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Receptor model-based source apportionment of particulate pollution in Hyderabad, India

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Abstract Air quality in Hyderabad, India, often exceeds the national ambient air quality standards, especially for particulate matter (PM), which, in 2010, averaged 82.2±24.6, 96.2±12.1, and 64.3±21.2 μg/m^3 of PM_{10}, at commercial, industrial, and residential monitoring stations, respectively, exceeding the national ambient standard of 60 μg/m^3. In 2005, following an ordinance passed by the Supreme Court of India, a source apportionment study was conducted to quantify source contributions to PM pollution in Hyderabad, using the chemical mass balance (version 8.2) receptor model for 180 ambient samples collected at three stations for PM_{10} and $PM_{2.5}$ size fractions for three seasons. The receptor modeling results indicated that the PM_{10} pollution is dominated by the direct vehicular exhaust and road dust (more than 60 %). $PM_{2.5}$ with higher propensity to enter the human respiratory tracks, has mixed sources of vehicle exhaust, industrial coal combustion, garbage burning, and secondary PM. In order to improve the air quality in the city, these findings demonstrate the need to control emissions from all known sources and particularly focus on the low-hanging fruits like road dust and waste burning, while the technological and institutional advancements in the transport and industrial sectors are bound to enhance efficiencies. Andhra Pradesh Pollution Control Board utilized these results to prepare an air pollution control action plan for the city.

Keywords Hyderabad · India · Particulate pollution · Source apportionment

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Introduction

Hyderabad, a 400-year-old city, is the state capital of Andhra Pradesh, India. It is the fifth largest and one of the fastest growing cities in India, with seven million inhabitants and a population density of 17,000 persons/km^2. A booming information technology industry has led to expansion of the city, which now includes the satellite districts, collectively known as the Hyderabad Urban Development Area (HUDA) (Fig. 1). A growing demand for personal and public transportation, expansion of the manufacturing estates, and booming construction sector resulted in deteriorating urban air quality (IES 2004; APPCB 2006; IES 2008; Gummeneni et al. 2011).

For the Hyderabad City, an integrated air pollution analysis conducted by the US Environmental Protection Agency (USEPA) in 2002–2004 and updated in 2007–2008, estimated total health costs at

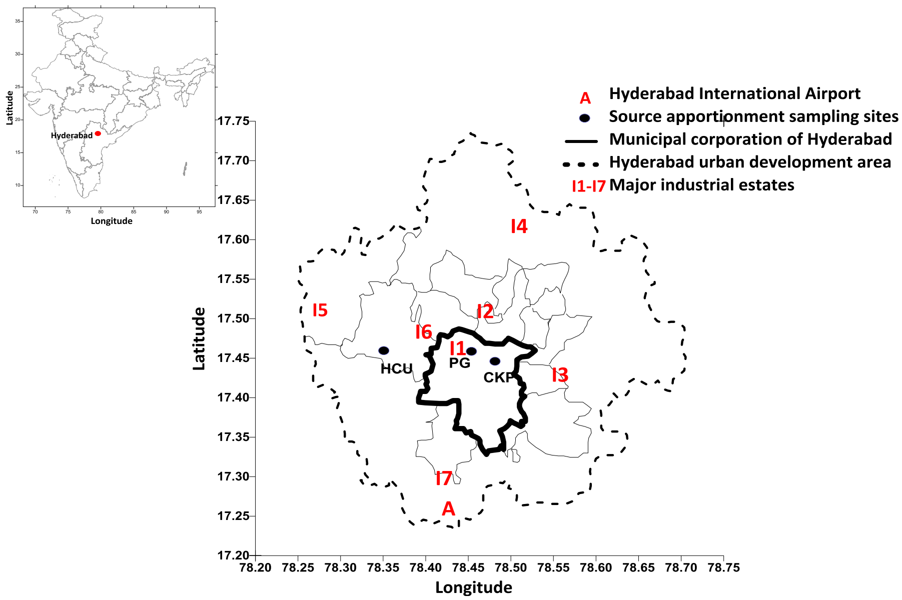


Fig. 1 Geographical location of Hyderabad Urban Development Area; **a** major industrial development areas are *I1* Balanagar, *I2* Jeedimetla, *I3* Nacharam, *I4* Medchal, *I5* Patancheru, *I6* Kukatpally, *I7* Gaganpahad; **b** location of the particulate pollution source apportionment study sampling sites Punjagutta (PG), Chikkadpally (CKP), and Hyderabad Central University (HCU)

