



Atmospheric Particulate Pollutants and their Relationship with Meteorology in Ahmedabad

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ABSTRACT

Urban air pollution is rapidly becoming an environmental problem of public concern worldwide. It can influence public health and local/regional weather and climate. In the present study, airborne particulate pollutants data were collected for a period of 4 years (2005–2008) at 13 locations in Ahmedabad, a mega city in Gujarat State in western India. The particulate pollutants data were collected by the Gujarat Pollution Control Board with respirable dust samplers (RDSs). The observed Suspended Particulate Matter (SPM) concentrations varied from 66.0 to 786.0 $\mu\text{g}/\text{m}^3$, and concentrations of Particulate Matter of aerodynamic diameters less than 10 microns (PM_{10}) ranged between 17.0 to 327.0 $\mu\text{g}/\text{m}^3$. The seasonal- and annual-average concentrations of the two pollutants were mostly above Indian air quality standards and were generally comparable with those observed in most other Indian urban areas. During this study period, there was a continuous decrease of particulate pollutants concentrations within Ahmedabad; however, the concentrations were just above the permissible limits set by the Central Pollution Control Board (CPCB). These particulate pollutants concentrations were compared with meteorological variables such as rainfall, humidity, temperature, and wind speed. Both SPM and PM_{10} showed significant negative correlations with rainfall. An Air Quality Index (AQI) was calculated for all stations for all months. AQI values varied from 25 to 193.3. AQI was high in summer season and low in monsoon season. AQI values varied from Good (0–50) to Hazardous (300–500). On the basis of the AQI scale, it is found that the atmospheric environment of Ahmedabad is moderately polluted to unhealthy range.

Keywords: Urban air pollution; Particulate pollutants; Meteorological variables; Air Quality Index; Statistical analysis.

INTRODUCTION

The origin of urban air pollution is mainly in anthropogenic emission sources, which include automobiles, industries, and domestic fuel combustion. In arid and semi-arid regions, deserts contribute to urban air pollution as does the sea in coastal regions. The air pollutants so generated are detrimental to human health. In addition, they cause negative impacts directly or indirectly, if at elevated concentrations, on vegetation, animal life, buildings and monuments, weather and climate, and on the aesthetic quality of the environment (Stern, 1976; Godish, 1985; Takemura *et al.*, 2007; Shen *et al.*, 2009). Rates of increase of air pollutant concentrations in developing countries such as India are higher than those in developed countries and hence atmospheric pollution is often severe in cities of developing countries all over the world (Mage *et al.*, 1996).

In recent years in Asian countries with monsoonal

climates, such as India and China, the aerosol problem has become increasingly acute due to increased loadings of atmospheric pollutants from increasing vehicular and industrial emissions as well as from increasing energy demands associated with a rapid pace of industrialization and increasing energy demands for domestic uses. (Srivastava *et al.*, 2008; Tsang *et al.*, 2008; Zhang *et al.*, 2008). On the other hand, sustainable development in the Asian monsoon countries depends on the monsoons (Lua *et al.*, 2008; Li *et al.*, 2009). It is well recognized that pollution problems are exacerbated by stable atmospheric conditions, such as subsidence and formation of inversion layers during the dry pre-monsoon season, or during monsoon break periods. During the monsoon season, heavy rain can wash out aerosols and clean the air. Recent studies have suggested that aerosols in the atmosphere can also affect the monsoon water cycle by significantly altering the energy balance in the atmosphere and at the surface (Ramanathan *et al.*, 2001; Li, 2004) and by modulating cloud and rainfall processes (Rosenfeld, 2000; Menon *et al.*, 2002; Ramanathan *et al.*, 2005; Lau and Kim, 2006).

The Indian subcontinent experiences tropical and subtropical climatic conditions resulting in extreme

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temperatures, rainfall, and relative humidity. These features introduce large variability in aerosol characteristics on a range of spatial and temporal scales over India (Ramachandran, 2007). Atmospheric particulate matter is the major air pollutant in India. In many Indian cities, the levels of particulate pollutants in the ambient air have been found to be above the permissible limit (Meenakshi and Saseetharan, 2003). Ahmedabad is a mega city (human population over 5 million) in Gujarat State in western India. The urban climate and air pollution of Ahmedabad are connected in several ways. Apart from topography, climatic parameters such as stability of the near-surface atmosphere, wind direction, and wind speed govern the dispersion of air pollution. Understanding the interaction between air pollution and meteorology can be a valuable tool for urban planners to mitigate negative effects of air pollution. In the present study, the levels of particulate air pollutants were measured at 13 stations within Ahmedabad and these particulate pollutants concentrations were statistically compared with meteorological variables such as rainfall, temperature, humidity and wind speed. The results of this study will be very useful to understand the role of particulate pollutants such as PM₁₀ (Particulate Matter less than 10 microns in aerodynamic diameter) and SPM (Suspended Particulate Matter) in urban weather and climate variability and changes. PM₁₀ is a particle whose diameter is less than 10 microns that include both fine and coarse dust particles. Particles less than 100 micrometers in diameter that are suspended in the air are referred to as suspended particulates matter (SPM). So, naturally PM₁₀ is a constituent of SPM.

This paper is organised as follows. Data and analysis techniques, including the geography of the study area, the data collection method, data processing, and analytical techniques are described in section 2. Annual, seasonal and monthly variations along with the role of meteorology; and a comparison of the results for Ahmedabad with other locations in India are described in section 3. Air Quality Index (AQI) results are described in section 4. Major conclusions are presented in section 5.

DATA AND ANALYSIS TECHNIQUES

Ahmedabad is located at 72.35°E longitude and 23.02°N latitude in western India at an elevation of 53 meters (174 ft). The city is on the banks of the Sabarmati River in north-central Gujarat. It spans an area of 205 km² (79.15 square miles). The city is located in a semi-arid region. As a consequence, many roads and open areas of the city are often covered in sand. The steady expansion of the Rann (Desert) of Kutch threatens to increase desertification around Ahmedabad. Except for the small hills of Thaltej – Jodhpur Tekra, the city is almost flat. Except during the June to September monsoon season, the climate is usually dry. The weather is hot from March to June with daily maximum temperatures ranging from 23°C to 43°C. From November to February, the average temperature is less than the 30°C (85°F), the average minimum is 15°C (59°F), and the climate is extremely dry. Cold northerly winds are responsible for a mild chill in January. The southwest

monsoon brings a humid climate from mid-June to mid-September. The average rainfall is 93.2 cm (36.7 inches) and infrequent, heavy rains during the monsoon cause the Sabarmati River to flood.

For the present study, we used particulate air pollutant data collected by the Gujarat Pollution Control Board (GPCB) at 13 sampling sites shown in Fig. 1 in Ahmedabad over a period of four years from January 2005 to December 2008. General uses of the area around each sampling station are shown in Table 1. The particulate pollutants samples were collected by the GPCB with commercially available Respirable Dust Sampler (RDS; Envirotech APM 460BL) instruments. The RDS had a free flow condition without filter and the flow rate of air sampler varied between 0.9 and 1.4 m³/min. It could be operated up to 28 hrs and the sampling duration was 24 hrs as accepted by the Environmental Protection Agency (EPA) of the U.S.A. and the Central Pollution Control Board of India (CPCB). Whatmann micro fibre filter papers (EPM, 2000) were used for the collection of PM₁₀ particles. Data about the micro meteorological conditions required for air quality assessment viz. temperature, wind speed, solar radiation, rainfall and relative humidity were collected from the U.S. National Climatic Data Center (NCDC) for Ahmedabad. Gridded rainfall data at 1° longitude – 1° latitude resolution were collected from the India Meteorological Department.

The pollutants data are monthly, whereas meteorological variables viz. rainfall, temperature and wind speed are daily, so monthly-mean time series of meteorological variables were prepared. A basic statistical analysis was carried out for all 13 stations for both pollutants and meteorological variables. These basic statistics include maximum, minimum, mean, and standard deviation of each variable. The seasonal as well as the annual range mean, and standard deviation were also estimated for all four years. In this study the Pearson correlation analysis has been performed between particulate pollutants and meteorological data (wind speed, temperature, rainfall and relative humidity) to investigate the relationships between them. The Pearson correlation coefficient is a measure of the relationship between two variables, this statistic will give an idea about which meteorological parameter play a major role in pollutants concentrations over Ahmedabad.

Air Quality Index (AQI) is a numerical rating. Air Quality Index (AQI) was calculated for all sites to get an insight into how polluted the air at each site was. Let there be n air quality parameters P_i ($i = 1, 2, 3 \dots n$), which are to be taken into account for calculating the AQI. Let V_i be the observed value of the i th parameter P_i in the ambient air and let V_{si} be the standard value recommended for this parameter. Then the quality rating Q_i for this parameter is given by

$$Q_i = 100 (V_i/V_{si}) \quad (1)$$

If $Q_i < 100$, it is to be noted that the given parameter is within the prescribed limit. On the other hand, if $Q_i > 100$, it implies that the i^{th} parameter exceeds the prescribed

