/PM_{2.5}$ were ranged between 0.17–0.84, 0.08–0.71, 0.39–0.93 and 0.10–0.76, 0.04–0.65, 0.25–0.88, respectively. From the analysis it was observed that, the upper limit of the $PM_{2.5}/PM_{10}$, and PM_1/PM_{10} ratios during winter season were slightly higher when compared to the post–monsoon and summer seasons. The mean $PM_{2.5}/PM_{10}$ and PM_1/PM_{10} ratios during winter season were also significantly higher when compared to other seasons. This may be because of the trapping of fine PM emissions due to poor dispersion conditions.

Table 2 also presents the statistics of PM_{10}, $PM_{2.5}$ and PM_1 concentrations during traffic flow hours (6:00 am–10:00 pm) and trickle traffic flow hours (10:00 pm–6:00 am) and their ratios for post–monsoon, winter and summer seasons. In general, it was found that, the average PM_{10} concentrations during 6:00 am to 10:00 pm were significantly higher when compared to concentrations during 10:00 pm to 6:00 am for all of the three seasons. This is clearly indicates that at the study area, PM concentrations strongly correlate with vehicular emission rates i.e., PM_{10} levels increase with increase in traffic flow (PM source emission rate) and it decreases in nighttime due to reduction in source emission rate (trickle traffic flow). The average $PM_{2.5}$ and PM_1 concentrations showed marginal variation between traffic flow hours (6:00 am to 10:00 pm) and trickle traffic flow hours (10:00 pm to 6:00 am). This is mainly because of the slower settling of fine particles. During daytime, considerable amount of PM mass is generated because of movement of vehicles (exhaust emissions and re–suspension of road dust). The PM emissions released during evening rush hours were accumulated (trapping of pollutants) in the ambient air because of inversion conditions. These PM concentrations are gradually reduced during nighttime and reach to minimum levels at midnight.

Further, the season–wise data analysis indicated that the proportion of fine particles is highest in post monsoon and winter seasons compared to summer season. Figure 5 presents the average particle size distribution during post–monsoon, winter and summer seasons. The particle size distribution follows two distinct modes one with lower range i.e. 5.0 < d < 0.82 µm (d_{mean} = 2.2 µm, distribution = 40%) where d is the average particle size of median diameter and other with higher range i.e. 11.0 < d < 5.0 µm (d_{mean}= 7.15 µm, distribution = 60%). These two peaks represent the characteristic sources of particles. Similar, bimodal distribution was observed by (Aceves and Grimalt, 1993; Michaud et al. 1996; Gokhale and Patil, 2004) for urban PM. In general, particulate matter in the atmosphere is present in three modes, i.e. nuclei, accumulation, and coarse. The nuclei (combustion particles from motor vehicles) and accumulation (combustion and photochemical smog particles) modes together constitute fine particles. The coarse particle mode mainly consists of airborne (windblown) dust, salt particles from sea spray, and mechanically generated particles.

Table 2. *Hourly average PM concentrations, PM ratios and standard deviations during post–monsoon, winter and summer seasons*

Description		PM_{10} (µg/m^3)	$PM_{2.5}$ (µg/m^3)	PM_1 (µg/m^3)	$PM_{2.5}/PM_{10}$	PM_1/PM_{10}	$PM_1/PM_{2.5}$
Post Monsoon	Entire season	188.75±71.29	83.91±33.19	65.81±28.49	0.45±0.10	0.35±0.10	0.77±0.07
	Day hours	199.26±75.82	84.36±30.38	66.41±25.98	0.43±0.09	0.34±0.09	0.78±0.05
	Night hours	163.22±51.06	82.81±39.30	64.34±33.89	0.50±0.11	0.38±0.12	0.76±0.09
Winter	Entire season	134.58±64.55	72.95±39.26	59.00±31.15	0.54±0.11	0.44±0.10	0.80±0.06
	Day hours	141.38±68.78	73.79±40.71	59.57±31.37	0.52±0.11	0.42±0.10	0.80±0.06
	Night hours	117.43±49.05	70.62±35.43	57.40±30.60	0.59±0.10	0.48±0.09	0.80±0.05
Summer	Entire season	102.12±53.73	49.89±26.01	34.20±19.85	0.49±0.09	0.34±0.09	0.68±0.09
	Day hours	108.62±57.73	51.53±26.96	35.74±20.72	0.48±0.09	0.33±0.09	0.69±0.09
	Night hours	91.21±39.88	48.48±23.44	32.70±17.41	0.53±0.08	0.36±0.08	0.67±0.08

