

Source emissions and health impacts of urban air pollution in Hyderabad, India

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Received: 24 August 2013 / Accepted: 5 November 2013 / Published online: 19 November 2013
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Abstract The source apportionment study in Hyderabad listed transportation, industries, and waste burning as critical sources of particulate matter (PM) pollution in the city. In this paper, we present sector-specific emissions for 2010–2011 for the Greater Hyderabad Municipal Corporation region, accounting for 42,600 t of PM₁₀ (PM size <10 μm), 24,500 t of PM_{2.5} (PM size <2.5 μm), 11,000 t of sulfur dioxide, 127,000 t of nitrogen oxides, 431,000 t of carbon monoxide, 113,400 t of non-methane volatile organic compounds, and 25.2 million tons of carbon dioxide emissions. The inventory is spatially disaggregated at 0.01° resolution on a GIS platform, for use in a chemical transport model (ATMoS). The modeled concentrations for the urban area are 105.2±28.6 μg/m³ for PM₁₀ and 72.6±18.0 μg/m³ for PM_{2.5}, when overlaid on gridded population, resulted in estimated 3,700 premature deaths and 280,000 asthma attacks for 2010–2011. The analysis shows that aggressive pollution control measures are imperative to control pollution in Hyderabad and reduce excess exposure levels on the roads and in the residential areas. The planning and implementation of measures like advancing the public transportation systems, integrating the road and metro-rail services, promotion of walking and cycling, introduction of cleaner brick production technologies, encouraging efficient technologies for the old and the new industries, and better waste management systems to control garbage burning need to take priority, as these measures are expected to result in health benefits, which surpass any of the institutional, technical, and economic costs.

Keywords Particulate pollution · Emissions inventory · Dispersion modeling · SIM-air · ATMoS

Introduction

In Hyderabad, to address the growing air pollution problem, the Andhra Pradesh Pollution Control Board (APPCB), along with national and international bodies, coordinated efforts to quantify major sources of air pollution and support development of a comprehensive pollution control action plan for the city. In the Greater Hyderabad Municipal Corporation (GHMC), for three monitoring sites, filter sampling was conducted in 2005–2006, followed by chemical analysis, and receptor modeling using the chemical mass balance model (Guttikunda et al. 2013a). The study estimated, on average for PM₁₀ pollution (PM size <10 μm), the most contribution is from vehicle exhaust—30 % from direct vehicle exhaust and 30–45 % (depending on the season) from resuspension of road dust, followed by coal combustion in the industrial sector, and open waste burning. Similar results were reported for one urban site in the city (Gummeneni et al. 2011). For six other Indian cities, similar studies highlighted transport and road dust as major sources to PM₁₀ pollution (CPCB 2010).

The particulate matter (PM) source apportionment via receptor modeling, while presents results pertinent to the monitoring locations, they also provide a basic understanding of the mix of sources currently contributing to the total emissions and total ambient pollution. However, a major limitation is in the spatial spread of the results (Johnson et al. 2011). Since the methodology is expensive, involving sampling and chemical analysis, the number of sites involved and the number of samples collected are limited, which tend to undermine the overall mixed nature of residential, industrial, and transport centric areas in the city. For urban air quality management, the capacity to conduct top-down receptor modeling and bottom-

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up emissions inventory studies is a necessity and knowing the emission sources across the city and their strengths for mitigating air pollution is vital (Fenger 1999; Shah et al. 2000; Schwela et al. 2006).

In this paper, results of a GIS-based emissions inventory for the base year 2010–2011 for the GHMC region (Fig. 1) are presented, which includes the earlier municipal corporation of Hyderabad, surrounding ten municipalities and eight panchayats from the Rangareddy district and two municipalities from the Medak district. Also discussed are the relative contributions of major sources to total PM pollution loads via dispersion modeling to consolidate and compare with the source apportionment results from receptor modeling, health impacts assessment for the base year, and a series of actions currently underway in the city to control pollution. Similar analysis was conducted to estimate total emissions and health impacts for base year 2010, for seven other cities in India (Guttikunda and Jawahar 2012; Guttikunda and Calori 2013).

Source emission modeling

Every city has unique air quality challenges that require customized approaches to estimate emissions and model pollution. Critical pollutants, sources, meteorology, geography, population distribution, history, institutions, and information base vary for every city. The SIM-air, “Simple Interactive Models for better AIR quality,” family of tools are developed in a customizable format using available information to provide a framework to organize and update critical data on air quality (SIM-air 2013). All the databases, calculations, and interfaces are maintained in

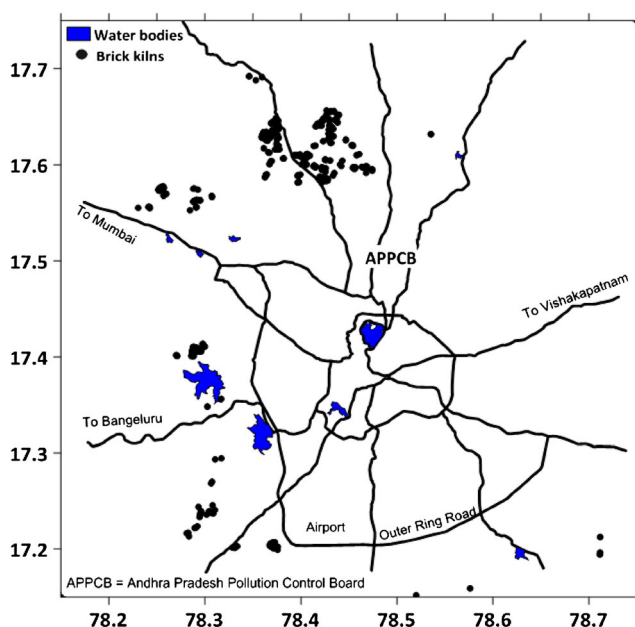


Fig. 1 The modeling domain for the Greater Hyderabad Municipal Corporation marked with main highways, water bodies, and brick kilns

spreadsheets for easy access and model transparency. For Hyderabad, these tools were utilized for emissions and air pollution assessment in 2006–2007 (IES, 2008) and for seven other cities in India—Pune, Chennai, Ahmedabad, Indore, Surat, Rajkot, and Delhi (Guttikunda and Jawahar 2012; Guttikunda and Calori 2013), Dhaka, Bangladesh (Guttikunda et al. 2013b), and Ulaanbaatar, Mongolia (Guttikunda et al. 2013c).

Methodology and inputs

The methodology for estimating total emissions is updated from IES (2004), based on fuel consumption data and applicable emission factors for transport, industrial, and domestic sectors (SEI 2006; CPCB 2010; GAINS 2010). The emissions inventory is developed for total PM in two bins (PM₁₀ and PM_{2.5}), sulfur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), and carbon dioxide (CO₂).