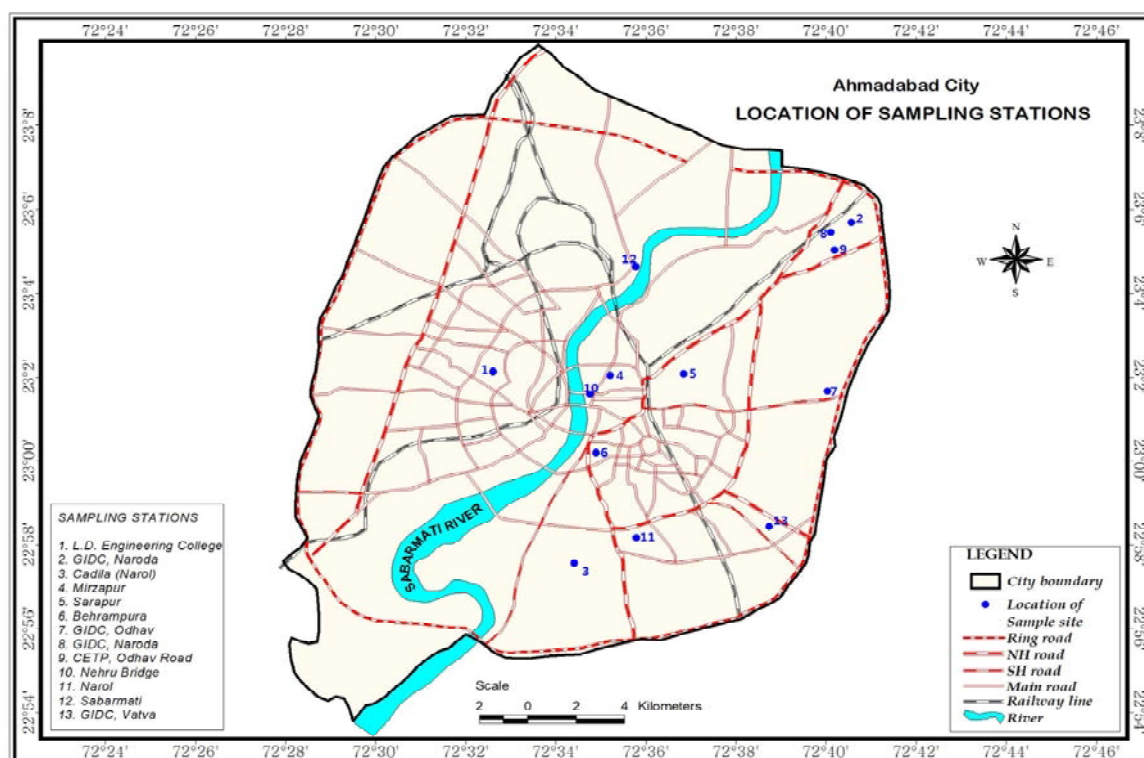


Fig. 1. Location of the sampling stations in Ahmedabad City.

Table 1. Nature of sampling Sites in Ahmedabad.

Site number	Sites	Area
1	L.D. Engineering College	Sensitive area
2	GIDC, Naroda	Industrial area
3	Cadila	Industrial area
4	Mirzapur	Residential rural and other area
5	Sarapur	Residential rural and other area
6	Behrampur	Residential rural and other area
7	GIDC, Odhav	Industrial area
8	GIDC, Naroda	Industrial area
9	CETP, Odhav	Industrial area
10	Nehru bridge	Residential rural and other area
11	Narol	Industrial area
12	Sabarmati	Industrial area
13	GIDC, Vatva	Industrial area

standard and the ambient air is harmful for breathing by human beings. It is assumed here that all the parameters have the equal importance and so only the unweighted air quality indices are calculated.

RESULTS AND DISCUSSION

Annual Distribution of Particulate Pollutants

Primary statistics of pollutants PM_{10} and SPM are listed in Tables 2 and 3, respectively. The statistics include minimum, mean, maximum, standard deviation and

coefficient of variation. The overall annual average PM_{10} concentrations varied from $103.64 \mu\text{g}/\text{m}^3$ to $131.79 \mu\text{g}/\text{m}^3$ in 2005 to 2008 at all 13 stations. The highest annual average $131.79 \mu\text{g}/\text{m}^3$ was recorded in the years 2005 and lowest annual average, $103.64 \mu\text{g}/\text{m}^3$ was recorded in the year 2008. As far as SPM is concerned, annual concentrations varied from 278.29 to $327.77 \mu\text{g}/\text{m}^3$. Highest concentrations $327.77 \mu\text{g}/\text{m}^3$ was recorded in the year 2005 and lowest concentration $278.29 \mu\text{g}/\text{m}^3$ was recorded in the year 2008. Out of 13 stations Narol has highest annual average for both PM_{10} & SPM. The PM_{10}

Table 2. Annual statistics of PM₁₀ in Ahmedabad.

Sites	PM ₁₀ concentrations (µg/m ³) 2005–2008					
	Min	Max	Mean	Permissible limit	SD	CV (%)
Site-1	48	155	76	50	24.4	32.1
Site-2	88	219	144	120	26.8	18.6
Site-3	66	208	114.6	120	33.8	29.5
Site-4	58	132	89.3	60	17.8	19.9
Site-5	28	115	84.7	60	15.5	18.3
Site-6	64	118	85.9	60	13.3	15.5
Site-7	17	172	112.5	120	28.4	25.2
Site-8	71	185	119.7	120	28.6	23.9
Site-9	70	159	117.7	120	17.4	14.7
Site-10	80	211	127.9	60	34.8	27.2
Site-11	116	327	199.2	120	37.9	19
Site-12	29	184	96	120	37.7	39.3
Site-13	88	189	128.2	120	24.8	19.4

Table 3. Annual statistics of SPM in Ahmedabad.

Sites	SPM concentrations (µg/m ³) 2005–2008					
	Min	Max	Mean	Permissible limit	SD	CV (%)
Site-1	104	364	177	70	56.7	32
Site-2	216	542	343.7	360	62.3	18.1
Site-3	186	513	268.2	360	77	28.7
Site-4	139	306	207.7	140	38.9	18.8
Site-5	129	257	201.5	140	29.5	14.7
Site-6	141	279	199.7	140	31.5	15.8
Site-7	171	424	265.5	360	55.9	21.1
Site-8	161	455	277.7	360	68.4	24.6
Site-9	180	397	273.1	360	40.1	14.7
Site 10	229	615	393.7	140	88.8	22.5
Site-11	342	786	557.1	360	106.1	19.1
Site-12	66	499	271.4	140	122.2	45
Site-13	178	459	284.8	360	75.3	26.4

concentration varied from 145 to 222 µg/m³ and for SPM it ranged between 432 to 616 µg/m³. Lowest PM₁₀ concentration was noted in the residential areas Sarangpur and it ranged between 38.7 to 92.2 µg/m³. In the case of SPM lowest concentration was recorded in the Behrampura and it is a residential area, SPM concentrations ranged between 98 to 208 µg/m³. The particulate pollutants concentrations were mostly high in the industrial and traffic areas and they are less in the residential areas. The influence of industrial sources may also be argued to discuss these polluted areas being the suspicious sites not too far from industrial emissions. The maximum value at industrial locations was measured and may be likely associated to the nearby stationary sources. Besides stationary combustion sources, mobile sources have also become a major contributor to urban air pollution in the urban environments due to the sulphur content in locally available petroleum resources. It is worth mentioning that gas-to-particulate conversion process occurs during favorable meteorological conditions (Fraser *et al.*, 1999). So, the particulates

generated due to photochemical reactions may also be correlated with the recorded concentrations. Figs. 2a and 2b show the trend of SPM and PM₁₀ over Ahmedabad city during the study period. It was noted that both SPM and PM₁₀ have decreasing trend. The decreasing concentrations of PM₁₀ and SPM are perhaps due to the decreasing usage of petrol and diesel in most of the buses and three-wheeler auto rickshaws within the city. The Gujarat Pollution Control Board has implemented many action plans to bring down the particulate pollutants level over Ahmedabad. It includes installation of CNG fuel supply stations within the city. GSRTC has increased the number of vehicles using CNG. There are more than 38000 auto rickshaw are running with GNC as a fuel. As far as industrial pollution is concerned, identified industries having major boilers are in process of further up-gradation of air pollution control measures in form of ESP [electro static precipitators], Bag Filters. The industrial units are categorized based on fuel consumption & performance of existing APCD [air pollution control devices]. Out of 129 units, first 32 units have already