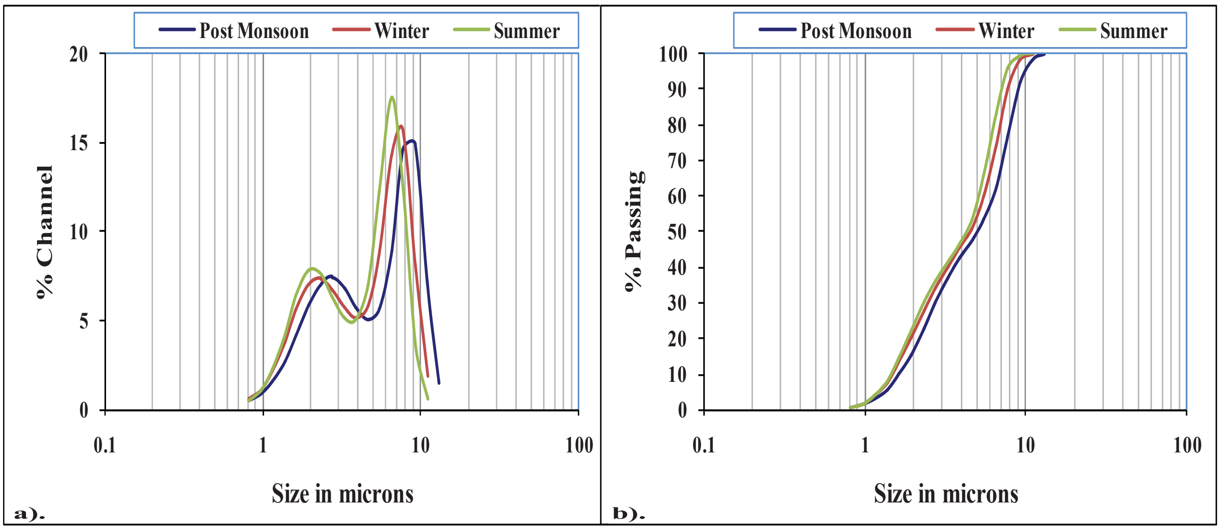

Figure 5. *Average particle size distribution plot **(a)** size vs. % channel **(b)** size vs. % passing. Note: % Passing– Cumulative values of each size of particles from 0 to 100 %; % Channel– Size distribution values for each size of particles.*

It was observed that there is slight shift in average lower and upper sizes of particles between post–monsoon, winter and summer seasons. In post–monsoon and winter periods the percentages of both accumulation and coarse mode particles were relatively higher than the summer period. During post–monsoon and winter season, the winds are blowing from east north east direction. Under these wind angles, the line source becomes perpendicular to the wind direction, which brings pollutants to the monitoring station located downwind.

3.4. Impact of meteorology on PM concentrations

The particulate matter concentration varies considerably with time, location and depending on meteorological conditions and source emissions rate (Beer, 2001; Elminir, 2005). Under poor meteorological conditions i.e. inversion conditions the PM concentrations may rise to several times higher than the normal level (Elminir, 2005). In order to study the impact of meteorology on PM levels, the local meteorological data collected form IMD for the same study period was analyzed.

Table 3 provides the details of the meteorological variables and their ranges during post–monsoon, winter, and summer seasons. The hourly average rainfall, humidity, pressure, temperature and wind speed in Chennai during post–monsoon, winter, and summer seasons were 0.4 mm, 74%, 1010 hPa, 26.3°C and 0.66 m/s; 0.08 mm, 71%, 1010.5 hPa, 26.7°C and 0.78 m/s; 0.16 mm, 67%, 1005 hPa, 30.5°C and 1.11 m/s, respectively.