US \$260 million and 430 million, respectively (IES 2004, 2008). These estimates include cost of 3,000 annual premature deaths due to air pollution and morbidity from chronic bronchitis, respiratory and cardiac hospital admissions, emergency room visits, asthma attacks, restricted activity, and respiratory symptom days. Similar analysis for six more cities in India—Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot—estimated a total of 15,200 premature deaths for 2010 (Guttikunda and Jawahar 2012). While we can study and estimate the impacts, knowing the emission sources and their strengths for mitigating air pollution is vital for better air quality management (Shah et al. 2000; Schwela et al. 2006; Johnson et al. 2011).

In light of increasing air quality impacts in Hyderabad and other Indian cities, the Supreme Court of India in August 2003 directed the state governments of Andhra Pradesh, Maharashtra, Uttar Pradesh, Karnataka, and Tamilnadu to prepare action plans for improving air quality and to submit their plans to the Environmental Pollution (Prevention and Control) Authority. One of the directives was to conduct particulate pollution source apportionment studies in order to effectively address air quality issues based on the pollution sources and their potential to be controlled. The Central Pollution Control Board (CPCB), New Delhi, India, coordinated source apportionment studies in six cities across India: Delhi, Mumbai, Kolkata, Kanpur, Bangalore, and Pune (CPCB 2010). To address this issue in Hyderabad, the Andhra Pradesh Pollution Control Board (APPCB) coordinated this study to quantify sources of air pollution and support development of an action plan for better air quality in Hyderabad. In this paper, we present the methodology and results of particulate matter (PM) source apportionment study for Hyderabad, and discuss source contributions to total pollution loads.

Ambient monitoring and sampling sites

Ambient monitoring data from 20 stations operated by APPCB is presented in Table 1 and Fig. 2. Since 2006, city average PM_{10} concentrations increased by 25 % with industrial hotspots and transport corridors measuring above 200 μg/m^3. PM_{10} refers to particulate matter with aerodynamic diameter less 10 μm. In 2000, a total of 650 industries were registered under HUDA jurisdiction which was reduced to 390 by either merging them into clusters or relocating to larger industrial clusters (Fig. 1). These clusters cover metal and agro-processing, paints, tanning, and pharmaceuticals. During the same period, liquefied petroleum gas was introduced as an alternative fuel for the three-wheelers and increased public transport fleet size; all of which resulted in reduction of ambient PM_{10} concentrations in the early 2000s.

The monitoring stations are classified into (1) residential, (2) commercial, (3) industrial, and (4)

Table 1 List of monitoring stations operated by the Andhra Pradesh Pollution Control Board and measured annual average concentrations (in micrograms per cubic meter) of PM_{10} and NO_x in 2006, 2008, and 2010 in Hyderabad, India