A large percentage of the increase in air pollution was attributed to the growing vehicle population (Guttikunda et al. 2013a). According to the Ministry of Road Transport and Highways, the in-use vehicular population grew from 1.45 million in 2001 to 2.0 million in 2007 and 3.0 million vehicles in 2011. Of the total registered fleet, two-wheelers (including mopeds, scooters, and motorcycles) and passenger four-wheelers are the dominant, followed by heavy duty (HDV) and light duty (LDV). Besides cars, motorcycles, and trucks, the registered fleet information includes the public, contract, school, and private sector buses and para-transit vehicles that can carry three to seven passengers per trip. Detailed break-up of the registered vehicles in the city is presented in Table 1. For the transport sector, the ASIF principles were utilized (Schipper et al. 2000) to calculate the

Table 1 Registered vehicle fleet in Hyderabad, as of March 31st of 2010 and 2011

Vehicle category	2010	2011
Two-wheelers	1,929,000	2,145,000
Cars and jeeps	446,000	501,000
Buses (local carriages)	23,000	25,500
Buses (omni—long distance)	23,000	26,000
Taxis	26,500	30,000
Light duty (passengers—3-seater)	82,500	90,500
Light duty (passengers - 4–6-seater)	3,000	3,000
Light duty (goods—3-wheeled)	16,500	19,500
Light duty (goods—4-wheeled)	60,000	65,500
Heavy duty vehicles	107,000	115,000
Tractors and Trailers	8,000	8,500
Others	6,500	7,000
Total	2,731,000	3,036,500

exhaust emissions using total travel activity (A), modal shares (S) in vehicle kilometer traveled per day, modal energy intensity (I) representing energy use per kilometer, and an emission factor (F) defined as the mass emitted per vehicle kilometer traveled. The average vehicle kilometers traveled per day are assigned at 150 km for public transport buses (operational for 8–10 h at an average speed of 15 km/h during the day), 40 km for passenger cars and multi-utility vehicles, 80 km for taxis and light commercial vehicles, 150 km for three-wheelers and other para-transit vehicles, and 200 km for heavy duty vehicles (most of them operating on the highways and in the industrial areas). A summary of fleet average emission factors is presented in Table 2. These emission factors were developed for the Indian fleet, as part of a six-city source apportionment and emissions inventory study conducted by the Ministry of Environment and Forests (CPCB 2010). The transport emissions inventory also includes landing and take-off emissions at the airport, located south of the city center (Fig. 1).

Many studies have developed empirical functions that estimate resuspension rates. We estimated resuspension of dust on roads using the United States Environmental Protection Agency (USEPA) AP-42 methodology (USEPA 2006; Kupiainen 2007), which suggests its application for average road speeds less than 55 mph. The average speeds in Hyderabad are less than 25 km/h for the highways and less than 20 km/h for the main and arterial roads in the city. The total gridded road dust emissions are estimated based on the vehicle density data from the Ministry of Road Transport and Highways and fractions assigned for each vehicle type to two road categories (main and arterial). Silt loading was manually

measured on three road types ranging between 30 and 100 g/m² depending on the paved or unpaved conditions.

The industrial emissions inventory is based on in-city surveys conducted by APPCB, which also audited emission rates at 335 industrial locations, ranging from steel to textiles, paper, agricultural processing, pharmaceuticals, and paint manufacturing. Besides the emission rates measured at the stacks, the audit also assessed the fuel mix—including coal, biomass, gaseous fuels, diesel, and furnace oil. A summary of the emission rates and aggregate emissions by fuel type is presented in Table 3, along with the list of major industrial estates in GHMC. This was further substantiated with the industrial fuel consumption data from the Ministry of Statistics.

Besides the traditional manufacturing industries, there are kiln clusters around the metropolitan city, supporting the growing demand for traditional red and fired clay bricks in the construction sector. The location of the brick kiln clusters is marked in Fig. 1, predominantly in the north and northwest parts of the city. More clusters were identified further south of the modeling domain, which are not included in this analysis. The brick manufacturing includes land clearing for sand and clay, combustion of fuel for burning, operation of diesel engines on site, and transport of the end product to various parts of the city. Traditionally, the rectangle-shaped clay bricks are sun dried and readied for firing in “clamps”—a pile of bricks with intermittent layers of sealing mud, and fuel. This fuel would vary from agricultural waste to biofuels like cow dung and wood to fossil fuels like coal and heavy fuel oil. The clamp style is a batch process and the most inefficient of the practices. Unlike the cities of Delhi (Guttikunda and Calori

Table 2 Fleet average emission factors (in gm/km) for Indian vehicles

Vehicle	Fuel	CO	HC	NO _x	CO ₂	PM
2-Wheelers	Petrol—2 stroke	3.62±2.50	2.87±1.78	0.028±0.011	25.9±6.5	0.054±0.019
2-Wheelers	Petrol—4 stroke	1.33±0.85	0.55±0.19	0.297±0.113	29.6±9.7	0.016±0.009
3-Wheelers	Petrol	1.98±0.79	2.36±2.17	0.318±0.150	64.9±7.8	0.048±0.036
3-Wheelers	Diesel	8.55±12.6	0.63±0.83	0.890±0.510	145.2±24.8	0.545±0.580
3-Wheelers	CNG	0.84±0.21	1.16±1.27	0.345±0.219	67.7±14.1	0.066±0.072
3-Wheelers	LPG	3.04±1.90	2.31±1.81	0.06±0.028	61.3±9.6	0.425±0.417
Cars	Petrol	2.91±1.67	0.36±0.28	0.369±0.348	127.0±28.8	0.007±0.006
Cars	Diesel	0.52±0.33	0.19±0.07	0.534±0.207	151.0±13.7	0.118±0.077
Cars	CNG	0.50±0.40	0.53±0.22	0.426±0.375	141.0±9.3	0.003±0.002
Cars	LPG	4.75±2.87	0.54±0.43	0.350±0.212	135.0±6.5	0.001±0.000
MUVs	Diesel	1.29±0.96	0.79±0.62	1.220±0.829	213.0±37.7	0.361±0.242
LCVs	Diesel	3.24±0.36	1.63±0.55	2.543±0.458	353.0±41.0	0.709±0.265
Buses	Diesel	8.40±4.86	1.10±1.03	11.13±3.572	752.0±144.	1.080±0.725
Buses	CNG	3.72±0.00	3.75±0.00	6.210±0.000	806.0±0.00	0.00±0.00
HCVs	Diesel	12.6±9.40	1.50±1.59	11.57±3.210	799. ± 53.1	1.602±0.512

Source: CPCB (2010)

MUVs multi-utility vehicles, LCVs light commercial vehicles, HCVs heavy commercial vehicles

Table 3 Range of measured emission rates (kg/h) and fuel consumption (tons per day) at major industrial clusters in Hyderabad, India