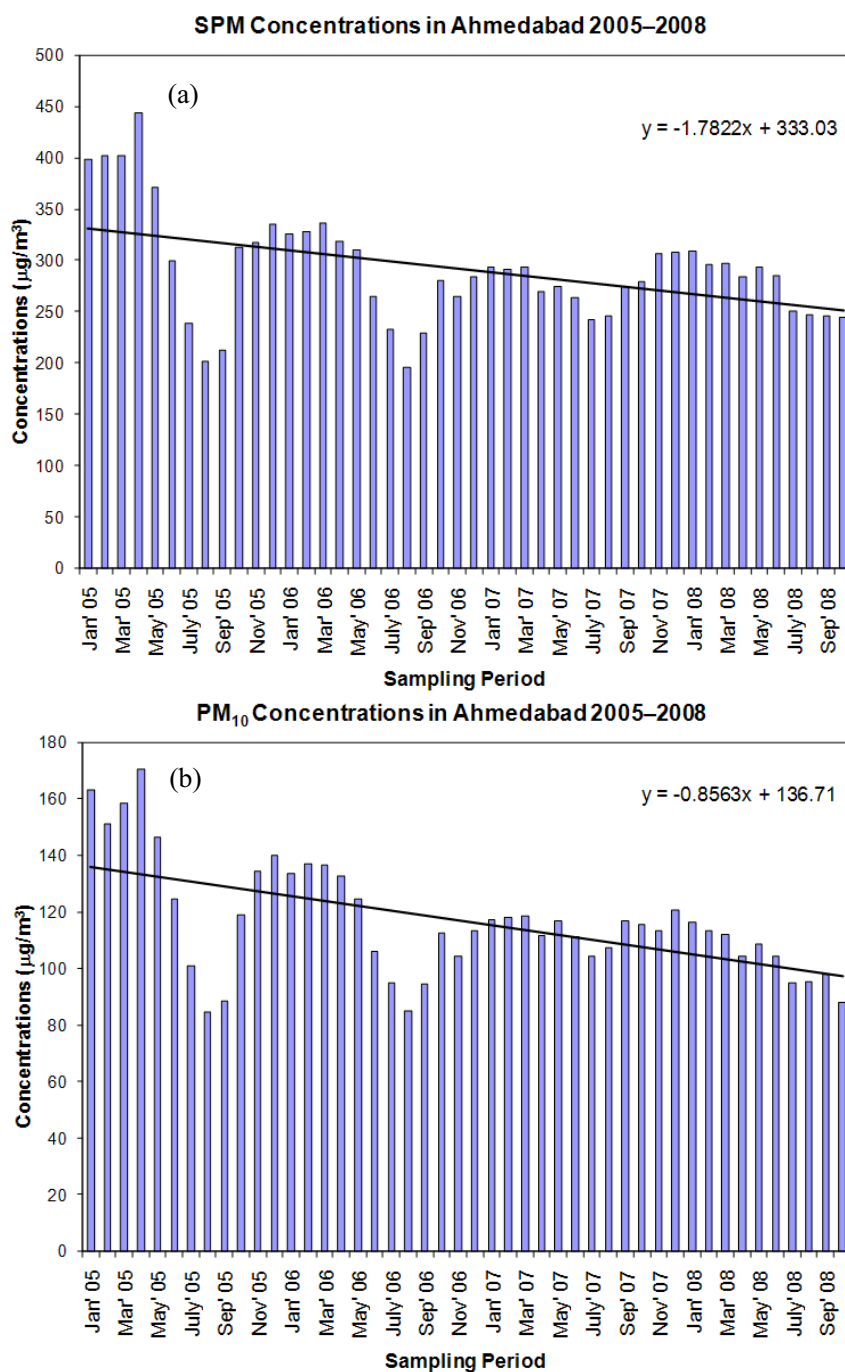


Fig 2. Trend of (a) SPM and (b)PM₁₀ over Ahmedabad during 2005–2008.

procured bag filters & ESP. Remaining units are in process of upgrading their APCD. Over 200 industrial units in Ahmedabad have switched over to Natural Gas as fuel (GPCB, 2008). As shown in Tables 2 and 3, it was found that the annual-average concentrations of PM₁₀ and SPM at most of the sites exceeded permissible limits set by the CPCB.

Seasonal Distribution

Seasonal statistics of particulate pollutants are given in Tables 4 and 5, and Figs. 3a and 3b show seasonal averages of PM₁₀ and SPM for the four years of this study; seasons are defined as winter (January and February),

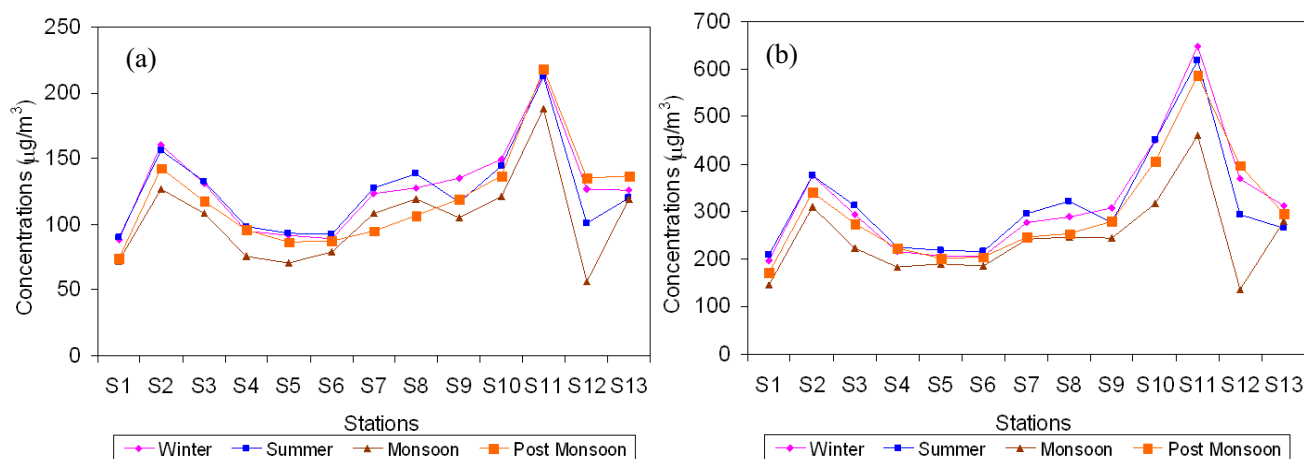
summer (March–April–May), monsoon (June–July–August–September), and post-monsoon (October–November–December) as per Indian Meteorological Department (IMD) classification. Table 4 shows that there is a clear variation with respect to seasons in pollutant concentrations over Ahmedabad. It was noted that highest SPM concentrations were noted in the winter seasons except the year 2005. In the year 2005, highest seasonal average $332 \mu\text{g}/\text{m}^3$ was recorded in the post monsoon season and lowest $216 \mu\text{g}/\text{m}^3$ was noted in the monsoon season. In the year 2006, maximum seasonal average $339 \mu\text{g}/\text{m}^3$ was recorded in the winter season and lowest

Table 4. Seasonal variations of PM₁₀ and SPM ($\mu\text{g}/\text{m}^3$) in Ahmedabad.

Year	Winter		Summer		Monsoon		Post Monsoon	
	SPM	PM ₁₀	SPM	PM ₁₀	SPM	PM ₁₀	SPM	PM ₁₀
2005	300	118	309	117	216	87	332	134
2006	339	140	330	131	236	94	291	113
2007	300	117	285	115	250	105	293	113
2008	300	107	293	106	249	92	282	104

Table 5. Seasonal statistics of PM₁₀ and SPM in at different stations in Ahmedabad.

Sites	Seasonal averages of particulate pollutants ($\mu\text{g}/\text{m}^3$) 2005–2008							
	Winter		Summer		Monsoon		Post Monsoon	
	PM ₁₀	SPM	PM ₁₀	SPM	PM ₁₀	SPM	PM ₁₀	SPM
Site-1	88.88	196.25	89.63	208.83	72.04	146.69	74.01	171.67
Site-2	160.25	374.75	155.92	375.83	126.35	311.13	142.56	339.67
Site-3	131.13	293.75	132.33	311.83	108.27	223.35	117.56	275.44
Site-4	94.67	216.33	98.22	226.44	75.81	184.35	95.67	223.33
Site-5	91.67	206.67	93.22	217.78	70.56	189.25	86.78	202.22
Site-6	89.17	207.5	92.33	215.22	78.83	184.67	87.22	203.44
Site-7	123.5	277.13	127.42	296.58	108.17	242	94.56	246.78
Site-8	127.88	288.75	138.17	321.17	118.92	245.75	106.33	253
Site-9	134.88	308	116.33	278.33	105.21	244.31	118.89	278.44
Site-10	149	451.88	144.42	450	120.85	316.38	136.78	405.67
Site-11	214.13	648.38	212.5	617.83	187.94	461.06	217.89	586.44
Site-12	127	369.88	100.67	292.5	56.29	135.63	135.22	397.11
Site-13	126.13	311.5	120.08	265.25	119.08	279.81	137	296.22

**Fig. 3.** Seasonal Variations of (a) PM₁₀ (b) SPM over Ahmedabad during 2005–2008.

seasonal average $236 \mu\text{g}/\text{m}^3$ was recorded in the monsoon season. In the year 2007, highest seasonal average $300 \mu\text{g}/\text{m}^3$ was noticed in the winter season and lowest seasonal average $250 \mu\text{g}/\text{m}^3$ was recorded in the monsoon season. In the case of year 2008, the maximum seasonal average $300 \mu\text{g}/\text{m}^3$ was recorded in the winter season and lowest seasonal average $249 \mu\text{g}/\text{m}^3$ was recorded in the monsoon season. As far as PM₁₀ is concerned, highest seasonal average $134 \mu\text{g}/\text{m}^3$ was recorded in the post monsoon season and lowest $87 \mu\text{g}/\text{m}^3$ was noted in the monsoon season. In the year 2006, maximum seasonal

average $140 \mu\text{g}/\text{m}^3$ was recorded in the winter season and lowest seasonal average $94 \mu\text{g}/\text{m}^3$ was recorded in the monsoon season. In the year 2007, highest seasonal average $117 \mu\text{g}/\text{m}^3$ was noticed in the winter season and lowest seasonal average $105 \mu\text{g}/\text{m}^3$ was recorded in the monsoon season. In the case of year 2008, the maximum seasonal average $107 \mu\text{g}/\text{m}^3$ was recorded in the winter season and lowest seasonal average $92 \mu\text{g}/\text{m}^3$ was recorded in the monsoon season. The high monsoon season had the least amount of SPM and PM₁₀ concentration. Higher SPM and PM₁₀ concentration levels were found mostly during

winter and it was followed by the summer season. During the monsoon season of June–September the winds are stronger, moist and are from the marine and western regions surrounding India. The lowest concentration of particulate matters in the monsoon can be attributed to the scavenging of particulate pollutants from the atmosphere due to rainfall (Stern, 1976). Although the wind speed varied little between the seasons, other meteorological parameters such as temperature and relative humidity, pointed to poor mixing during winter season. Moreover, winter received much less rainfall in comparison to other seasons. As a result, removal of atmospheric aerosol particles by wet scavenging is much reduced in winter (Karar and Gupta, 2006).

Monthly Distribution

Monthly variations of concentrations of PM_{10} and SPM are depicted in Figs. 4a–5d. In the case of PM_{10} , it can be seen that high concentrations were recorded mostly in the summer months of March, April and May at almost all sites but the highest average ($327 \mu\text{g}/\text{m}^3$) was recorded in November 2005 at Narol (site 11) because it is a major industrial area of the city, and therefore a source of high amounts of emissions; this may be due to favorable meteorological conditions supporting accumulations of the pollutants at high concentrations. From 2006 to 2008, highest concentrations were recorded mostly in summer months. The lowest concentration ($17 \mu\text{g}/\text{m}^3$) was recorded in August at Odhav GIDC (site 7) during the monsoon, perhaps because particulate pollutants were washed out by rainfall. The lowest concentrations were always recorded in the monsoon months of all years of the study period. The highest PM_{10} concentrations were continuously recorded in Narol (site 11) and it was followed by Naroda (site 2) and Naroda GIDC (site 8). All three sampling stations are located in industrial-cum-heavy traffic areas. The lowest SPM concentrations were recorded in the L.D. College of Engineering (site 1) and residential areas like Mirzapur (site 4), Saraspur (site 5) and Behrampura (site 6). Here, there is no major industrial activity but the presence of SPM is due to automobiles and the usage of fuels such as kerosene and wood for cooking and other domestic purposes.