Table 3. *Season wise minimum, maximum and average values of the meteorological parameters*

Description		Temperature (°C)	Pressure (hPa)	Wind Speed (m/sec)	Humidity (%)	Rainfall mm (Hourly)
Post Monsoon	*MIN*	20.20	1 004.30	Calm	28	0.00
	MAX	32.20	1 015.10	6.23	98	38.10
	AVG	26.26	1 010.01	0.66	74	0.40
Winter	*MIN*	20.60	1 004.30	Calm	41	0.00
	MAX	32.60	1 016.50	5.35	95	16.50
	AVG	26.77	1 010.50	0.78	71	0.08
Summer	*MIN*	22.50	997.90	Calm	17	0.00
	MAX	42.00	1 013.40	6.23	96	36.30
	AVG	30.46	1 005.26	1.12	67	0.16

Figures 6 (a), (b) and (c) presents the wind rose diagrams for post–monsoon, winter and summer seasons, respectively. During winter, air masses flow from ENE, whereas, wind direction fluctuates during post–monsoon and summer between NW to SE and E to SW directions.

Figures 7 (a), (b) and (c) present the weekly cycles PM_{10}, $PM_{2.5}$, and PM_1 concentrations versus corresponding wind direction during post–monsoon, winter, and summer seasons, respectively. During post–monsoon and winter seasons predominant wind direction was found to be ENE with the average PM_{10}, $PM_{2.5}$ and PM_1 concentrations of 177, 70 and 53 µg/m^3 and 117, 58 and 47 µg/m^3, respectively. In summer season wind was from SE direction with the average PM_{10}, $PM_{2.5}$ and PM_1 concentrations of 89, 43 and 28 µg/m^3, respectively. The maximum 1–h average PM_{10}, $PM_{2.5}$ and PM_1 concentrations observed corresponding to the predominant wind directions of the post–monsoon, winter and summer seasons were 529, 211 and 175 µg/m^3; 315, 153 and 122 µg/m^3; and 426, 104 and 59 µg/m^3, respectively.

The wind speed was found to be low during winter and post–monsoon seasons and gradually increased during summer. The average wind speeds during post–monsoon winter and summer were 0.66, 0.77, and 1.11 m/sec, respectively. Frequent changes in wind speed and direction increased the atmospheric turbulence during summer months, thereby increasing the dispersion of PM emissions. In Chennai, the mixing height, wind speed and temperature are lower in winter than summer and post–monsoon seasons. Further, in winter months, winds are relatively calm (wind speed is less than 0.27 m/s). These prevailing calm conditions favored more stable atmospheric conditions, consequently reducing the dispersion of particulate matter. Thus, meteorological conditions in winter months resulted in higher PM levels in Chennai. In summer months, the increase in wind speed and temperature bring down PM concentrations remarkably.

Figure 8 (a), (b) and (c) presents the weekly cycles PM_{10}, $PM_{2.5}$ and PM_1 concentrations versus corresponding wind speed during post–monsoon, winter and summer seasons, respectively. These figures clearly indicate that, PM concentrations were inversely proportional to the wind speed, i.e. PM concentration increases with decreasing wind speed. During winter season, calm conditions were observed between 1:00 am–8:00 am on all the days. The calm periods coupled with the low temperatures develop stagnant weather conditions (inversions). As a result, the PM concentrations of the atmosphere increased significantly (Figure 8b). For example the maximum PM concentration of 471 µg/m^3 was observed on Monday at 8:00 am during winter period. During that period, the corresponding meteorological parameters such as the ambient temperature was slightly lower (22.9°C), pressure was higher (1013.4 hPa), and on the average wind speed is less than < 0.28 m/s (calm condition). All these parameters are favorable for increase of ground level PM concentrations (Table 1). The mean $PM_{2.5}/PM_{10}$, and PM_1/PM_{10} ratios during this season were also significantly higher compared to other seasons.

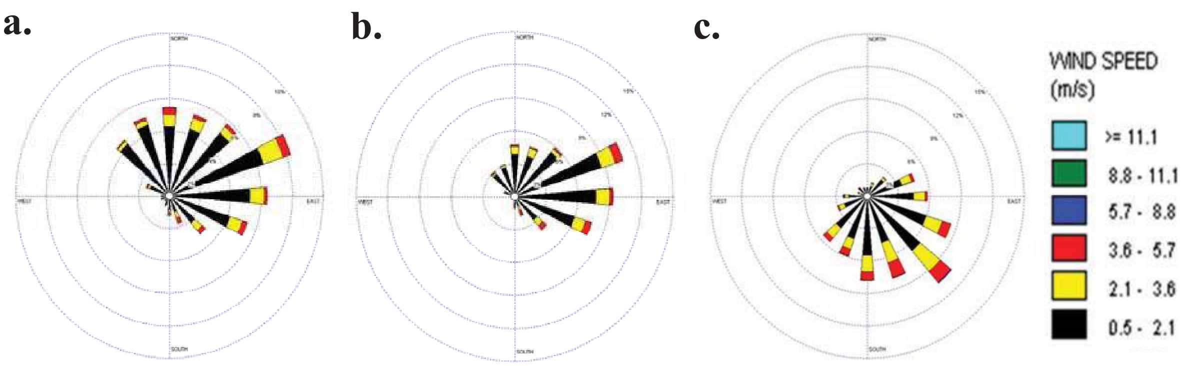

Figure 6. *The wind-rose diagrams for the (a) post-monsoon, (b) winter and (c) summer seasons.*