Industrial estate	Emission rate at stacks			Aggregate energy consumption by cluster				
	SPM (kg/h)	SO ₂ (kg/h)	NO _x (kg/h)	Coal (ton/day)	Biomass (ton/day)	Gas (kg/day)	Diesel (lit/day)	Furnace oil (lit/day)
Azamabad	1.92±1.28	0.44±0.28	0.24±0.14	275	–	–	–	700
Balanagar	0.31±0.45	0.36±0.22	0.18±0.17	20	–	–	886	1,300
Gaganpahad	1.05±0.58	0.45±0.40	0.43±0.54	74	88	–	40	8,800
Jeedimetla	0.64±0.90	0.70±1.71	0.54±1.26	174	–	–	2,750	28,900
Kattedan	1.47±0.51	0.50±0.55	1.60±1.71	15	37	–	40	–
Mallapur	0.35±0.32	0.29±0.33	0.20±0.30	4	6	–	1,060	40
Medchal	0.25±0.27	0.70±0.43	0.20±0.19	25	4	400	2,710	5,900
Nacharam	0.72±0.73	0.60±0.67	0.57±0.97	23	13	–	1,495	15,555
Qutubullapur	0.27±0.34	0.51±0.31	0.13±0.09	14	5	–	2,851	11,376
Uppal	1.50±1.06	0.75±0.73	1.07±1.39	9	3	–	770	4,440
All estates (including small estates)	0.84±1.07	0.67±1.22	0.47±0.94	819	406	400	44,532	126,475

2013) and Chennai (Guttikunda and Jawahar 2012), where advanced manufacturing technologies with 50-m chimneys to disperse the pollution are in practice, the brick kilns around Hyderabad are clamp style. In this type of kilns, all the material is fired at once and cooled to draw the bricks. A significant amount of energy is lost during the cooling with no possibility of recycling. The emerging technologies and emission factors for kilns in India are documented in Mathiel et al. (2012). The inventory also includes fugitive dust estimates for construction sites based on empirical functions proposed under the USEPA AP-42 methodology (USEPA 2006).

The domestic sector emissions inventory is based on fuel consumption estimates for cooking and waste burning. Using census statistics, household total energy consumed in the form of solid (coal and wood), liquid (kerosene), and gaseous (LPG) fuels was estimated at the grid level (IFMR 2013). In the city, the dominant fuel is LPG. In slum areas, construction sites, some restaurants, and areas outside the municipal boundary, however, use of coal, biomass, and agricultural waste is common. A survey conducted by APPCB estimated that on average 5 % of households in GHMC use coal and wood for cooking purposes (APPCB 2006). The gridded population at 30-s spatial resolution from GRUMP (2010) was interpolated to the model grid, with the high-density areas utilizing mostly LPG and the low-density areas utilizing a mix of fuels.

Garbage burning in the residential areas emit substantial amount of pollutants and toxins and this is a source with the most uncertainty in the inventories. Because of the smoke, air pollution, and odor complaints, the local authorities have banned this activity, but it continues unabated at makeshift landfills. According to the city development plan submitted to the Jawaharlal Nehru National Urban Renewable Mission, GHMC produces an estimated 4,500 t of solid waste, which

is transported to collection units and then to a landfill facility to the northeast of the city. The facility is located on approximately 350 acres of land, with a capacity to handle 3,500 t of waste per day (Galab et al. 2004). It is assumed that at least once a week, the garbage is put to fire at an estimated 1,000 makeshift sites in the city.

There are no power plants in the immediate vicinity of the modeling domain. While most of the electricity needs are met by the coal and gas-fired power plants situated to the north of the city (closer to the coal mines), a large proportion of mobile phone towers, hotels, hospitals, malls, markets, large institutions, apartment complexes, and cinemas supplement their electricity needs with in situ diesel generator sets. For example, a five-star hotel or a big hospital is estimated to consume 10,000 l of diesel per month, a mobile phone tower experience 2–4 h power cuts per day is expected to consume 3,000–5,000 l of diesel per month, and an apartment complex is expected to consume between 1,000 and 10,000 l of diesel per month, depending on the size of the complex. The total diesel consumption in the in situ generator sets is estimated at 11 PJ. Emission factors for diesel generators are obtained from GAINS (2010).

Results and discussion

For 2010, the emissions inventory results are summarized in Table 4, with estimates of 42,600 t of PM₁₀, 24,500 t of PM_{2.5}, 11,000 t of SO₂, 127,000 t of NO_x, 431,000 t of CO, 113,400 t of NMVOCs, and 25.2 million tons of CO₂. For reference, the estimated PM₁₀ inventory for other cities in India in tons/year for the year 2010 was 38,400 in Pune, 50,200 in Chennai, 18,600 in Indore, 31,900 in Ahmedabad, 20,000 in Surat, and 14,000 in Rajkot (Guttikunda and Jawahar 2012). The cities of

Table 4 Estimated particulate and gaseous pollutant emissions inventory for the Greater Hyderabad Municipal Corporation for the base year 2010–2011

Category	PM _{2.5} tons/year	PM ₁₀ tons/year	SO ₂ tons/year	NO _x tons/year	CO tons/year	VOC tons/year	CO ₂ Million tons/year
Vehicle exhaust	5,900 (24 %)	7,000 (16 %)	1,300 (12 %)	91,000 (72 %)	132,600 (31 %)	81,100 (72 %)	21.9 (87 %)
Road dust	1,400 (6 %)	9,000 (21 %)					
Domestic	3,300 (13 %)	4,100 (10 %)	800 (7 %)	1,400 (1 %)	87,700 (20 %)	9,400 (8 %)	0.8 (3 %)
Industries	7,300 (30 %)	10,300 (24 %)	6,200 (56 %)	17,000 (13 %)	140,000 (32 %)	11,700 (10 %)	1.3 (5 %)
Brick Kilns	2,900 (12 %)	4,100 (10 %)	2,000 (18 %)	2,500 (2 %)	49,600 (12 %)	5,500 (5 %)	0.3 (1.3 %)
Construction	1,800 (7 %)	5,800 (14 %)	100 (0.9 %)	1,600 (1.3 %)	2,000 (0.5 %)	100 (0.1 %)	0.1 (0.3 %)
Generator sets	700 (3 %)	700 (2 %)	500 (5 %)	13,000 (10 %)	13,600 (3 %)	5,100 (4 %)	0.7 (3 %)
Waste Burning	1,200 (5 %)	1,600 (4 %)	100 (0.9 %)	500 (0.4 %)	5,800 (1 %)	500 (0.4 %)	
Total	24,500	42,600	11,000	127,000	431,300	113,400	25.2

Pune, Chennai, and Ahmedabad are comparable sizes in geography, demography, and industrial activity.