Station	Type	2006		2008		2010	
		PM_{10}	NO_x	PM_{10}	NO_x	PM_{10}	NO_x
Abids	Commercial	103.8±19.2	31.9±3.1	112.2±11.0	31.7±3.1	97.5±7.8	28.0±1.6
Paradise	Commercial	107.4±18.1	34.3±3.2	113.5±9.3	35.5±4.1	99.5±6.6	29.1±2.4
Charminar	Commercial	98.3±15.6	30.4±3.7	113.0±10.1	34.8±2.8	99.9±8.8	28.3±1.9
Chikkadpally	Commercial	71.6±17.1	17.5±1.9	79.2±22.7	26.0±3.4	66.9±10.7	24.2±3.3
Imlibun	Commercial	74.2±17.9	23.1±6.1	81.8±7.6	27.6±4.6	74.0±7.7	23.4±1.2
Punjagutta	Commercial	104.1±14.7	32.4±3.0	117.4±9.8	34.3±3.8	108.0±3.6	30.2±2.7
Shameerpet	Commercial	57.9±12.8	16.2±0.7	51.2±14.0	18.5±3.1	52.5±11.8	20.2±2.1
Rajendra Nagar	Commercial	49.2±19.6	15.2±1.5	41.2±11.5	16.1±2.0	38.9±6.3	16.7±1.9
Kukatpally	Commercial	72.8±13.0	16.7±1.7	84.9±15.7	26.2±3.1	92.2±12.8	24.0±1.5
Langar House	Commercial	121.8±30.6	17.9±2.4	103.8±19.3	26.9±5.3	105.9±20.3	26.4±2.6
Balanagar	Industrial	101.5±28.2	34.6±5.8	106.0±8.3	36.6±4.2	99.4±9.7	28.7±3.4
Jeedimetla	Industrial	98.2±16.0	21.6±2.2	92.3±14.3	27.2±3.4	96.5±14.3	25.5±2.8
Uppal	Industrial	100.7±24.7	31.9±1.4	107.5±10.4	34.6±2.8	92.8±12.1	27.0±2.6
Sainikpuri	Residential	66.5±11.1	16.0±1.2	58.8±12.6	18.4±2.9	58.1±14.0	18.7±1.3
Jublee Hills	Residential	57.7±14.0	16.4±1.2	58.4±9.6	17.3±2.6	54.1±10.8	16.6±0.9
Madhapur	Residential	70.2±41.3	16.2±5.1	70.8±14.6	18.8±3.0	81.4±26.1	22.3±1.7
Nacharam	Residential	76.1±25.4	17.5±6.4	87.1±18.7	27.7±5.6	83.8±7.7	24.5±2.3
University of Hyderabad	Residential	54.7±9.5	16.3±1.1	41.6±13.9	28.5±4.7	44.1±6.7	16.1±1.2
KBRN Park	Sensitive	46.1±13.5	14.1±0.9	49.5±8.0	14.9±0.8	49.4±15.3	15.3±0.7
Zoo Park	Sensitive	52.5±14.6	14.8±0.7	54.7±7.1	17.5±1.9	57.9±17.0	16.3±0.5

sensitive locations (Table 2). Of the 20 stations, annual averages in 2010 at the commercial, industrial, and residential monitoring stations were 82.2±24.6, 96.2±12.1, and 64.3±21.2 $\mu g/m^3$ of PM_{10}, respectively, exceeding the national ambient standard of 60 $\mu g/m^3$. Sensitive locations in the middle of state parks measured 53.6±16.4 $\mu g/m^3$ of PM_{10}. The variation in Tables 1 and 2 is 1 SD of daily average concentrations

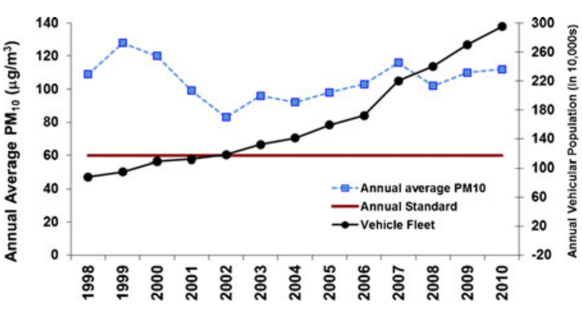


Fig. 2 Annual average ambient PM_{10} concentrations (microgram per cubic meter) vs the total number of registered vehicles in Hyderabad, India

in each year. A large percentage of this increase was attributed to the number of vehicles on road, which grew from 1.45 million in 2001 to 2.0 million in 2007 and 2.9 million in 2010.

After physical survey of the 20 stations, the following three sites were selected for sampling, based on upwind and downwind locations and representative exposure to commercial, traffic, and residential activities:

1. Punjagutta (PG) is an urban residential/commercial/transportation site. The monitors are located close to the traffic junction on top of the traffic police station, a major transit point.
2. Chikkadpally (CKP) is an urban residential/commercial site with significant traffic to the east. The monitors are located on top of the police station. The location is lined with shops, small-scale industries burning coal and oil, and constant traffic because of its proximity to 20 cinemas.
3. Hyderabad Central University (HCU) is a background sampling location, 20 km from the city

Table 2 The range of annual average concentrations (micrograms per cubic meter) of PM_{10} and NO_x in 2006, 2008, and 2010 by monitoring station type in Hyderabad, India

Station	Number	2006		2008		2010	
		PM_{10}	NO_x	PM_{10}	NO_x	PM_{10}	NO_x
Commercial	10	88.5±30.2	24.2±8.2	89.0±28.0	27.6±7.0	82.2±24.6	24.7±4.5
Industrial	3	100.0±22.8	29.2±6.8	101.9±13.0	32.8±5.3	96.2±12.1	27.1±3.1
Residential	5	66.8±23.8	17.6±4.9	63.3±20.5	22.2±21.1	64.3±21.2	19.7±3.6
Sensitive	2	49.4±14.1	14.5±0.8	52.1±7.8	16.2±1.97	53.6±16.4	15.8±0.8

center on the old Hyderabad-Mumbai highway. The campus stretches across 2,300 acres of scenic and serene land.