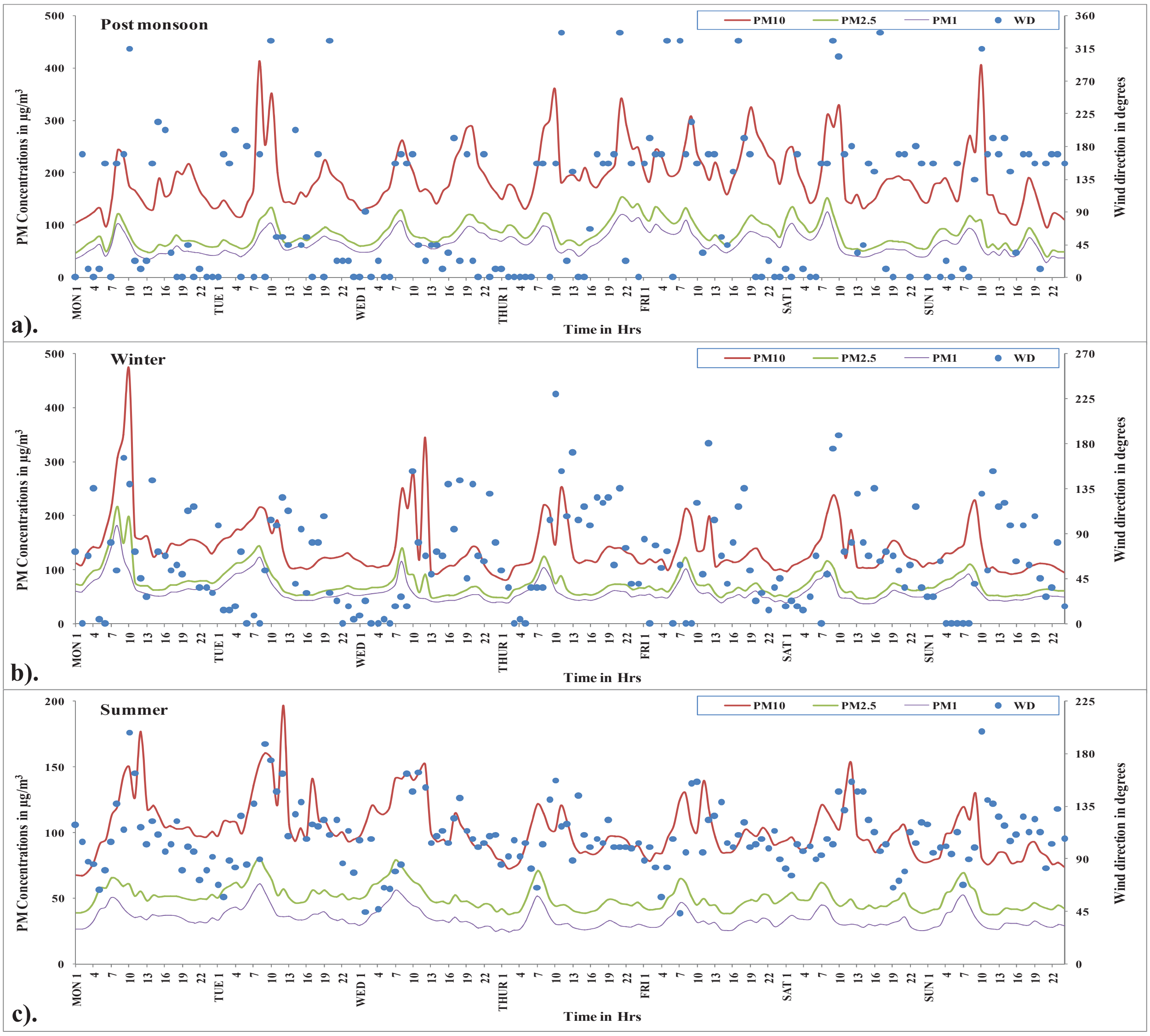

Figure 7. *Weekly cycles of (a) PM_{10}, (b) $PM_{2.5}$, and (c) PM_1 concentrations versus wind direction during post–monsoon, winter and summer seasons of the year 2007–2008.*