The percent contributions by sector are also presented in Table 4. For PM₁₀, vehicle exhaust and dust (due to constant movement of the vehicles on the roads) account for 37 % of the total inventory, followed by 34 % from the industries (including brick kilns), with the remainder from residential fuel combustion, garbage burning, construction activities, and generator usage at commercial and residential locations. For NO_x and VOC, transport remains the dominant source of emissions. For SO₂, main source of fuel is diesel and coal from the transport and industrial sectors.

For the transportation sector, the percentage contributions by vehicle type are presented in Fig. 2. Overall, the diesel-based vehicles in the public transportation system, HDVs and LDVs dominate the emissions for PM, SO₂, NO_x, and CO. The city public transportation system operates 15,000 point-to-point buses, the largest state-owned public transportation system in India, which connects important locations with good frequency. This includes a variety of bus categories from “ordinary buses” stopping at all stations, “metro buses” stopping at designated stations for faster movement, and “stage carriage” buses which are mostly used for shuttling school children and office staff during the rush hours (morning and evening) and for long haul trips—mostly intercity. Hyderabad also operates a light rail transportation system known as the Multi-Modal Transport System, covering 27 stations with a total rail length of 43 km. An estimated 100,000 commuters use this service every day, and the city is planning to expand the service. An expansion of the urban metro-rail system is expected to reduce some load of passenger vehicles on the roads through 2015.

A fleet of three-seat and seven-seat passenger vehicles is part of the public transportation system. In 1999, an ordinance was passed to replace petrol-based three-wheelers with LPG, which resulted in notable reduction in the PM pollution over the period of 4 years, decreasing from 128 µg/m³ in 1999 to 83 µg/m³ in 2002 (Guttikunda et al. 2013a). However,

recently, a much higher growth rate in the passenger cars (petrol and diesel) has nullified the impact of this conversion. Currently, 60 % of the three-seat and more than 90 % of the seven-seat passenger vehicles are LPG-based and city authorities expect full fleet conversion by 2013–2015.

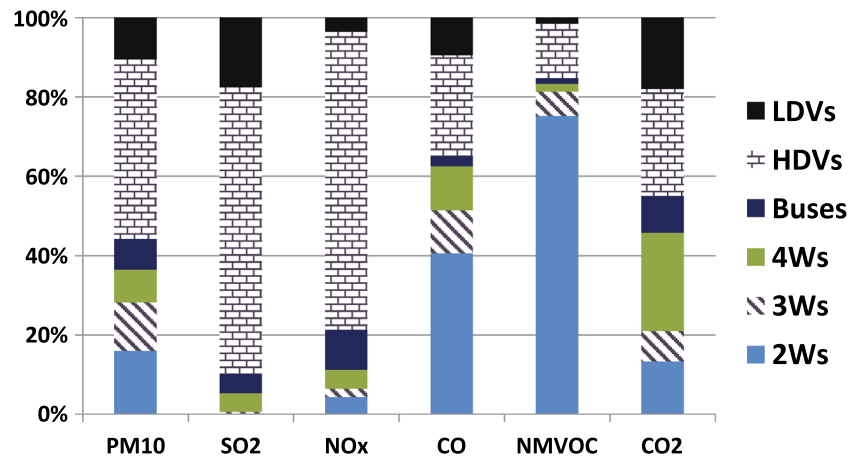
The primary source for SO₂ emissions is coal and diesel burned at industries (56 %) and diesel usage in HDVs, some passenger cars, and generator sets. Although better controls for desulfurization are being proposed and in use, an increase in production rates and need for more mobile towers in the city is leading the fuel consumption rates among the industrial and generator set sectors and thus the sulfur emissions. Diesel-based HDVs, LDVs, and buses contribute 90 % of total SO₂ emissions from the transportation sector.

The manufacturing industries range from steel, textiles, paper, pharmaceuticals, and paints spread across 20+ industrial estates. In 2001, an environmental audit as part compliance and regulation exercise conducted by APPCB listed more than 650 industries. In 2005, a similar environment audit listed only 390 industries in the clusters, as a result of a combination of closing down, relocation, and merging of industries into designated estates. Relocation and merging of the industries inherently led to improvement in the energy efficiency. The largest industrial estates in GHMC are in Jeedimetla, Patancheru, Medchal, Nacharam, and Azamabad. The list of industries in the estates is obtained from the APPCB industrial audit database.

Alternatively for CO₂, the emissions load is equally divided between two-wheelers, private cars, public transportation buses, and goods vehicles. In the transportation inventory, emissions from the aviation sector also include landings and take offs, service vehicles operating at the airport terminal, and idling of passenger vehicles at the terminals.

Overall, the emissions inventory estimation has an uncertainty of ±20–30 %. Since the inventory is based on bottom-up activity data in the city and secondary information on emission factors, mostly from the studies conducted in India and Asia, it is difficult to accurately

Fig. 2 Share of vehicle exhaust emissions by vehicle type for the Greater Hyderabad Municipal Corporation



measure the uncertainty in our estimates. In the transport sector, the largest margin is in vehicle kilometer traveled and vehicle age distribution with an uncertainty of $\pm 20\%$ for passenger, public, and freight transport vehicles. The silt loading, responsible for road dust resuspension, has an uncertainty of $\pm 25\%$, owing to continuing domestic construction and road maintenance works. In the brick manufacturing sector, the production rates which we assumed constant per kiln has an uncertainty of $\pm 20\%$. The data on fuel for cooking and heating in the domestic sector is based on national census surveys with an uncertainty of $\pm 25\%$. Though lower in total emissions, open waste burning along the roads and at the landfills has the largest uncertainty of $\pm 50\%$. The fuel consumption data for the in situ generator sets is obtained from random telephone surveys to hotels, hospitals, large institutions, and apartment complexes, with an uncertainty of $\pm 30\%$.

The emissions inventory for GHMC is maintained on a GIS platform and spatially segregated at a finer resolution of 0.01° in longitudes and latitudes (equivalent of 1 km) and for further use in atmospheric modeling. The gridded total PM_{10} and NO_x emissions are presented in Fig. 3. We used spatial proxies to allocate the emissions for each sector to the grid, similar to the methodology utilized for six other cities in India (Guttikunda and Jawahar 2012). In the case of the transport sector, we used grid-based population density, road density (defined as number of kilometers per grid), and commercial activity like industries, brick kilns, hotels, hospitals, apartment complexes, and markets to distribute emissions on feeder, arterial, and main roads. Emissions from industries were allocated the respective industrial estates and brick kiln emissions were directly assigned to their respective clusters. The domestic sector and garbage burning emissions are distributed based on the population density (GRUMP 2010). From Fig. 3, for PM_{10} , the highest density of emissions is in the city

due to vehicle exhaust and around the city along the industrial estates including brick kiln clusters, and for NO_x , the highest density of emissions is due to vehicle exhaust in the city.