SPM concentrations varied from 66 to $786 \mu\text{g}/\text{m}^3$ during 2005–2008. The lowest SPM concentration, $66 \mu\text{g}/\text{m}^3$, was recorded in the Sabarmati (site 12) area and the highest SPM concentration, $786 \mu\text{g}/\text{m}^3$, was again recorded in Narol (site 11). From 2005 to 2008, high SPM concentration was recorded in Narol and it ranged between 342 and $786 \mu\text{g}/\text{m}^3$, with an average of $557.1 \pm 106.2 \mu\text{g}/\text{m}^3$. The highest concentration for the four-year period was recorded mostly in March, April and May. During these months, air temperature is high, and winds are usually from arid and semi-arid regions of western India. The lowest concentration was observed in January as well as in the monsoon months. During these months, winds are stronger and moist, and are usually from the southwest and the west. High SPM concentrations were recorded in Narol (site 11) during the entire study period; and it was

followed by Nehru Bridge (site 10), Naroda (site 2), and Naroda-GIDC (site 8). The lowest SPM concentration was recorded in L.D. College of Engineering (site 1) and it is followed by and residential areas like Mirzapur (site 4), Saraspur (site 5) and Behrampura (site 6). It is likely that tall buildings near the latter site restrict background concentrations from nearby semi-industrialized areas. It is also noted that only a few commercial establishments carry out combustion activities. Over these sites, as the number of sources is substantially fewer, SPM are also usually found to be low. In a comparison of monthly SPM averages with ambient air quality standards, it is observed that pollutant concentrations have often crossed the permissible limit.

Automobiles and industries are the major sources for atmospheric particulate pollution in Ahmedabad. Except automobiles, operation of diesel-powered generators (which are used in commercial establishments during electricity supply failures), emissions from paved roads, and background concentrations from industrial and semi-industrial areas of the city are the other important sources of particulate pollution. Cooking in houses, school and commercial establishments; and refuse incineration in houses, public places, and municipal incineration in open grounds offer their own contributions to the total load as well as the atmospheric particulate matter concentrations all over the city. The other important reason for the recorded concentrations at this site may be combustion of conventional fuels like firewood, charcoal, dry cow dung, biomass materials and agro residues not only at the nearby slum areas but also at the commercial centres especially in the roadside hotels. These sources emit large amount of particulates in to the atmosphere (Carvacho *et al.*, 2004; Monna *et al.*, 2006). As small chimneys are used for the release of the emissions, the particulate matter endures low lateral displacement which results in the accumulation in this confined geographical area. It is noted that the sand along the sides of the roads, which are dusty in nature, is not removed frequently. The road dust resuspension through mechanical and thermal turbulence also constitutes a source of primary atmospheric particles (Weckwerth, 2001; Sternbeck *et al.*, 2002; Adachi and Tainosho, 2004).

The observed PM_{10} and SPM concentrations are summarized in Tables 2 and Table 3, respectively. It was observed that the maximum average PM_{10} concentration was recorded at Narol (Site-11) followed in decreasing order by GIDC-Naroda (site-2), GIDC-Vatva (site-13), Nehru Bridge (site-10), Naroda GIDC (site-8), CETP Odhav (site-9), Cadila (site-3), Odhav GIDC (site-7), Sabarmati (site-12), Mirzapur (site-4), Behrampura (site-6), Saraspur (site-5), L.D. Engineering College (site-1) respectively. In the case of SPM, the observed maximum average is found at Narol (Site-11) followed in decreasing order by Nehru bridge (site-10), GIDC-Naroda (site-2), GIDC-Vatva (site-13), GIDC- Naroda (site-8), CETP Odhav (site-9), Sabarmathi (site-12), Cadila (site-3), Odhav GIDC (site-7), Mirzapur (site-4), Saraspur (site-5), Behrampura (site-6), and L.D. Engineering College (site-1) respectively. The maximum

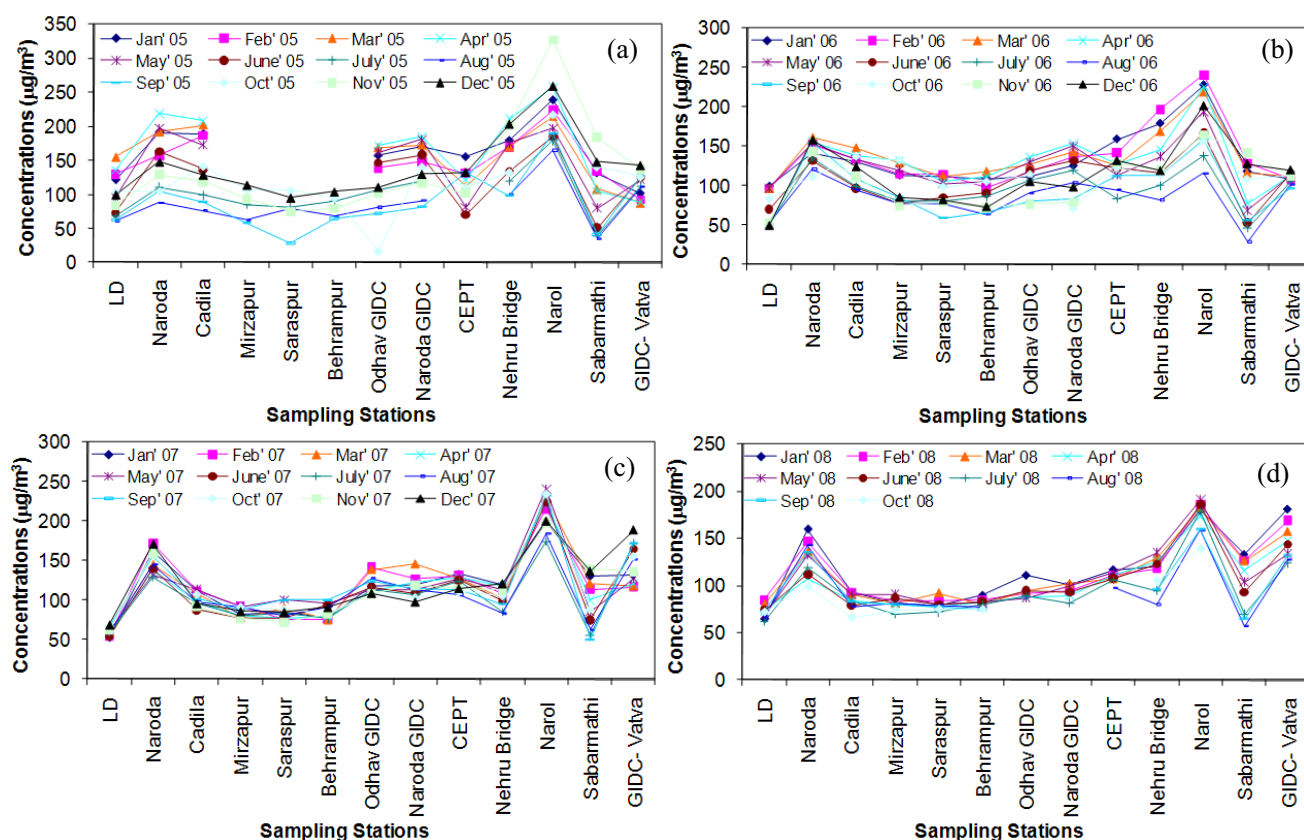


Fig 4. Monthly Variations of PM_{10} over Ahmedabad (a) 2005, (b) 2006, (c) 2007, (d) 2008.