Figure 8. *Weekly cycles of* ***(a)*** *PM_{10},* ***(b)*** *$PM_{2.5}$, and* ***(c)*** *PM_1 concentrations versus wind speed during post–monsoon, winter and summer seasons of the year 2007-2008.*

3.5. Comparative assessment of PM concentrations

Figure 9 presents the frequency distribution of PM_{10}, $PM_{2.5}$ and PM_1 concentrations for post–monsoon, winter and summer seasons. The daily PM_{10}, $PM_{2.5}$ and PM_1 concentrations of all the three seasons were divided into six ranges (i.e., 0–25, 25–50, 50–100, 100–200, 200–300 and > 300 μg/m^3). The daily PM_{10} values were compared with the Indian air quality reference values for PM_{10} concentrations in the range of 0 to 100 as good, 100 to 200 as moderate, 200 to 300 as poor and above 300 as very poor or severe categories.

The frequency distribution of PM_{10} concentrations for post–monsoon season indicated that 60% of the time the PM values fall under the category of moderate while 26% of the time they fall under the poor category. Similarly, for winter, PM_{10} concentrations fall under the category of moderate to poor and during summer, about 58% of the PM_{10} concentrations fall under the good category. This shows that there is a significant improvement in the air quality during summer at the study area. The frequency distribution of $PM_{2.5}$ concentrations during post–monsoon and winter seasons indicates that the $PM_{2.5}$ values fall under the range of 50–100 μg/m^3. Similar to PM_{10} concentrations, the $PM_{2.5}$ values during summer season mainly fall under the lower ranges of 0–25 and 25–50 μg/m^3 due to better dispersion conditions.

The air quality through November 2007 to May 2008 at the study site was assessed by comparing observed 24–h average PM_{10}, $PM_{2.5}$ and PM_1 concentrations with NAAQS and WHO standards. According to PM_{10} standards set by the CPCB and WHO, the 24–h average values should not exceed 100 μg/m^3 and 50 μg/m^3, respectively. The season–wise data analysis indicated that more than 50% of the time the 24–h average PM_{10} concentrations were violating the Indian national ambient air quality standards (NAAQS) (100 μg/m^3) and world health organization (WHO) standard (50 μg/m^3). The NAAQS values specified for both PM_{10} and $PM_{2.5}$ are applicable to industrial, residential, rural, ecologically sensitive areas and other areas including traffic sites. Further, the 24–hour average $PM_{2.5}$ concentrations were also exceeding the NAAQS (60 μg/m^3) and WHO standards (25 μg/m^3) by 75% of time, irrespective of seasons.

4. Conclusions

In the present study, the diurnal, weekly and seasonal cycles of PM_{10}, $PM_{2.5}$ and PM_1 concentrations emitted from heterogeneous traffic in Chennai city was investigated. The analysis of PM