Source dispersion modeling

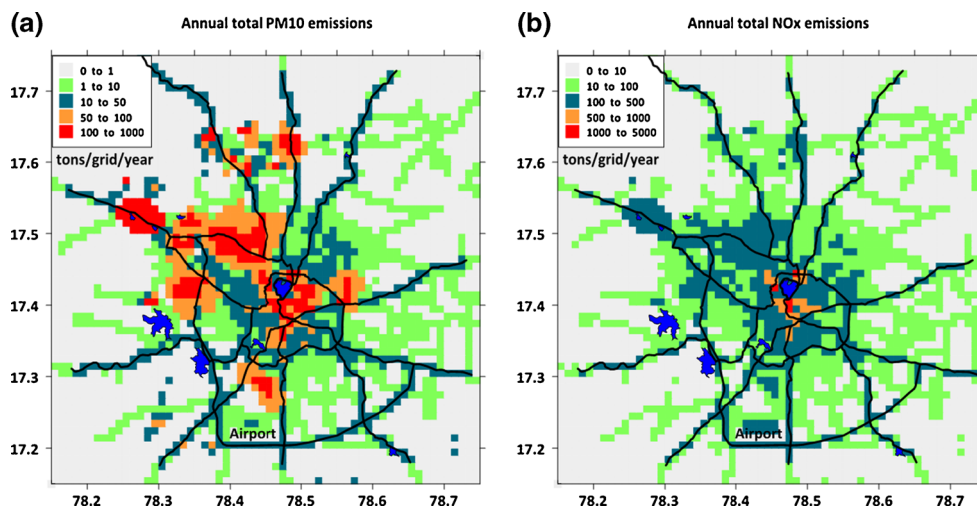
The emissions inventory analysis provided apportionment of emissions at the source level, as the weight of pollution from various sources (mass/year). The physical and chemical characteristics of the sources, such as emission release height, particle sizes, and composition, influences the dispersion potential of these emissions, which determine the ambient concentrations. In order to compare the source apportionment study results with the contributions based on the emissions inventory analysis, we conducted the atmospheric dispersion modeling over the modeling domain.

Model description

The modeling domain is divided into 60×60 grids extending between 78.15 and $78.75^\circ E$ in longitude and between 17.15 and $17.75^\circ N$ in latitude, at a grid resolution of 0.01° in longitude and latitude (Fig. 1). The vertical resolution is maintained in three layers—surface, mixing layer, and upper layer, reaching up to 6 km. The multiple layers allow the model to differentiate the contributions of near-ground diffused area sources, like transport and domestic sectors and elevated sources like industrial and brick kilns.

We utilized the Atmospheric Transport Modeling System (ATMoS) dispersion model—a regional (and urban) forward trajectory Lagrangian Puff transport model to estimate the ambient PM concentrations (Calori and Carmichael 1999). A detailed review of the model parameters and meteorological inputs are presented in previous applications of the model (Arndt et al. 1998; Holloway et al. 2002; Guttikunda et al. 2003; Guttikunda and Jawahar 2012; Guttikunda and Goel

Fig. 3 Gridded total PM₁₀ and NO_x emissions inventory for the Greater Hyderabad Municipal Corporation



2013). The dispersion model schematics are summarized in the equation below for changes in concentrations (δC) and emissions (δE) by grid.

$$\delta C_{\text{grid}} = \int_{i=1}^{\# \text{sources}} \int_{j=1}^{\# \text{grids}} \int_{\text{met}=1}^{\# \text{hours}} \delta E_{\text{advection}} - \delta C_{\text{deposition}} \pm \delta C_{\text{reactions}} \quad (1)$$

The emissions puffs for each source are advected through the model grid using the meteorological data (three-dimensional wind, temperature and pressure, surface heat flux, and precipitation fields) derived from the National Center for Environmental Prediction (NCEP 2013) and interpolated on the model grid. The advected puffs are subjected to dry and wet deposition schemes, which are activated when the puffs are in the surface layer and when there is precipitation, respectively. Because GHMC is located on the Deccan plateau, the mixing layer heights over the region are typically higher. On average, annual daytime average heights are more than 1,000 m and night time heights are more than 400 m. The summer time heights can be as high as 2,500 m. This is different from cities like Delhi, which experience a diverse variation in mixing layer heights between summer and winter months and severely affecting the ground level pollutant concentrations (Guttikunda and Gurjar 2012).

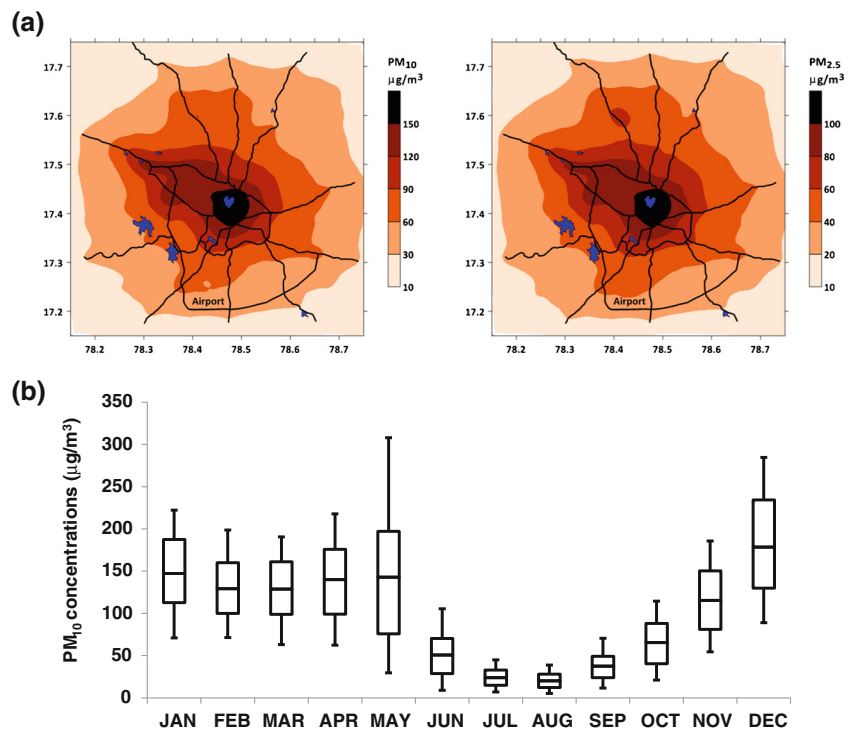
The total PM concentrations include both the primary PM contributions and secondary contributions from SO₂ to sulfate aerosols and NO_x to nitrate aerosols via chemical transformation. The nitrate aerosol transformation is explained in Holloway et al. (2002) and sulfate aerosol transformation is explained in Guttikunda et al. (2003). The primary PM emissions are also modeled in two bins due to differential deposition and advection characteristics—coarse fraction comprises of PM₁₀ to PM_{2.5} mass and fine fraction comprises of everything less than PM_{2.5} mass. All the secondary aerosols are considered as part of the fine PM less than PM_{2.5}.