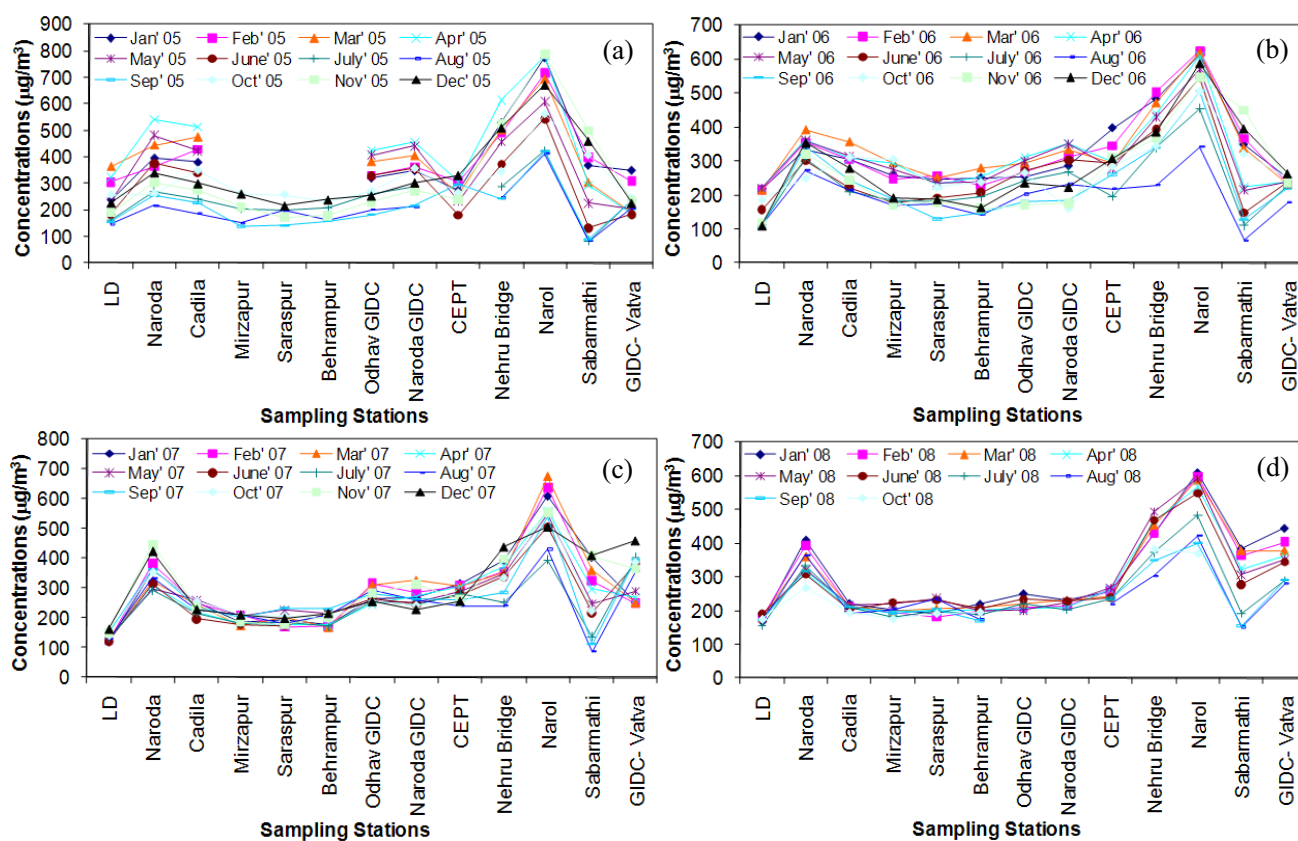


Fig 5. Monthly Variations of SPM over Ahmedabad during (a) 2005, (b) 2006, (c) 2007, (d) 2008.

standard deviation for PM₁₀ was observed at Narol (Site-11) followed in decreasing order by Sabarmati (site-12), Nehru bridge (site-10), Cadila (site-3), Naroda GIDC (site-8), Odhav GIDC (site-7), GIDC-Naroda (site-2), GIDC-Vatva (site-13), L.D. Engineering College (site-1), Mirzapur (site-4), CETP Odhav (site-9), Saraspur (site-5), and Behrampur (site-6). Similarly, it was observed that the maximum deviation of SPM was highest, at Sabarmathi (site-12), Narol (Site-11), Nehru bridge (site-10), Cadila (site-3), GIDC-Vatva (site-13), GIDC-Naroda (site-8), GIDC-Naroda (site-2), L.D.Engineering College (site-1), Odhav GIDC (site-7), CETP-Odhav (site-9), Mirzapur (site-4), Behrampur (site-6) and Saraspur (site-5). Both of particulate pollutants (SPM, PM₁₀) standard deviations are maximum in the industrial area because emissions are high due to maximum number of point sources, and also emissions from the other sources like area sources and line sources. Minimum standard deviations are noticed in commercial cum residential areas because of nature of the sampling sites and sources are less when compared with industrial areas.

The Coefficient of Variation (CV) is defined as the ratio between the standard deviation to mean. The CVs of the recorded concentrations of PM₁₀ are 32.1%, 18.6%, 29.5%, 19.9%, 18.3%, 15.5%, 25.2%, 23.9%, 14.7%, 27.2%, 19.0%, 39.3%, and 19.4% for the 13 sites respectively. Similarly, calculated CVs of the recorded concentrations of SPM are 32.0%, 18.1%, 28.7%, 18.8%, 14.7%, and 15.8%, 21.1%, 24.6%, 14.7%, 22.5%, 19.1%, 45.0%, and 26.4% for the 13 sites respectively. The calculated CVs of the recorded concentrations range from 14.7% to 39.3% for PM₁₀ and from 14.7% to 45.0% for SPM.

The Role of Meteorology

Meteorology plays a crucial role in ambient distributions of air pollution. In fact, there is a strong seasonality in meteorological variables that modulate air quality levels (Espinosa *et al.*, 2004; Karar *et al.*, 2005). The importance of meteorological factors in the transport and diffusion stage of the air pollution cycle is well recognized. Meteorological factors such as wind speed, precipitation and mixing height all play important roles in determining the pollutant levels for a given rate of pollutant emission (Tayanc, 2000; Singal and Prasad, 2005). The entering of pollutants from the ground surface, their residence in the atmosphere, and the formation of secondary pollutants is controlled not only by the rate of emission of the reactants into the air from the source, but also by wind speed, turbulence level, air temperature, and precipitation. Thus,

it is often important to understand the physical processes leading to an observed concentration of pollutants at a given point. Rainfall is one of the reasons for low particulate pollutants in the monsoon season as the pollutants are washed out by rain. Wet deposition by precipitation or wet removal is one of the main mechanisms for removal of aerosols from the atmosphere (Jaenicke, 1993). In addition, this particulate pollutant changes the precipitation pattern and spin down the hydrological cycle (Chung *et al.*, 2005).

Annual statistics of meteorological variables are listed in Table 6. Air temperature ranged between 20.3°C and 44.4°C from 2005 to 2008. The minimum temperature, 20.3°C, was recorded in February 2008 and the maximum temperature, 44.4°C, was recorded in May 2005. The annual average temperature varied from 25.9°C to 27.5°C. The lowest annual average temperature, 25.9°C, was recorded in 2005 and highest annual average temperature, 27.5°C, was recorded in 2006. Wind speed varied from 0.1 m/s to 5.4 m/s during the study period. The lowest wind speed was recorded in October 2007 and highest wind speed was recorded in August 2006 and June 2007. The annual average of wind speed ranged between 1.9 m/s to 2.2 m/s. The lowest annual average was recorded in 2008 and highest annual average was recorded in 2007. The humidity ranged between 10 to 94% during the study period. The maximum humidity was noted in the years 2006 and 2007 and minimum humidity was recorded in the year 2005. The annual averages of humidity varied from 56 to 59%. The cumulative rainfall ranges between 617.73 to 1398.4 mm from 2005 to 2008 period. Maximum rainfall, 213.1 mm, was recorded in 2006 and minimum was recorded in 0.01 mm in the same year. The cumulative rainfall was maximum in the year 2006 and it was low in the year 2008.

Time series of particulate pollutants and meteorological variables are shown in Figs. 6 and 9. It shows monthly and annual variations of temperature, wind speed, and SPM, PM₁₀ concentrations for all sites in Ahmedabad during 2005–2008. Rainfall is the only meteorological variable that is significantly negatively correlated with particulate pollutants as per statistical analysis results. Monsoon winds and rains control the extent of pollution seen over many of the South and East Asian countries like India and China. Monsoon winds, which come from the Southwest during the months of June, July, August, and part of September, are characterized by heavy rain and winds. The monsoon gathers moisture over the Indian Ocean and releases it over South and Southeast Asia. Conversely, the

Table 6. Annual statistic of meteorological parameters in Ahmedabad.

Year	Temperature (°C)			Wind speed (m/s)			Humidity (%)			Rainfall (mm)		
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Cumulative
2005	44.4	22.1	25.9	5.3	0.3	2.1	92	10	56	190.2	0.12	1153.04
2006	44.3	25	27.5	5.4	0.3	2.1	94	21	59	213.1	0.01	1398.4
2007	40	23.8	27.4	5.4	0.1	2.2	94	16	57	172.5	0.11	1141.11
2008	43.2	20.3	27.2	3.7	0.2	1.9	92	21	59	90.5	0.03	617.73

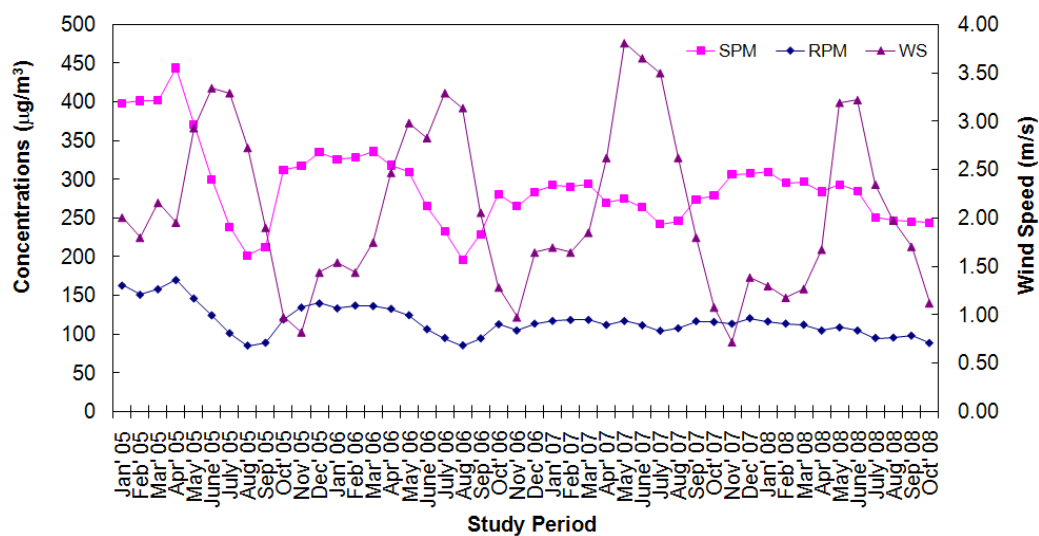


Fig. 6. Monthly Variations of particulate pollutants and Wind speed over Ahmedabad during 2005–2008.