Sampling and mass concentrations

Filter sampling was conducted between November 2005 and December 2006 in three measurement campaigns under different climatic conditions: phase 1 (November 12 to December 1, 2005) was classified as the winter season; phase 2 (May 9 to June 9, 2006) was classified as the summer season, and phase 3 (October 27 to November 18, 2006) was classified as the monsoon (rainy) season. Aerosol samples were collected using Airmetrics MiniVol™ portable air samplers operating at 5 l/min for 24-h sampling periods. Filter collection times at the three locations varied from 0900 to 1100 hours, depending on traffic. The collection and filter-change sequence were maintained in all periods (PG→CKP→HCU). The travel distance between PG and CKP is 5 km, and between CKP and HCU is 15 km. At each station, pairs of Teflon® and quartz fiber filters were used to collect aerosol samples for PM_{10} and $PM_{2.5}$ (four samples per site) every 2 days.

Samples were subjected to mass measurements by gravimetric analysis. For the three stations, the monitored total mass concentrations and associated uncertainties in the three seasons are summarized in Table 3. The 24-h average PM_{10} concentrations ranged from 115 to 153 $\mu g/m^3$ for PG, 85 to 134 $\mu g/m^3$ for CKP, and 59 to 105 $\mu g/m^3$ for HCU. The 24-h average $PM_{2.5}$ concentrations ranged from 47 to 86 $\mu g/m^3$ for PG, 42 to 68 $\mu g/m^3$ for CKP, and 25 to 55 $\mu g/m^3$ for HCU. The variations presented in Table 3 are 1 SD for the samples by season and size fraction. The highest concentrations were observed for the winter season and were attributed to poor dispersion conditions during low inversion at night and an increase in emissions from heating, primarily from biomass burning. PG station measured the highest average attributed to vehicle exhaust, resuspended dust, and constant idling of vehicles at the traffic junction. Of the 30 days of sampling per station, the daily average PM_{10} standard of 100 $\mu g/m^3$ was exceeded for 19, 17, and 11 days at PG, CKP, and HCU, respectively, and the daily average $PM_{2.5}$ standard of 60 $\mu g/m^3$ was exceeded for 19, 13, and 6 days at PG, CKP, and HCU, respectively. The ratio of $PM_{2.5}$ to PM_{10} ranged between 38 and 54 % for samples collected in the winter and summer months, compared to 57 to 67 % in the rainy season. This is partly due to entrainment of large particles during rains, thus increasing the fraction of fine particles.

Chemical analysis and speciation

Samples were subjected to ion chromatography for chloride, nitrate, and sulfate ions; colorimetry for ammonium; atomic absorption and X-ray florescence for metals; and thermal optical reflectance for organic carbon (OC) and elemental carbon (EC). The ion and select metal concentrations and associated standard deviation (among the samples) are summarized in Table 3.

A high fraction of total carbon implies a mix of diesel and coal combustion in the vicinity of the sampling location (Watson et al. 2008; Chen et al. 2010). In Hyderabad, EC and OC dominated in observed $PM_{2.5}$, emphasizing the role of transportation emissions. Total carbon (EC+OC) in the $PM_{2.5}$ fraction ranged from 51 to 74 % (for the 90 samples) with the highs observed for PG and CKP stations, due to their proximity to traffic junctions. The EC to $PM_{2.5}$ ratio is ~20 % at HCU compared to ~30 % at

Table 3 Measured concentrations (microgram per cubic meter) of total mass, ions, and select metals following the chemical analysis of ambient samples