Modeled particulate concentrations

The modeled annual average concentrations for PM_{2.5} and PM₁₀ due to all sources are presented in Fig. 4a. All the concentrations exceed the national annual standards of 40 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 60 $\mu\text{g}/\text{m}^3$ for PM₁₀. The results from the dispersion model are also available by month to study the seasonality of the emissions and air quality. The monthly average maps are not presented in this paper. However, we extracted the monthly data for all the grids covering the municipal area and presented in Fig. 4b. The variation of monthly average concentrations is among the grid cells, with the box plot representing the 25th, 50th (mean), and 75th percentile and the error bars representing the 5th and 95th percentile concentrations. The seasonality with the lowest concentrations in the summer months is primarily due to significant rains, and as the dry season picks up over the winter months, the concentrations rise. For the selected city area, covering 675 km², the modeled annual average PM₁₀ concentrations is 105.2 \pm 28.6 $\mu\text{g}/\text{m}^3$ and for PM_{2.5} concentrations is 72.6 \pm 18.0 $\mu\text{g}/\text{m}^3$. The range of average PM₁₀ concentrations measured at the 20 monitoring stations operated by APCCB in 2010 was 82.2 \pm 24.6, 96.2 \pm 12.1, and 64.3 \pm 21.2 $\mu\text{g}/\text{m}^3$ of PM₁₀, at commercial, industrial, and residential monitoring stations, respectively (Guttikunda et al. 2013a). None of these stations currently measure PM_{2.5}. These are manual stations where the samples are collected every 2 or 3 days. There is only one continuous air quality monitoring station in the city, operated on the premises of APCCB.

For the three sites where the receptor modeling was conducted, we extracted the modeled annual average concentrations for comparisons. The station measurements are representative of the surroundings of the monitoring location, so the model results are extracted and presented in Fig. 5 over 25 grids surrounding the monitoring station—the plot represents 25th and 75th percentiles for the box and 5th and 95th

Fig. 4 **a** Modeled annual average total PM_{10} and $PM_{2.5}$ concentrations for the Greater Hyderabad Municipal Corporation and **b** range of modeled daily-grid-average PM_{10} concentrations by month, for the municipal Hyderabad of 675 km^2



percentiles for the error bars. The variation in the measured concentrations is temporal over three seasons and ranged 90–167 $\mu g/m^3$ for Punjagutta station, 84–133 $\mu g/m^3$ for Chikkadpally station, and 54–104 $\mu g/m^3$ for Hyderabad Central University station for ambient PM_{10} . The comparisons are reasonably captured to ensure that the emission estimates, the spatial disaggregation of the emissions, and the dispersion model runs are representative of the regional geography and meteorological conditions.

Source contributions

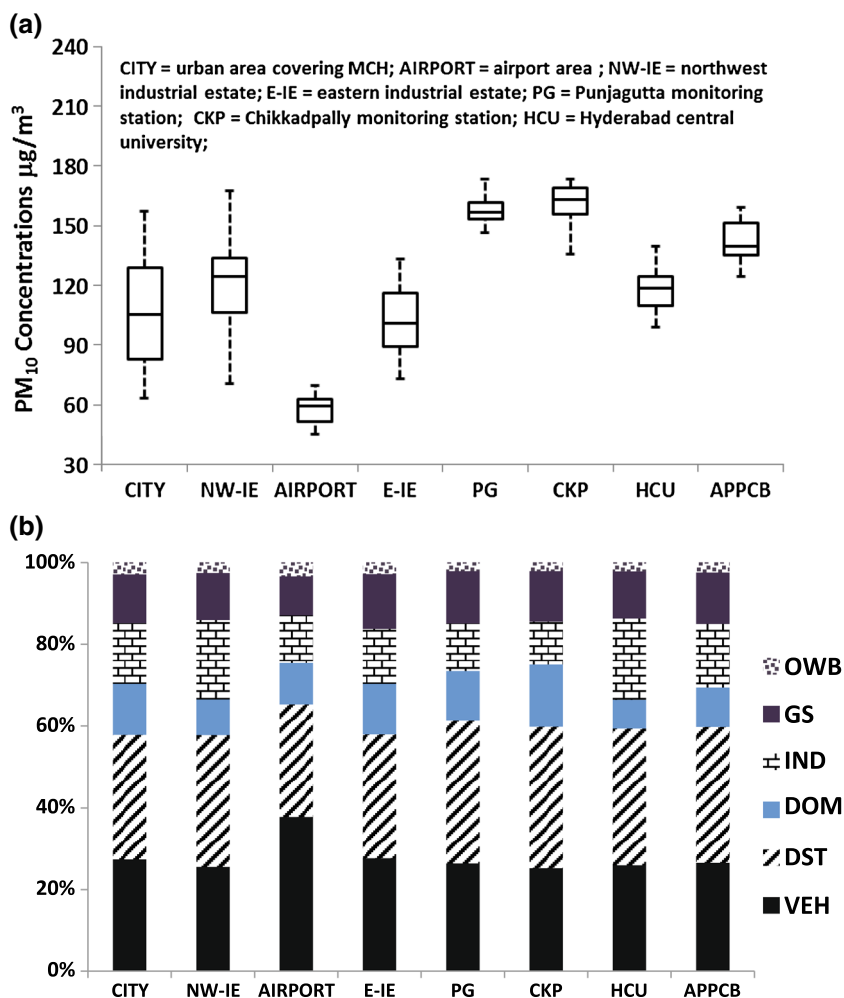
The dispersion modeling was also conducted at the sectoral level. For this exercise, emissions from individual sectors were modeled separately for PM, SO_2 , and NO_x . The percentage contribution of the major sectors—vehicle exhaust, resuspended dust (including dust due to vehicle movement on the roads and due to the construction activities), industries (including brick kilns), and residential sector (including domestic cooking and open waste burning) to the ambient annual average PM_{10} concentrations—is presented in Fig. 6. For convenience, only PM_{10} maps are presented in this paper. Similar information exists for $PM_{2.5}$ and all sectors listed in Table 4.