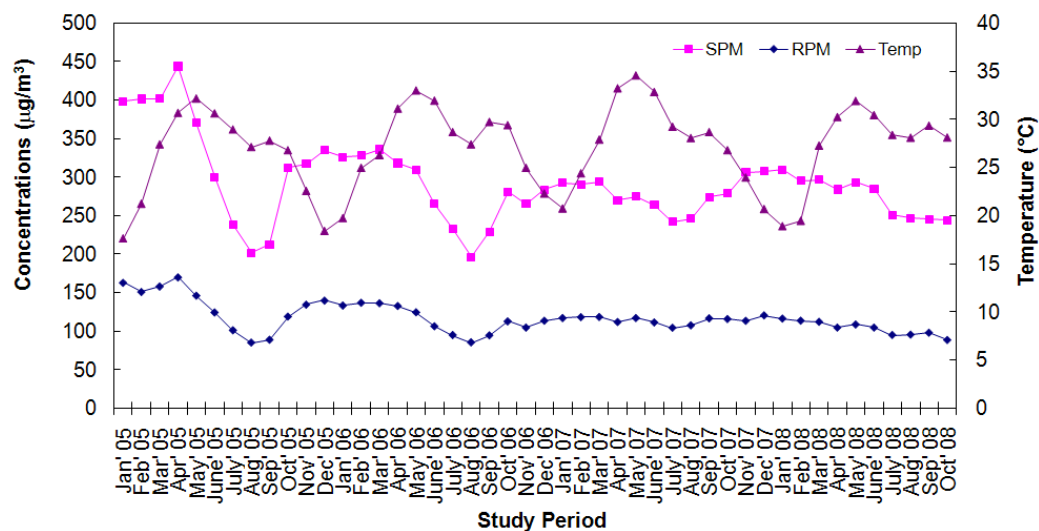


Fig. 7. Monthly Variations of particulate pollutants and temperature over Ahmedabad during 2005–2008.

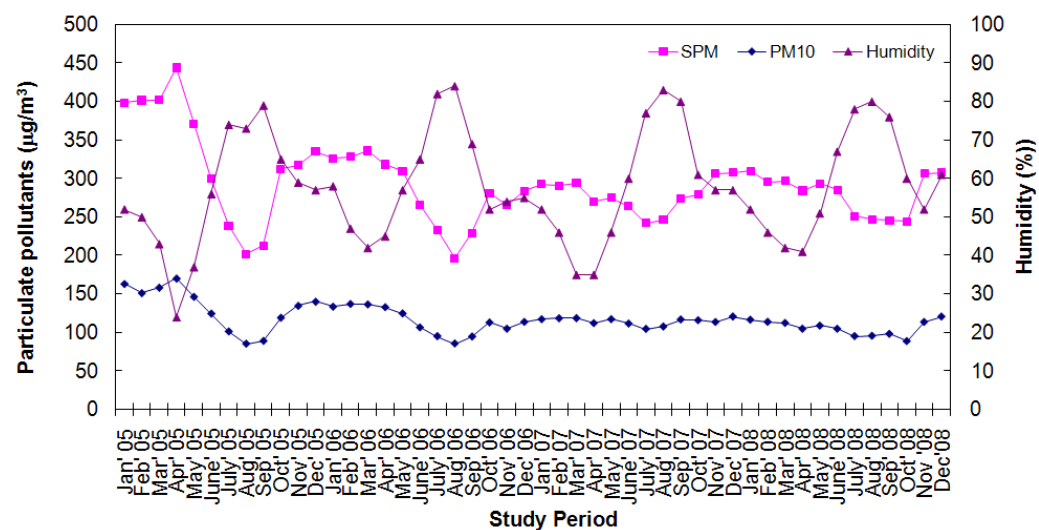


Fig. 8. Monthly Variations of particulate pollutants and humidity over Ahmedabad during 2005–2008.

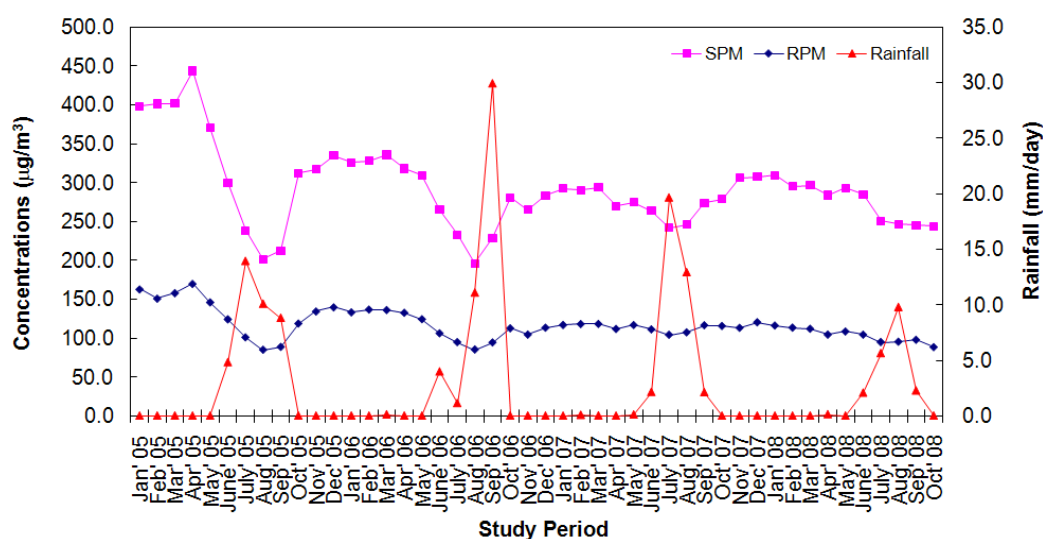


Fig. 9. Monthly Variations of particulate pollutants and rainfall over Ahmedabad during 2005–2008.

predominant wind direction during the winter is from the Northeast, and is characterized by a dry air mass producing almost no rain as the air mass travels over continental landmass. Highest PM_{10} and SPM concentrations were also affected because of wind speed. Wind affects turbulence near the ground, thus affecting the dispersion of pollutants released into the air. Turbulence (largely the up- and-down motion of air) is generated in part by airflow over rough ground. The greater the wind speed, the greater the turbulence, and hence the greater the dispersion of pollutants that are near the ground (Oren, 2001). It was found that precipitation and wind speed cause reduction in particulate level in the atmospheric environment. It also found that precipitation has relatively higher degree of correlation with reduction in the particulate level than that of the other parameters mainly. Because of rainfall, the soil became damp restricting the possibility of soil derived particles being released (Misra *et al.*, 2008). This is because of wide range of precipitation level during the study period.

Topography also one of the parameter to be considered in the air quality studies. Surrounding topography restricts the transport of pollution away from the urban area. When a weak background synoptic circulation combines with a valley air temperature inversion and surrounding orographic blockade, the result is often a lack of dispersion of significant lower atmospheric pollutants away from the urban center (Berman *et al.*, 1995; Lu and Turco 1995; Ellis *et al.*, 2000). As far as the topography of Ahmedabad is concerned, the ground rises away from the city on all sides bounded by the gently sloping beautiful terrain. But the elevation is very insignificant. So, the flat topography of this city experiences horizontally homogeneous wind flow and steady state meteorological conditions, which does not allow the accumulation of pollutants (Benson, 1989). But in the central parts of the city, building geometry is an important parameter for characterizing the transport and dispersion of pollutants. Though Ahmedabad was a well planned city but resulting in heterogeneous

nature and narrow and congested streets, so the distances between these buildings along the narrow roads are very less and this geometry causes tunnel like formation which is open at the top. So, the building ratios H/W (H–height of the building, W–distance between the buildings) seem to be important in the present study as the concentrations of pollutants rise with narrower street widths and increasing building heights. Central parts of the city are found to be influenced by this parameter.

Correlation analyses were carried out to quantify the relationship, if any, between the meteorological and pollution variables. Correlation coefficient has been done between SPM and PM_{10} and measured meteorological parameters to obtain the relationship between them. The relationship between particulate matters (SPM & PM_{10}) and meteorological parameters such as wind speed, temperature, relative humidity and rainfall was statistically analyzed and the results were presented in Table 7. From this table it was noted that particulate pollutants both SPM & PM_{10} showed a significant negative correlation with rainfall during 2005–2008. In the case of PM_{10} and rainfall correlation coefficient values are ranged between -0.51 to -0.86 and for SPM -0.6 to 0.83 . The highest correlation coefficient -0.83 was noted in the year 2005 for both SPM and. In the case of wind speed, for SPM the correlation coefficient values varied from 0.01 to -0.73 and for PM_{10} it ranged between -0.07 to -0.52 . In the case of wind speed particulate pollutants area negatively correlated with wind speed. Correlation coefficient between wind speed and SPM varied from -0.17 to -0.51 and for PM_{10} it ranged between -0.17 to -0.60 . It was concluded that SPM and PM_{10} were negatively correlated with wind speed but it is not in significant level for some of the study year. As far as humidity is concerned, it is negatively correlated with both of the particulate pollutants. Correlation coefficient for SPM and humidity it varied form -0.54 to -0.91 and for PM_{10} and humidity it ranged between -0.44 to -0.89 . The humidity have significant correlation coefficient with SPM and PM_{10} during the study period.

Table 7. Correlation coefficient for PM₁₀ and SPM and meteorological parameters.

Years	PM ₁₀				SPM			
	Temp	Wind Speed	Humidity	Rainfall	Temp	Wind Speed	Humidity	Rainfall
2005	0.16	−0.39	−0.89	−0.25	0.15	−0.24	−0.91	−0.83
2006	0.24	−0.47	−0.86	−0.23	0.27	−0.51	−0.88	−0.6
2007	−0.13	−0.6	−0.52	−0.41	−0.78	−0.73	−0.54	−0.79
2008	−0.34	−0.17	−0.44	−0.53	−0.23	−0.23	−0.72	−0.61

There is no significant correlation with temperature and PM₁₀. But there is a significant correlation was found between SPM and temperature in 2007. From this correlation analysis, it was concluded that meteorological factors such as rainfall and relative humidity have significant negative impacts on air pollutants concentrations in the city. Wind speed is also having negative impacts on pollutants concentrations but it is not in significant level in some times.