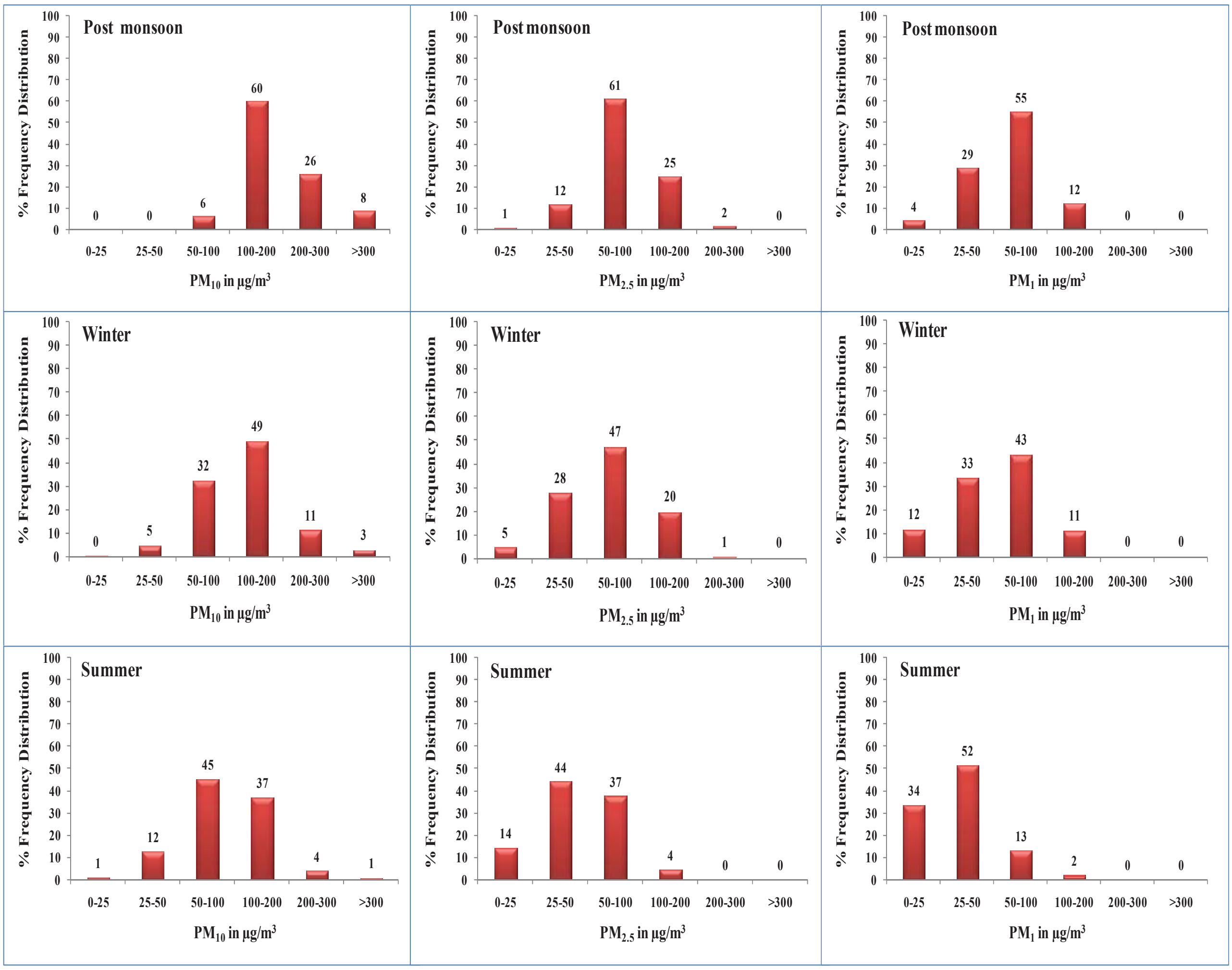

Figure 9. *Frequency distribution of PM_{10}, $PM_{2.5}$ and PM_1 concentrations during post–monsoon, winter and summer seasons.*

concentrations measured between November 2007 and May 2008 near an urban roadway showed clear diurnal, weekly and seasonal cycles. In the diurnal cycle, two PM peaks were corresponded to morning and evening rush hour traffic. High level PM concentrations were observed during weekday's peak hour traffic flow. Post–monsoon and winter period showed maximum PM concentrations near the urban roadway due to poor dispersion conditions (inversions). High proportion of fine particles was observed during post–monsoon and winter seasons compared to summer season. The relationship between $PM_{2.5}$ with PM_1 and PM_{10} with $PM_{2.5}$ concentrations showed good correlations. The significant correlation between $PM_{2.5}$ and PM_{10} indicates the traffic related emissions are the main sources of emissions at the study site.

The frequency distribution of PM_{10} concentrations during post–monsoon and winter seasons fall under the category of moderate to poor. During summer, it falls under the category of good. The assessment of 24–h average PM concentrations showed exceedances of the standards specified by CPCB and WHO. More than 50% of the time the 24–h average PM_{10} concentrations were violating the NAAQS (100 µg/m^3) and the WHO standard (50 µg/m^3). The 24–hour average $PM_{2.5}$ concentrations were also exceeding the NAAQS (60 µg/m^3) and WHO standards (25 µg/m^3) by 75% of the time, irrespective of seasons. The high levels of PM_{10} and $PM_{2.5}$ concentrations in the ambient air raise concerns about adverse health effects at the study region.