In GHMC, the vehicular activity dominates the ambient PM concentrations, followed by other ground level sources such as domestic combustion, generator sets, open waste burning, and then the industries. For the vehicle exhaust emissions, the shares are lesser in the southern parts compared to the northern parts due to the presence of the industries and

brick kilns (Fig. 1) in the north and northwest parts. The highest shares are recorded over the airport region because the aviation emissions are included in this sector, and for the grids covering the airport, the only source of emissions is the transport sector. The highways leading into and out of the city are also marked with higher shares due to presence of long-distance transport buses, HDVs, and to a limited extent light passenger vehicles and LDVs. For the residential sector, the shares ranged 10–15 % over the industrial area and 15–20 % for the over the high-density areas—marked with a significant share of low and medium income groups using a mix of fuels of cooking and likely emissions from open waste burning. The highest shares are recorded for the areas outside the main city area which is also marked with smaller annual average concentrations (Fig. 4). The resuspended dust is consistently present over most parts of the city, with higher shares over the urban area—marked with booming construction (residential, commercial, and road sectors), the highways—marked with movement of HDVs, which tend to resuspend more than the light weight vehicles. Overall, for the municipal region, the contributions ranged between 20 and 50 % for vehicular sources, 40 and 70 % when combined with road dust, and 10 and 30 % for industrial sources. Domestic and garbage burning sources ranged between 3 and 10 % and concentrated outside of the municipal boundaries.

The source contributions are also consistent with the results from the receptor modeling (Guttikunda et al. 2013a). For the sampling sites at Punjagutta, the modeled sectoral contributions are extracted from 25 grid cells covering the site. The

Fig. 5 a Variation of modeled annual average PM_{10} concentrations over the select regions and around receptor model sampling sites in the Greater Hyderabad Municipal Corporation. **b** Modeled annual average contributions by sector to the same regions



variation in the concentrations at these sites and the average contributions by sector are summarized in Fig. 5, along with concentrations and contributions for four other select areas. There are a number of caveats when making comparison of receptor modeling results with the modeled contribution results. In the case of receptor modeling, there is no distinction made between diesel utilized by vehicles and generator sets, since the source profile for diesel is the same in either case because of which the entire diesel portion is often assigned to the vehicular contribution. This tends to over predict the contribution of vehicular emissions and under predict (or not predict) any industrial and generator set contributions. Similarly, it is difficult to distinct between the molecular markers of coal combustion in the industries and in the domestic sector. In addition, all types of dust (road and soil) are lumped together; leading to an over prediction of the road dust resuspension. Also, the air pollution modeling results are annual average values, whereas the receptor modeling results are averaged over the three sampling months and three sampling sites spread over 1 year. In spite of these issues, the results from two different approaches are similar and highlight the need to

control emissions from vehicles and industries in order to reduce ambient PM_{10} and $PM_{2.5}$ levels in Hyderabad. This first-order comparison of results from two different approaches provided a baseline for future pollution control policy analysis and dialogue for the city authorities.

Health impacts

The global burden of disease assessment for 1990–2010 quantified the trends of more than 200 causes of deaths and listed outdoor air pollution among the top ten causes of deaths for India (IHME 2013). For India, total premature mortality due to outdoor particulate matter (PM) pollution is estimated at 627,000, with a vast portion of this occurring in the urban centers. The World Health Organization studied publicly available air quality data from 1,100 cities, including cities with populations of more than 100,000 people and listed 27 cities in India among the top 100 cities with the worst air quality in the world (WHO 2011). For Hyderabad, an integrated air pollution analysis conducted by the USEPA in

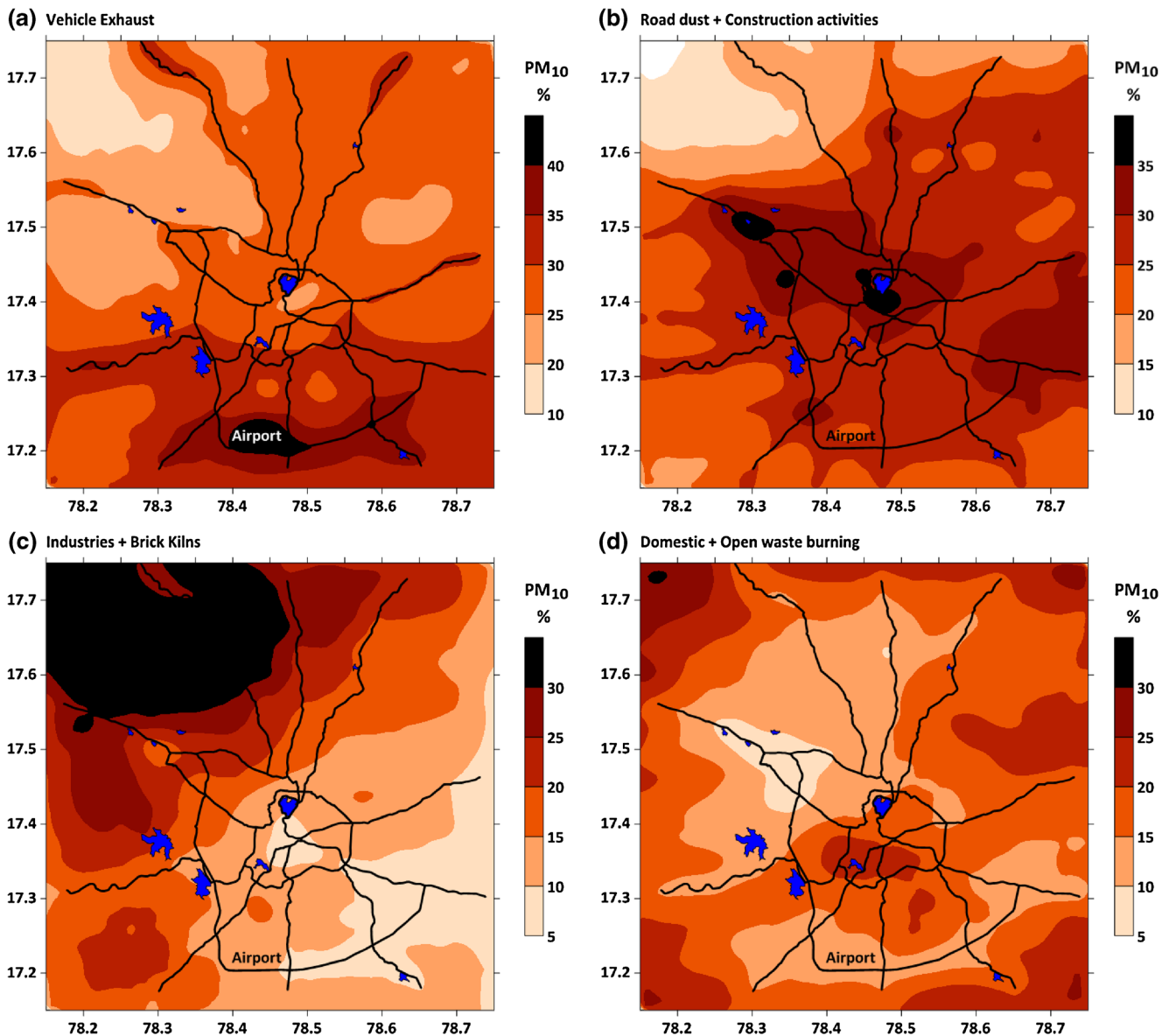


Fig. 6 Modeled percentage contributions to annual average PM_{10} concentrations in the Greater Hyderabad Municipal Corporation from **a** vehicle exhaust, **b** re-suspended dust (including construction activities),

c industries (including brick kilns), and **d** residential sector (including domestic cooking and open waste burning)

2002–2004 and updated in 2007–2008, estimated total health costs at USD 260 and 430 million, respectively (IES 2004; IES 2008). These studies estimated 3,000 premature deaths per year attributable to air pollution in 2006; and the costs include morbidity (from chronic bronchitis, respiratory and cardiac hospital admissions, emergency room visits, asthma attacks, restricted activity, and respiratory symptom days).