Period	Station	Total mass	Ions				Carbon		Metals						
			Cl	SO_4	NO_3	NH_4	OC	EC	Na	Mg	K	Al	Si	Ca	Fe
PM_{10}, winter	PG	159±8.0	1.4±0.1	8.9±0.5	3.9±0.2	3.4±0.1	44+3.3	29+2.1	1.0±0.1	1.0±0.1	3.6±0.73	10±3.2	19±6.1	5.0±0.8	3.1±0.1
	CKP	134±6.7	1.3±0.1	8.8±0.5	3.5±0.1	3.2±0.1	37+2.8	16+1.1	0.8±0.1	0.9±0.1	3.4±0.68	10±3.0	17±5.6	4.6±0.7	3.0±0.1
	HCU	105±5.3	0.9±0.1	8.4±0.5	2.9±0.1	2.8±0.1	24+1.8	12+0.9	1.3±0.1	0.7±0.1	2.9±0.58	9.0±2.7	15±5.0	2.7±0.4	2.4±0.1
$PM_{2.5}$, winter	PG	86±4.3	0.9±0.1	7.9±0.4	1.7±0.11	3.2±0.1	34+2.6	27+2.0	0.6±0.1	0.1±0.1	1.5±0.07	0.6±0.08	1.1±0.07	0.4±0.02	0.4±0.03
	CKP	68±3.5	0.9±0.0	8.0±0.4	1.5±0.10	3.1±0.1	30+2.3	13+1.0	0.5±0.1	0.1±0.1	1.4±0.07	0.6±0.08	1.2±0.07	0.3±0.02	0.5±0.03
	HCU	55±2.8	0.7±0.0	7.9±0.4	1.3±0.09	2.9±0.1	20+1.5	11+0.8	0.9±0.1	0.1±0.1	1.2±0.06	0.6±0.08	1.1±0.07	0.2±0.01	0.4±0.03
PM_{10}, summer	PG	110±5.6	1.4±0.1	4.8±0.3	2.8±0.2	1.2±0.09	27+2.2	16+1.8	1.5±0.3	1.1±0.1	2.8±0.5	9.1±2.7	16±5.1	4.9±0.8	2.7±0.1
	CKP	112±5.7	1.2±0.1	4.5±0.2	2.7±0.2	1.1±0.09	25+2.1	11+1.2	1.6±0.4	1.2±0.1	2.6±0.5	9.9±2.9	17±5.6	6.1±1.0	3.1±0.1
	HCU	63±3.3	0.8±0.1	4.5±0.3	2.0±0.1	1.4±0.11	10+0.9	4.6+0.5	1.3±0.3	0.8±0.1	1.6±0.3	6.8±2.0	12±3.8	3.4±0.5	1.9±0.0
$PM_{2.5}$, summer	PG	47±2.5	0.4±0.07	3.8±0.2	1.0±0.09	1.2±0.09	20+1.6	14+1.6	0.8±0.3	0.2±0.1	1.0±0.05	0.6±0.05	1.2±0.07	0.4±0.02	0.4±0.02
	CKP	42±2.4	0.3±0.07	3.6±0.2	0.9±0.09	1.2±0.09	18+1.5	10+1.1	0.8±0.3	0.2±0.1	0.8±0.04	0.6±0.05	1.2±0.07	0.5±0.02	0.5±0.02
	HCU	25±1.7	0.2±0.06	4.4±0.3	0.7±0.08	1.5±0.11	12+1.1	4.6+0.5	0.6±0.3	0.2±0.1	0.6±0.03	0.7±0.05	1.4±0.08	0.5±0.02	0.4±0.02
PM_{10}, rainy	PG	115±5.8	1.2±0.09	9.8±0.5	3.5±0.2	3.0±0.17	31+2.4	17+1.4	0.9±0.3	0.7±0.1	3.0±0.6	8.0±2.3	14±4.6	3.9±0.6	2.0±0.10
	CKP	85±4.4	1.4±0.10	10±0.5	3.0±0.1	3.4±0.19	20+1.6	11+0.9	0.9±0.3	0.4±0.1	2.1±0.4	5.0±1.4	8.7±2.7	2.1±0.3	1.5±0.07
	HCU	59±3.1	0.6±0.07	8.6±0.4	2.4±0.1	3.1±0.17	14+1.1	8.6+0.7	0.6±0.3	0.3±0.1	1.5±0.2	3.6±1.1	6.0±1.9	1.2±0.2	0.9±0.05
$PM_{2.5}$, rainy	PG	65±3.4	0.7±0.07	8.6±0.4	2.2±0.13	3.6±0.19	22+1.8	16+1.4	0.6±0.3	0.2±0.1	1.2±0.06	0.7±0.06	1.2±0.08	0.5±0.02	0.4±0.02
	CKP	53±2.9	0.6±0.07	9.6±0.5	1.6±0.11	3.7±0.20	17+1.4	11+0.9	0.7±0.3	0.1±0.1	1.0±0.05	0.6±0.05	1.0±0.07	0.4±0.02	0.4±0.02
	HCU	40±2.2	0.4±0.07	8.0±0.4	1.4±0.10	3.2±0.18	12+1.0	8.2+0.7	0.5±0.3	0.1±0.1	0.7±0.03	0.4±0.05	0.7±0.05	0.2±0.01	0.2±0.01