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References

Aceves, M., Grimalt, J.O., 1993. Seasonally dependent size distributions of aliphatic and polycyclic aromatic hydrocarbons in urban aerosols from densely populated areas. *Environmental Science and Technology* 27, 2896–2908.

Air Quality Expert Group (AQEG), 2005. Particulate Matter in the United Kingdom-Summary, Department for the Environment, Food and Rural Affairs, Nobel House, 17 Smith Square, London.

Beer, T., 2001. Air Quality as a Meteorological Hazard. *Natural Hazards* 23, 157–169.

Brandon, C., Hommann, K., 1995. The cost of inaction: valuing the economy-wide cost of environmental degradation in India. United Nations University, Proceedings of the Symposium on Global Sustainability, Tokyo.

Cacciola, R.R., Sarva, M., Polosa, R., 2002. Adverse respiratory effects and allergic susceptibility in relation to particulate air pollution: flirting with disaster. *Allergy* 57, 281–286.

Central Road Research Institute (CRRI), 2006. Annual report, Government of India, New Delhi.

Datta, P., 2006. Urbanization in India, Regional and Sub-Regional Population Dynamic Population Process in Urban Areas. European Population Conference, 21-24 June, 2006.

Department of Economics and Statistics (DoES), 2007. Statistical Hand Book of Tamil Nadu, Government of Tamil Nadu, India.

Department of Transport (DoT) (UK), 2002. Sources of Particulate Matter in Urban Areas: TRAMAQ Project UG 250.

Economopoulou, A.A, Economopoulos, A.P., 2002. Air pollution in Athens Basin and health risk assessment. *Environmental Monitoring and Assessment* 80, 277–299.

Elminir, H.K., 2005. Dependence of urban air pollutants on meteorology. *Science of the Total Environment* 350, 225– 237.

Gokhale, S.B., Patil, R.S., 2004. Size distribution of aerosols (PM_{10}) and lead (Pb) near traffic intersections in Mumbai (India). *Environmental Monitoring and Assessment* 95, 311–324.

Gomiscek, B., Hauck, H., Stopper, S., Preining, O., 2004. Spatial and temporal variations of PM_1, $PM_{2.5}$, PM_{10} and particle number concentration during the AUPHEP-project. *Atmospheric Environment* 38, 3917–3934.

Lee, S.C., Cheng, Y., Ho, K.F., Cao, J.J., Louie, P.K.K., Chow, J.C., Watson, J. G., 2006. $PM_{1.0}$ and $PM_{2.5}$ characteristics in the roadside environment of Hong Kong. *Aerosol Science and Technology* 40, 157–165.

Michaud, D., Baril, M., Dion, C., Perrault, G., 1996. Characterization of airborne dust from two nonferrous foundries by physico-chemical methods and multivariate statistical analysis. *Journal of the Air and Waste Management Association* 46, 450–457.

Pohjola, M.A., Kousa, A., Kukkonen, J., Harkonen, J., Karppinen, A., Aarnio, P., Koskentalo, T., 2002. The spatial and temporal variation of measured urban PM_{10} and $PM_{2.5}$ in the Helsinki metropolitan area. *Water, Air, and Soil Pollution:Focus* 2, 189–201.

Shendell, D.G., Naeher, L.P. 2002. A pilot study to assess ground-level ambient air concentrations of fine particles and carbon monoxide in urban Guatemala. *Environment International* 28, 375–382.

United Nations (UN), 2004. World Urbanization Prospects: The 2003 Revision, ST/ESA/SER.A/237. Department of Economic and Social Affairs, Population Division, New York.

Wang, G., Wang, H., Yu, Y., Gao, S., Feng, J., Gao, S., Wang, L., 2003. Chemical characterization of water-soluble components of PM_{10} and $PM_{2.5}$ atmospheric aerosols in five locations of Nanjing, China. *Atmospheric Environment* 37, 2893–2902.

World Health Organization (WHO), 2000. Air Quality Guidelines for Europe. WHO Regional Publications, European Series No. 91, WHO Regional Office for Europe, Copenhagen.

Wrobel, A., Rokita, E., Maenhaut, W., 2000. Transport of traffic-related aerosols in urban areas. *Science of the Total Environment* 257, 199–211.

Yang, K.L., 2002. Spatial and seasonal variation of PM10 mass concentrations in Taiwan. *Atmospheric Environment* 36, 3403–3411.