Methodology and inputs

We calculated the health impacts of mortality and morbidity based on concentration-response functions established from epidemiological studies. Pope et al. (2002), Englert (2004),

HEI (2010), Atkinson et al. (2011), and WHO (2013) summarize the current understanding and scientific literature on the health impacts of outdoor air pollution based on cohort and meta-analysis. Wong et al. (2008) present results from recent epidemiological studies in Asia conducted under the Public Health and Air Pollution in Asia program. Studies in India have also consistently demonstrated higher rates of respiratory and cardiovascular diseases in populations exposed to PM , NO_x , and ozone pollution (Chhabra et al. 2001; Pande et al. 2002; Gupta et al. 2007; Siddique et al. 2010; Balakrishnan et al. 2013). The risk assessment methodology, explained below, was applied for similar health impact studies, for example Kan et al. (2004) for Shanghai, China; WHO

(2004) for global disease burden; Bell et al. (2006) for Santiago, Mexico city, and Sao Paulo; GAINS (2010) for Asia and Europe regional studies; Cropper et al. (2011) for power plants pollution in India; and Guttikunda and Jawahar (2012) for six cities in India. Details on various concentration-response functions and coefficients and their associated confidence intervals are further summarized in a case study for Hong Kong and Guangzhou cities (Jahn et al. 2011).

The total health risk for mortality is quantified using the relative risk functions for various endpoints defined as follows (WHO 2004):

$$\delta E = \sum_{i=1}^{\#grids} \delta P_{exp}^i * \delta POP_i * IR \quad (2)$$

$$\delta P_{exp}^i = (RR_i - 1) / (RR_i) \quad (3)$$

$$RR_i = \exp(\beta * \delta C_i) \quad (4)$$

The total health risk for morbidity is quantified using the following equation for various endpoints:

$$\delta E = \sum_{i=1}^{\#grids} \beta * \delta C_i * \delta POP_i \quad (5)$$

Where

- δE Number of estimated health effects (various endpoints for mortality and morbidity)
- IR Incidence rate of the mortality and morbidity endpoints. A total death incidence rate for India is set at 7.1 per 1,000 inhabitants.
- δPOP The population exposed to the incremental concentration δC in grid i ; defined as the vulnerable population in each grid
- δP_{exp} Prevalence of exposure to the total pollution level in grid i
- RR Relative risk for mortality and morbidity end points at the total pollution level
- β The concentration-response function which is defined as the change in number cases per unit change in concentrations per capita. For all-cause mortality in this study, the function is defined as 3.9 % change in the mortality rate per $4 \mu\text{g}/\text{m}^3$ of change in the $\text{PM}_{2.5}$ concentrations (Hart et al. 2011). We also estimate morbidity in terms of asthma cases, chronic bronchitis, hospital admissions, and work days lost. The following assumptions are applied (a) that the concentration-response to changing air pollution among Hyderabad residents is similar to those of residents where the epidemiological studies were

performed and (b) that the public health status of people in the future years remain the same as in year 2010. The uncertainty in estimating and using the concentration-response functions is explained in Atkinson et al. (2011) and Hart et al. (2011).

δC The change in concentrations from the ambient standards in grid I ; an output from the ATMoS dispersion model. The modeled concentrations from the dispersion model are available as 24-h average and 24-h maximum over 1 year. This information is utilized to estimate the range of exposure rates.

Mortality and morbidity estimates

For the modeled $\text{PM}_{2.5}$ concentrations in Fig. 4, we estimated 3,700 premature mortalities and 280,000 asthma attacks per year for the GHMC region. For comparison, Guttikunda and Goel (2013) estimated 7,350 to 16,200 premature deaths per year for the city of Delhi. For cities similar in size with Hyderabad, the estimated premature mortality was 3,600 for Pune, 3,950 for Chennai, and 4,950 for Ahmedabad per year (Guttikunda and Jawahar 2012). For the year 2000, Gurjar et al. (2010) estimated 14,700 premature deaths for Dhaka, 14,100 for Cairo, 11,500 for Beijing, and 11,500 for Delhi.

Conclusions

Hyderabad city grew in size and activities from a municipal corporation in the early 1990s to an urban development area in the early 2000s to GHMC in the 2010s. Increasing urbanization and motorization led to deteriorating air quality in the city. We estimated 3,700 premature deaths and 280,000 additional asthma attacks per year due to the PM pollution in the GHMC region. The city is now listed in the top ten cities with the worst air quality in India, with major contributions from transportation and industrial sectors. The consolidated results from the receptor and source modeling studies provided the city authorities with greater understanding on the spatial spread and the temporal trends of the emissions and pollution. Given the uncertainties in both the methods, results from two different approaches were necessary to further emphasize the need for integrated studies to support air quality management and to address policy-relevant questions like which sources to target and where to target such efforts (e.g., suspected hot spots).

The air quality management cannot be addressed without concerted action on emission and ambient standards, monitoring, and enforcement of inspection and maintenance across all sectors. In an effort to improve monitoring and enforcement, The APCCB will expand the manual monitoring

network and convert some of the stations to support continuous monitoring for multiple pollutants.

In the city, PM, NO_x, and CO remains the primary concern. Due to a growing number of vehicles in the city and increasing vehicle exhaust emissions, the ground level ozone is now exceeding the prescribed norms, which needs further policy interventions. In November 2009, ozone and PM_{2.5} were added to the list of criteria of pollutants under the national ambient air quality program. In this study, we presented the results for the total PM, a key criteria pollutant and often exceeding the national ambient standards in the city. However, the emissions inventory includes ozone precursor pollutants (NO_x, VOCs, and black carbon) and their spatial and temporal disaggregation, suitable for photochemical transport modeling. We intend to extend the dispersion modeling analysis to total chemical transport modeling using models like CAMx to evaluate impacts of ozone on health and environment (CAMx 2013).

In an effort to continuously improve the quality of the data, the emission inventory and activity datasets will be made available via the internet. The inconsistencies in the procedures, such as emission factors and spatial weights for gridding, will be corrected and supplemented with additional data as they become available in future research in Indian cities.

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