PG Punjagutta monitoring station, *CKP* Chikkadpally monitoring station, *HCU* Hyderabad Central University monitoring station, *Cl* chlorine, SO_4 sulfates, NO_3 nitrates, NH_4 ammonium, *OC* organic carbon, *EC* elemental carbon, *Na* sodium, *Mg* magnesium, *K* potassium, *Al* aluminum, *Si* silicon, *Ca* calcium, *Fe* iron

PG, indicating proximity to direct sources—in this case, diesel emissions.

Crustal elements (silicon, aluminum, calcium, potassium, magnesium, and iron) are directly related to resuspended dust lofted by natural wind plus movement of vehicles on roads and are major contributors to PM_{10}. The ratio between soil dust elements (silicon and aluminum) observed in PM_{10} to that observed in $PM_{2.5}$ ranged from 7 to 12. On average, ~10 % of resuspended road dust emissions are accounted for by the $PM_{2.5}$ fraction. Similarly, using potassium as an indicator for biomass burning, ~40 % on average of estimated garbage burning emissions are accounted for by the $PM_{2.5}$ fraction.

Receptor modeling and results

Following completion of the laboratory analyses, we determined PM pollution source contributions for the three sampling sites and three seasons using the Chemical Mass Balance (CMB) model version 8.2 (Watson et al. 1984; Coulter 2004). This model has two advantages: (1) it calculates uncertainties of source contributions from both the source and receptor uncertainties, and (2) chemical species measured more precisely in both the source and receptor samples are given greater influence in the solution than those that are less precisely measured species. The percent contributions and associated standard deviation (among the samples) are presented in Table 4. The average source contributions by season (for all stations) are presented in Fig. 3. Chemical source profiles utilized for similar studies in other Indian cities are collected for receptor modeling (Chowdhury et al. 2007; CPCB 2010; Gummeneni et al. 2011).

At the receptor sites, vehicle exhaust was the largest contributor to ambient pollution, both at the commercial sites of PG and CKP and the background site of HCU. For all seasons and at all stations, on average, transportation sector contributed the most to PM_{10} pollution: 30 % from direct vehicle exhaust and 30–45 % (depending on the season) from resuspension of road dust. The movement of vehicles is dominated by heavy duty trucks at HCU, and it is a mix of passenger cars and jeeps, light-duty commercial vehicles, and public transport buses for PG and CKP. All the heavy- and light-duty trucks and most of the public transport buses operate on diesel fuel. The contribution of vehicle exhaust is dominant at the receptor sites

Table 4 Estimated percent source contributions from CMB 8.2 receptor modeling for Hyderabad, India