Many researchers at various parts of India have conducted several monitoring studies on air quality and some of them are presented here. Salve *et al.* (2006) monitored the pollutants PM₁₀, TSP, SO₂, NO₂, CO, O₃ and Pb in the urban atmosphere of Chandrapur city in Maharashtra during summer period of the year 2006. It was noticed that the ambient concentrations of the pollutants PM₁₀ ranged between 141 and 199 µg/m³, TSP varied from 301 to 441 µg/m³ and Pb concentrations were with the minimum of 0.09 µg/m³ and the maximum of 0.62 µg/m³. The ambient air quality was monitored for one year (2004–2005) at four stations in and around Santa cement work, Chitrakoot and it was observed that the PM₁₀ concentrations varied from 94.51 to 108.02 µg/m³ and the SPM concentrations ranged between 213.84 and 269.90 µg/m³ (Singh *et al.*, 2006). Vanerkar *et al.* (2006) studied respirable dust levels in limestone mine area at Chhattisgarh. The respirable dust samples were found to be in the range of concentrations, which were from 0.160 to 1.170 mg/m³. Kumar (2005) studied the ambient air quality status around Tughlakabad area in the year 2004 with reference to PM₁₀, SPM, SO₂, and NO₂. It was reported that the highest PM₁₀ concentration was 233.13 µg/m³ and the lowest was 51.38 µg/m³ in Tughlakabad. But, the PM₁₀ concentration ranged from 215 µg/m³ to 50 µg/m³ in Sir fort. The SPM concentration varied from 512.83 to 120.62 µg/m³ in Tughlakabad, while the concentrations varied from 547 µg/m³ to 145 µg/m³ in Sir Fort. Katiyar *et al.* (2005) studied the SPM concentrations in Shillong during the year 1997 to 1999. The overall SPM concentrations ranged from 50 to 350 µg/m³ in plain and sloping areas of Shillong. Sharma and Pervez (2004) studied the concentration of selected elements in ambient particles from September 2000 to June 2001 in some steel plants in central part of India. While the PM₁₀ concentrations ranged between 50 and 103 mg/m³, the SPM concentrations varied from 206 to 371 mg/m³ during the rainy season. The PM₁₀ concentrations varied from 55 to 213 mg/m³, while SPM concentration varied from 564 to 1249 mg/m³ during the winter season. The status of

ambient air quality at Madurai was studied in the year 2006. The estimated concentrations of PM₁₀ were found to vary from 88 to 226 µg/m³ and it was found that there is no major industrial activities in Madurai city, the pollutants concentration were high in the traffic areas and it was less in the sensitive areas of the city (Bhaskar *et al.*, 2008).

AIR QUALITY INDEX

An air quality index (AQI) is defined as a numerical rating that reflects the composite influence on overall quality of a number of air quality parameters which will be helpful not only for advising the public but also for urban planning (Inhaber, 1975; Kassomenos *et al.*, 1999; Srivastava and Sarkar, 2006; Bishoi *et al.*, 2009). The AQI focuses on health effects we may experience within a few hours or days after breathing polluted air. The AQI varies from 0 to 500 and its health indicators are mentioned in Table 8. The higher the AQI value, the greater the level of air pollution and the greater are the health concerns. An AQI value of 100 generally corresponds to the national air quality standard, which is the level set to protect public health in India. AQI values below 100 are generally considered satisfactory. When AQI values are above 100, air quality is considered to be unhealthy at first for certain sensitive groups of people, then for everyone for higher AQI values (Mohan and Kandya, 2007).

Average, monthly AQI over Ahmedabad during 2005–2008 is shown in Table 9. AQI values varied from 25 to 193.3. High AQI were estimated mostly in the summer season at some sites and in the winter season at some other sites. Low AQI values were observed in the monsoon season. The highest AQI values observed in the winter season can be attributed to the meteorological conditions, during this season less general circulation and more stagnant air masses. In summer season it may be due to dust movement and PBL is also increasing during this season. Lowest AQI were noted in the monsoon season. In this season due to precipitation and high wind velocity changes in the general wind direction also a major reason for low AQI. The precipitation helps in wet deposition of pollutants. The changes in wind velocity and reversal of its direction carry the pollutants away from sources as well as increase the possibilities of dilution of concentration of pollutants also (Bishoi *et al.*, 2009). It is to be noted that highest AQI values were observed in mixed-use areas, which have low levels of permissible limits. Lowest AQI values were observed in industrial areas because they have high permissible limits. From these AQI estimates, it is

Table 8. AQI values and level of health concerns.

Sl. No	AQI value (when the AQI value is in this range)	Level of health concern (air quality conditions)
1	0–50	Good
2	51–100	Moderate
3	101–150	Unhealthy for sensitive group
4	151–200	Unhealthy
5	201–300	Very unhealthy
6	301–500	Hazardous

Table 9. Level of Air Quality Index in Ahmedabad (2005–2008).

Site	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1	149.3	164.1	176.1	167.7	149.6	126.4	109.9	108.9	114.6	148.5	120.9	131.9
2	92.1	89.7	90.9	89.9	87.9	78.2	71.3	71.1	77.9	67.8	83.7	90.3
3	72.7	73.5	77.9	75.1	72.9	57.5	53.4	49.4	54.9	65.5	60.9	65.7
4	99.8	103	103.5	104.8	108.9	88.7	86.5	84.9	84	110.2	88.2	102.9
5	98.5	96.5	103.9	93.83	105.4	90.3	87.1	88.6	77.3	100.9	81.8	93.9
6	99.8	93.2	100.1	98.1	101.8	96.8	89.3	80.6	82.3	98.8	84.2	96.3
7	68.7	69	74.3	71.9	70.2	67.3	59.1	56.6	52.3	53	54.5	61
8	71.4	71.7	79.4	78	77.1	69.4	60.7	57.8	53.2	60.4	60.4	61.4
9	78.1	73.4	66.8	70	63.1	60.3	58.6	55.9	66.3	64.8	65.5	72.1
10	189.6	185.3	182.7	193.3	178.1	157.4	128.3	106.8	126.5	145.1	180.1	185.3
11	135.6	136.7	134.9	136.3	126.7	117.1	99.7	92.2	108.6	112.2	139.5	132.4
12	80.3	78.4	73.7	61.7	53.1	42	30.6	25	29.8	69.3	97	88.1
13	76	70.4	65.7	65.6	68.4	74.5	71.8	66.6	72.7	73.4	70.7	81.9

amply clear that the two particulate pollutants are emerging as critical pollutants for urgent attention because they are degrading air quality in Ahmedabad with consequent effects on public health. On the basis of the rating scale in Table 8, it is found that the atmospheric environment of Ahmedabad is polluted from moderate to unhealthy levels. This indicates an urgent need for systematic control of atmospheric pollutants from anthropogenic sources especially the particulate pollutants to safeguard the human population, flora, and fauna as well as social assets such as cultural sites in the city.

CONCLUSIONS

The present study shows that particulate pollutants PM₁₀ and SPM are mostly above permissible limits at many sampling sites in Ahmedabad. A comparison of our results for Ahmedabad with earlier studies for other cities in India shows that particulate pollutant concentrations are also high in Ahmedabad as in other cities. In Ahmedabad, SPM concentrations are continuously decreasing but there are no substantial changes in PM₁₀ concentrations. This implies that fine-mode particles are still produced by vehicles, industrial activities, and combustion of conventional fuels for domestic and commercial purposes.

The two particulate pollutants show a negative correlation with rainfall, humidity and wind speed during the study period. High concentrations were recorded in the winter seasons for both particulate pollutants. In winter season, temperature is low and wind speed is generally low.

Because of this condition planetary boundary layer height is decreasing, so pollutants will not disperse and pollutants will accumulate during this season. During the monsoon season, particulate pollutants are washed out of the atmosphere by rainfall. Wet deposition by precipitation or wet removal is one of the main mechanisms for removal of aerosols from the atmosphere. So, lower concentrations of the two pollutants are observed in the monsoon season. The results of this study will be useful for further research on interactions between atmospheric aerosols, and local and regional weather and climate in Ahmedabad. High AQI values were estimated, mostly in winter and summer seasons. Low AQI values were observed in the monsoon season due to the earlier-mentioned washout effect. On the basis of the AQI rating scale, we found that the atmospheric environment of Ahmedabad is in moderately-polluted to unhealthy range.

The Ahmedabad mega-city area is expanding rapidly; and human and animal populations, vehicular traffic, industrialization, and per-capita energy consumption are increasing. These developments are increasing atmospheric aerosol concentrations which, in turn, are increasing ambient air pollution substantially. It is certain that these increases will make adverse effects on climate as well as health, and both personal and social wealth of the people living in Ahmedabad and in downwind regions. So, it can be concluded that a strict implementation of adequate abatement measures and environmental regulations is urgently necessary.