Period	Station	Mass ($\mu g/m^3$)	Road dust (%)	Vehicle exhaust (%)	Secondary sulfates (%)	Secondary nitrates (%)	Biomass burning (%)	Coal burning (%)
PM_{10}, winter	PG	159±8.0	28.5±6.0	37.4±7.7	4.8±1.1	2.3±0.6	6.3±2.9	20.0±4.5
	CKP	134±6.7	35.7±4.2	33.5±4.4	5.5±1.4	2.3±0.4	6.9±3.1	15.2±5.0
	HCU	105±5.3	33.6±6.2	43.6±6.6	7.1±1.8	2.6±0.5	6.9±2.8	6.1±3.4
$PM_{2.5}$, winter	PG	86±4.3	13.1±6.8	24.8±3.4	11±3.5	2.2±0.7	11.3±9.2	36.3±8.0
	CKP	68±3.5	16.6±5.6	29.5±3.1	12.6±3.7	2.2±0.3	12.0±8.9	26.0±8.3
	HCU	55±2.8	18.0±7.8	35.9±6.7	16.2±4.6	2.6±0.7	16.4±10.5	9.7±8.4
PM_{10}, summer	PG	110±5.6	35.7±10.2	46.1±9.2	2.8±1.0	2.2±0.7	6.9±3.9	9.8±10.5
	CKP	112±5.7	46.2±9.8	36.0±10.6	2.7±1.1	2.0±0.7	4.6±2.0	7.7±5.9
	HCU	63±3.3	51.2±15.5	30.1±12.9	5.8±3.3	2.9±1.5	5.4±4.8	4.2±3.4
$PM_{2.5}$, summer	PG	47±2.5	12.7±9.4	48.6±15.4	7.1±2.4	2.2±0.8	23.0±13.2	13.9±10.3
	CKP	42±2.4	21.7±6.5	52.1±9.4	7.2±3.8	1.9±0.7	11.0±8.9	14.5±10.6
	HCU	25±1.7	27.6±5.5	48.4±8.7	12.9±6.1	2.4±1.0	4.1±3.4	3.5±1.2
PM_{10}, rainy	PG	115±5.8	29.7±11.8	41.1±17.2	7.2±4.0	3.1±1.6	6.8±4.4	17.6±15.1
	CKP	85±4.4	25.3±16.1	45.8±15.9	10.7±4.4	3.4±1.3	8.7±5.9	11.2±9.9
	HCU	59±3.1	22.4±13.5	51.0±14.9	14.6±5.2	4.4±1.5	7.3±3.1	6.6±6.3
$PM_{2.5}$, rainy	PG	65±3.4	13.5±6.5	28.5±12.9	17.4±6.4	4.4±0.8	14.7±11.3	34.5±16.7
	CKP	53±2.9	12.1±8.2	28.0±10.5	20.8±5.2	3.6±1.0	9.9±7.2	29.9±11.2
	HCU	40±2.2	14.5±7.4	30.2±8.6	25.3±6.4	4.6±1.9	6.7±5.2	22.7±10.5

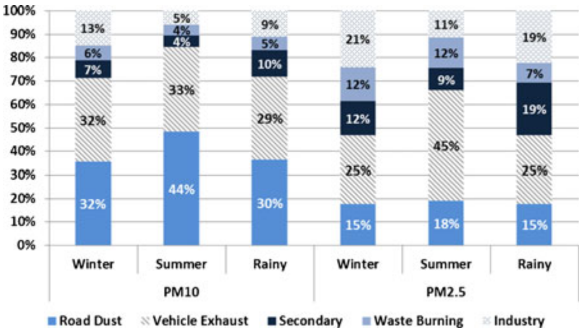


Fig. 3 Estimated average source contributions from receptor modeling by season (for all stations) for PM_{10} and $PM_{2.5}$ in Hyderabad, India

due to lower operating speeds in the city, the stop-and-go nature of traffic, and increasing idling times at major intersections for all vehicles. While city authorities are rallying to improve the public transport system and introduce alternative fuels to reduce daily emission rates, managing the growing number of personal vehicles and promoting alternative modes of transport are challenges.

The contribution of road dust resuspension is the highest for the PM_{10} fraction and dropped significantly for the $PM_{2.5}$ fraction to 15 %, which is also evident in the chemical analysis, where the heavy metals (i.e., aluminum and silicon) were largely present in the coarse mode of PM pollution (Table 3). Fugitive road dust emissions include soil dust, wear and tear from tires, and construction dust. These contributions also varied by season. For the rainy season, dust contributions ranged 22–28 %, while for the winter and summer months, dust contributions ranged 28–51 %. Road dust emissions are at a minimum in the rains, with little dust on the roads for resuspension. Daily average precipitation (in millimeters per day) estimated for the grid cell covering Hyderabad is presented in Fig. 4. During the experimental period, winter and summer sampling days were relatively dry; most rain was observed in the third phase, resulting in less ambient PM pollution and lower dust contribution. This is an important observation, given that many cities in India and other developing countries constantly experience higher levels of PM pollution due to resuspension of road dust, which can be easily solved with processes like wet sweeping.