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REFERENCES

- Adachi, K. and Tainosho, Y. (2004). Characterization of Heavy Metal Particles Embedded in the Tyre Dust. *Environ. Int.* 30: 1009–1017.
- Benson, P.E. (1989). Caline 4—A Dispersion Model for Predicting Air Pollution Concentrations near Roadways. Sacramento, USA: Division of New Technology and Research, Department of Transportation (State of California).
- Berman N.S. Boyer D.L. Brazel A.J. Brazel S.W. Chen R.R. Fernando H.J.S. and Fitch M.J. (1995). Synoptic Classification and Physical Model Experiments to Guide Field Studies in Complex Terrain. *J. Appl. Meteorol.* 34: 719–730.
- Bhaskar, B.V., Rajasekhar, R.V.J., Muthusubramanian, P. and Kesarkar, A.P. (2008). Measurement and Modelling of Respirable Particulate (PM₁₀) and Lead Pollution over Madurai, India. *Air Qual. Atmos. Health* 1: 45–55.
- Bishoi, B., Prakash, A. 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. Res.* 9: 1–17.
- Carvacho, O.F., Trzeple-Nabaglo, K., Ashbaugh, L.L., Flocchini, R.G., Melin, P. and Celis, J. (2004). Elemental Composition of Spring Time Aerosol in Chillan, Chile. *Atmos. Environ.* 38: 5349–5352.
- Chung, C.E., Ramanathan, V., Kim, D. and Podgorny, I.A. (2005). Global Anthropogenic Aerosol Direct Forcing Derived from Satellite and Ground Based Observations. *J. Geophys. Res.* 110: D24207, doi: 10.1029/2005JD006356.
- Ellis, A.W., Hildebrandt, M.L., Thomas, W.M., and Fernando, H.J.S. (2000). Analysis of the Climatic Mechanisms Contributing to the Summertime Transport of Lower Atmospheric Ozone Across Metropolitan Phoenix, Arizona, USA. *Clim. Res.* 15: 13–31.
- Espinosa, A.J.F., Rodriguez, M.T. and Alvarez, F.F. (2004). Source Characterisation of Fine Urban Particles by Multivariate Analysis of Trace Metal Speciation. *Atmos. Environ.* 38: 873–886.
- Fraser, M.P., Cass, G.R. and Simoneit, B.R.T. (1999). Particulate Organic Compounds Emitted from Motor Vehicle Exhaust and in the Urban Atmosphere. *Atmos. Environ.* 33: 2715–2724.
- Godish, T. (1985). *Air Quality*. Lewis Publishers, Inc. Chelsea, USA.
- Gujarat Pollution Control Board (2008). Annual Report.
- Inhaber, H. (1975). A Set of Suggested Air Quality Indices for Canada. *Atmos. Environ.* 9: 353–364.
- Jaenicke, R. (1993). Tropospheric Aerosols. *Int. Geophys. Ser.* 54: 1–31.
- Karar, K. and Gupta, A.K. (2006). Seasonal variations and chemical characterization of ambient PM₁₀ at residential and industrial sites of an urban region of Kolkata (Calcutta), India. *Atmos. Res.* 81: 36–53.
- Karar, K., Gupta, A.K., Kumar, A., Biswas, A.K. and Devotta, S. (2005). Statistical Interpretation of Week Day/week End Differences of Ambient Gaseous Pollutant, Vehicular Traffic and Meteorological Parameter in Urban Region of Kolkata. *J. Environ. Sci. Eng.* 47: 164–175.
- Kassomenos, P., Skouloudis, A.N., Lykoudis, S. and Flocas, H.A. (1999). Air Quality Indicators for Urban Indexing of Atmospheric Pollution over Large Metropolitan Areas. *Atmos. Environ.* 33: 1861–1879.
- Katiyar, S.C., Khathing, D.T., Dwivedi, K.K. and Agarwal, G.D. (2005). Vehicle Density and SPM in Ambient Air in an Urban Area; Shillong (Meghalaya). *Indian J. Air Pollut. Control.* 1: 44–49.
- Kumar, A. (2005). Air pollution studies at Tughlakabad environmentally sensitive area in New Delhi. *Indian J. Air Pollut. Control.* 1: 86–93.
- Lau, K.M. and Kim, M.K. (2006). Asian Summer Monsoon Anomalies Induced by Aerosol Direct Forcing: The Role of Tibetan Plateau. *Clim. Dyn.* 26: 855–864.
- Li, Z. (2004). In *Observations, Theory, and Modelling of the Atmospheric Variability*, Zhu, X. (Eds.), Aerosol and Climate: A Perspective from East Asia. World Scientific Pub. Co., p. 501–525.
- Lu, R. and Turco, R.P. (1995). Air Pollutant Transport in a Coastal Environment-II. Three- Dimensional Simulation over Los Angeles Basin. *Atmos. Environ.* 29: 1499–1518.
- Lua, K.M., Ramanathan, K., Wu, G.X., Li, Z., Tsay, S.C., Hsu, C., Sikka, R., Holben, B., Lu, D., Tartari, G., Chin, M., Koudelova, P., Chen, H., Ma, Y., Huang, J., Taniguchi, K. and Zhang, R. (2008). The Joint Aerosol Monsoon Experiment-A New Challenge for Monsoon Climate Research. *Bull. Am. Meteorol. Soc.* 89: 369–383.
- Mage, D., Ozolins, G., Peterson, P., Webster, A., Orthofer, R., Vandeweerd, V. and Gwynne, M. (1996). Urban Air Pollution in Mega Cities of the World. *Atmos. Environ.* 30: 681–696.
- Meenakshi, P. and Saseetharan, M.K. (2004). Urban Air Pollution Forecasting with Respect to SPM using Time Series Neural Networks Modelling Approach – A Case Study in Coimbatore City. *J. Environ. Sci. Eng.* 46: 92–101.
- Menon, S., Hansen, J., Nazarenko, L. and Luo, Y. (2002). Climate Effects of Black Carbon Aerosols in China and India. *Science* 297: 2250–2253.
- Misra, A. Jayaram, A. and Ganguly, D. (2008). Validation of MODIS Derived Aerosol Optical Depth over Western India. *J. Geophys. Res.* 113: D04203. doi: 10.1029/2007JD009075.
- Mohan, M. and Kandya, A. (2007). An Analysis of the

- Annual and Seasonal Trends of Air Quality Index of Delhi. *Environ. Monit. Assess.* 131: 267–277.
- Monna, F., Poujol, M., Losno, R., Dominik, J., Annegarn, H. and Coetzee, H. (2006). Origin of Atmospheric Lead in Johannesburg, South Africa. *Atmos. Environ.* 40: 6554–6566.
- Oren, C.N. (2001). *Air Pollution*. Access Science, McGraw-Hill Companies. <http://www.accessscience.com/>
- Ramachandran, S. (2007). Aerosol optical depth and fine mode fraction variations deduced from MODIS over four urban areas in India. *J. Geophys. Res.* 112; doi: 10.1029/2007JD008500.
- Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J.T., Washington, W.M., Fu, Q., Sikka, D.R. and Wild, M. (2005). Atmospheric Brown Clouds; Impact on South Asian Climate and Hydrologic Cycle. *Proc. Nat. Acad. Sci. U.S.A.* 102: 5326–5333.
- Ramanathan, V., Crutzen, P.J., Kiehl, J.T. and Rosenfeld, D. (2001). Atmosphere – Aerosols, Climate, and the Hydrological Cycle. *Science* 294: 2119–2124.
- Rosenfeld, D. (2000). Suppression of Rain and Snow by Urban and Industrial Air Pollution. *Science* 287: 1793–1796.
- Salve, P.R. Maurya, A. Ramteke, D.S. and Wate, S.R. (2006). A Study of Air Pollutants in Chandrapur. *Indian J. Environ. Prot.* 26: 742–747.
- Sharma, R. and Pervez, S. (2004). Enrichment and Exposure of Particulate Lead in a Traffic Environment in India. *Environ. Geochem. Health.* 25: 297–306.
- Shen Z.X., Cao, J.J., Tong, Z., Liu, S.X., Reddy, L.S.S., Han, Y.M., Zhang, T. and Zhou, J. (2009). Chemical Characteristics of Submicron Particles in Winter in Xi'an. *Aerosol Air Qual. Res.* 9: 80–93.
- Singal, S.P. and Prasad, R. (2005). Analytical Study of some Observed Micro Meteorological Data. *J. Air Pollut. Contr.* 1: 44–49
- Srivastava, A., Gupta, S. and Jain, V.K. (2008). Source Apportionment of Total Suspended Particulate Matter in Coarse and Fine Size Ranges Over Delhi. *Aerosol Air Qual. Res.* 8: 188–200.
- Srivastava, R.K. and Sarkar, R. (2006). Air Quality Index: A Brief Review. *Indian J. Environ. Prot.* 26: 344–347.
- Stern, A.C. (1976). *Air Pollution*. Vol. 1, 3rd edn. Academic Press, New York, USA.
- Sternbeck, J., Sjödin, A. and Andreasson, K. (2002). Metal Emission from Road Traffic and the Influence of Resuspension – Results from Two Tunnel Studies. *Atmos. Environ.* 36: 4735–4744.
- Takemura, T., Kaufman, Y.J., Remer, L.A., Nakajima, T. (2007). Two competing pathways of aerosol effects on cloud and precipitation formation, *Geophys. Res. Lett.* 34: L04802. doi: 10.1029/2006GL028349.
- Tayanc, M. (2000). An Assessment of Spatial and Temporal Variation of Sulfur Dioxide Levels over Istanbul, Turkey. *Environ. Pollut.* 107: 61–69.
- Tsang, H., Kwok, R. and Miguel, A.H. (2008). Pedestrian Exposure to Ultrafine Particles in Hong Kong under Heavy Traffic Conditions. *Aerosol Air Qual. Res.* 8: 19–27.
- Vanerkar, A.P. Zade, P.D. Kulkarni, N.P. and Kamavisdar, A. (2006). Studies on Monitoring Respirable Dust in Lime Stone Mine Area – A Case Study. *Indian J. Environ. Prot.* 26: 724–727.
- Weckwerth, G. (2001). Verification of Traffic Emitted Aerosol Components in the Ambient Air of Cologne (Germany). *Atmos. Environ.* 35: 5525–5536.
- Li, W.F., Bai, Z.P., Liu, A.X., Chen, J. and Chen, L. (2009). Characteristics of Major PM_{2.5} Components during Winter in Tianjin, China. *Aerosol Air Qual. Res.* 9: 105–119.
- Zhang, R.J. Shen, Z.X. Zou, H. Wang, W. Han, Y. and Zhou, J. (2008). Study of Elemental Mass Size Distributions of Aerosol in Lijiang, a Background Site in Southwest China. *Aerosol Air Qual. Res.* 8: 339–347.

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