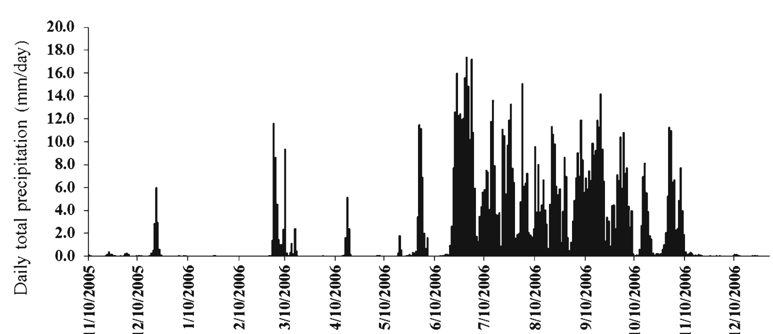
The contributions from coal combustion are 7 and 20 % for PM_{10} and 11 and 36 % for $PM_{2.5}$ for PG and CHK, respectively. The contribution is less than 10 % for HCU, except during the rainy season when 25 % for $PM_{2.5}$ was estimated. A portion of the coal combustion is associated with domestic cooking and heating. Since it is statistically impossible in a receptor model to distinguish between coal combustion in domestic and industrial sites, the coal markers were assumed in our analysis to represent the industrial contribution. Contributions from coal combustion were approximately three times higher in $PM_{2.5}$ than in PM_{10} due to higher EC and OC in the fine PM fractions.

Open waste burning, most often along roadsides or in residential areas, was the next significant source of PM pollution, especially for the fine fraction with more than 10 %. This source also has the largest uncertainty in knowing how much waste is actually collected from industrial and residential areas and how much is left to burn. While some programs are in place to promote recycling, reduce waste generation, and improve waste collection facilities in the city, the growing construction industry and expanding residential areas across the city reduce their efficiencies and thus increase the possibility of waste burning.

Summary and implications

Increasing urbanization and motorization have contributed to growing human health and environmental

Fig. 4 Total daily precipitation for the period of sampling; data extracted for the grid cell covering Hyderabad from the National Centers for Environmental Prediction reanalysis datasets



concerns in Hyderabad. Increasing pollution levels prompted the need for appropriate measures to combat air pollution, especially for PM, which is now linked to higher incidence of mortality and morbidity due to air pollution in Indian cities (HEI 2010; Guttikunda and Jawahar 2012). Major conclusions from this study include the following:

1. Ambient PM_{10} levels have increased significantly during the last 5 years due to population, vehicular, and industrial growth in the city.
2. Vehicular activity-based emissions (from direct vehicular exhaust and indirect fugitive dust) are the major sources of increasing PM pollution problems in the city.
3. Emissions from diesel combustion in passenger cars and trucks are a growing concern.
4. Though clustered into large pockets, long-range transport of effluent gases and particles from industries around the city are increasing. Addressing coal combustion and diesel usage in the generator sets can result in total emissions.
5. Road dust emissions were highest for the PM_{10} fraction.
6. Waste burning in residential areas, landfills, and along roadsides is a significant source for fine PM.

Based on these findings, a mix of interventions was proposed for better air quality management in Hyderabad. Overall, the potential for maximizing benefits for air quality and a reduction of greenhouse gas emissions and PM stays with the transportation sector. Details of the action plan and potential benefits analysis of various interventions, for transport, industrial, and waste management sectors are presented in IES (2008). Specific interventions discussed are (1) introduction of compressed natural gas in the public transport sector, which is currently underway on a pilot basis; (2) improving the inspection and maintenance program for personal and public transport vehicles; (3) improving the road maintenance in order to reduce the silt loading and dust resuspension; (4) abolishing diesel use in the generator sets in the industries; (5) abolishing the use of biomass and husk in the industries; (5) controlling illegal dumping and burning of garbage at the landfills; and (6) reducing the coal and biomass consumption in the domestic sector. With health as the primary indicator, an immediate benefit is recorded in mitigating the road dust emissions, either by reducing the number of vehicles on the road to reduce resuspension or by controlling the dust on various roads via wet sweeping. The largest co-benefit for health and greenhouse gas emissions are recorded in traffic management by promoting public transport and freight movement (via trucks) and improving energy efficiency in the industrial estates.

Finally, utilization of emerging techniques, such as source apportionment, is increasingly aiding environmental compliance studies (CPCB 2010; Johnson et al. 2011). In combination with better understanding of source contributions and their strength to control pollution levels, these studies can address policy-relevant issues like which sources to target for effective pollution control and where to target such efforts (e.g., suspected hot spots).

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