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A GIS based emissions inventory at 1 km × 1 km spatial resolution for air pollution analysis in Delhi, India

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HIGHLIGHTS

► An emissions inventory for PM, SO_2, NO_x, CO, and VOCs for Delhi, India.
► Resources for activity data utilized for emissions inventory.
► A gridding inventory at 1 km × 1 km spatial resolution and 1 h temporal resolution.
► Validation of the inventory via particulate dispersion modeling.

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ABSTRACT

In Delhi, between 2008 and 2011, at seven monitoring stations, the daily average of particulates with diameter <2.5 μm ($PM_{2.5}$) was 123 ± 87 μg m^{-3} and particulates with diameter <10 μm (PM_{10}) was 208 ± 137 μg m^{-3}. The bulk of the pollution is due to motorization, power generation, and construction activities. In this paper, we present a multi-pollutant emissions inventory for the National Capital Territory of Delhi, covering the main district and its satellite cities – Gurgaon, Noida, Faridabad, and Ghaziabad. For the base year 2010, we estimate emissions (to the nearest 000's) of 63,000 tons of $PM_{2.5}$, 114,000 tons of PM_{10}, 37,000 tons of sulfur dioxide, 376,000 tons of nitrogen oxides, 1.42 million tons of carbon monoxide, and 261,000 tons of volatile organic compounds. The inventory is further spatially disaggregated into 80 × 80 grids at 0.01° resolution for each of the contributing sectors, which include vehicle exhaust, road dust re-suspension, domestic cooking and heating, power plants, industries (including brick kilns), diesel generator sets and waste burning. The GIS based spatial inventory coupled with temporal resolution of 1 h, was utilized for chemical transport modeling using the ATMoS dispersion model. The modeled annual average $PM_{2.5}$ concentrations were 122 ± 10 μg m^{-3} for South Delhi; 90 ± 20 μg m^{-3} for Gurgaon and Dwarka; 93 ± 26 μg m^{-3} for North-West Delhi; 93 ± 23 μg m^{-3} for North-East Delhi; 42 ± 10 μg m^{-3} for Greater Noida; 77 ± 11 μg m^{-3} for Faridabad industrial area. The results have been compared to measured ambient PM pollution to validate the emissions inventory.

1. Introduction

The National Capital Territory of Delhi (NCT) covers an area of 1500 km^2 including parts of the neighboring states of Haryana, Uttar Pradesh, and Rajasthan. The region has grown rapidly over the past 20 years – in 1990, the total population of NCT stood at 8.6 million and in 2011 at 21.5 million (Census-India, 2012). As India's capital, Delhi has grown across all sectors – industry, transport, and housing – which contributed to an increase in air pollution (Narain and Bell, 2006; Kandlikar, 2007; Mohan et al., 2007; Firdaus and Ahmad, 2011; Guttikunda and Gurjar, 2012; Guttikunda, 2012).

While initiatives like conversion of diesel to compressed natural gas (CNG) public transport buses, 3-wheelers, and taxis, a 180 km metro rail system, and relocation of industrial estates away from the city, have helped improve the quality of air in Delhi, they have nevertheless fallen short in keeping up with the growing air pollution and increasing health risks due to air pollution (Chhabra et al., 2001; Pande et al., 2002; HEI, 2010; Siddique et al., 2010). At seven monitoring stations in Delhi, between 2008 and 2011, the daily average $PM_{2.5}$ (particulate matter with aerodynamic diameter < 2.5 μm) was 123 ± 87 μg m^{-3} and PM_{10} (particulate

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matter with aerodynamic diameter < 10 μm) was 208 ± 137 μg m^{-3}. The national ambient daily standard for PM_{10} and $PM_{2.5}$ are 100 μg m^{-3} and 60 μg m^{-3} respectively. Apte et al. (2011) reported that the exposure to $PM_{2.5}$ concentrations on the roads of Delhi is at least 1.5 times the ambient levels. In December 2011, at four stations, the daily average $PM_{2.5}$ was 267 ± 105 μg m^{-3} and PM_{10} was 368 ± 116 μg m^{-3}. The pollution levels are worse in the winter months with concentrations at least double the annual averages, due to increased emissions from heating and unfavorable meteorological conditions for dispersion (Guttikunda and Gurjar, 2012).

Receptor modeling studies conducted in Delhi identified road dust, vehicle exhaust, coal and biomass combustion, open refuse burning, secondary aerosols, and construction activities as key contributors to particulate pollution (Khillare et al., 2004; Chowdhury et al., 2007; Srivastava et al., 2009; Chelani et al., 2010; CPCB, 2010). While these studies have helped quantify the sector contributions around the monitoring stations, fewer studies have developed a comprehensive emissions inventory and spatial spread of emissions for the city. The Central Pollution Control Board (CPCB) of India published sector contributions based on receptor modeling and discussed an emissions inventory for areas surrounding the monitoring sites. Interestingly, CPCB (2010), among other sources, also identified LPG gas combustion in the domestic sector as a key contributor to $PM_{2.5}$, which no other studies have reported in the past (Pant and Harrison, 2012). A gridded PM_{10} and $PM_{2.5}$ emissions inventory for the region at 1.67 km × 1.67 km spatial resolution failed to account for brick manufacturing, one of the fastest growing industries in Delhi (Sahu et al., 2011). An earlier emissions inventory is available for the time period of 1990–2000 (Gurjar et al., 2004; Mohan et al., 2007).

In this paper, we present for the city of Delhi, a bottom-up emissions inventory, a gridding procedure to disaggregate the inventory to 1 km × 1 km spatial resolution, an analysis of the diurnal variations, and results from validation of the emissions inventory.

2. Data and models

2.1. Study domain

The study domain, presented in Fig. 1 covers Delhi and its satellite cities – Gurgaon, Noida, Greater Noida, Faridabad, and Ghaziabad, between 76.85°E to 77.65°E longitude and 28.2°N to 29.0°N latitude. Also in the figure are the two ring roads, main roads including highways, brick kilns, power plants, and some points of interest.

2.2. Air quality monitoring data

The monitoring data is from the continuous air monitoring stations operated by CPCB and the Delhi Pollution Control Committee. The following stations were analyzed (1) Delhi College of Engineering (DCE, university campus) (2) Netaji Subhas Institute of Technology in Dwarka (NSIT, university campus) (3) Income Tax Office (ITO, traffic junction) (4) Shadipur (SHAD, mixed residential, industrial, and traffic) (5) Institute of Human Behaviour & Allied Sciences (IHBAS, mixed residential and traffic) (6) Mandir Marg (MM, mixed traffic and industrial) (7) Ramakrishna Puram (RK, mixed traffic and residential) and the data is available in the public domain from CPCB's website. These stations measure SO_2, NO_x, and CO, one of the PM fractions - $PM_{2.5}$ or PM_{10}. Ozone and $PM_{2.5}$ were

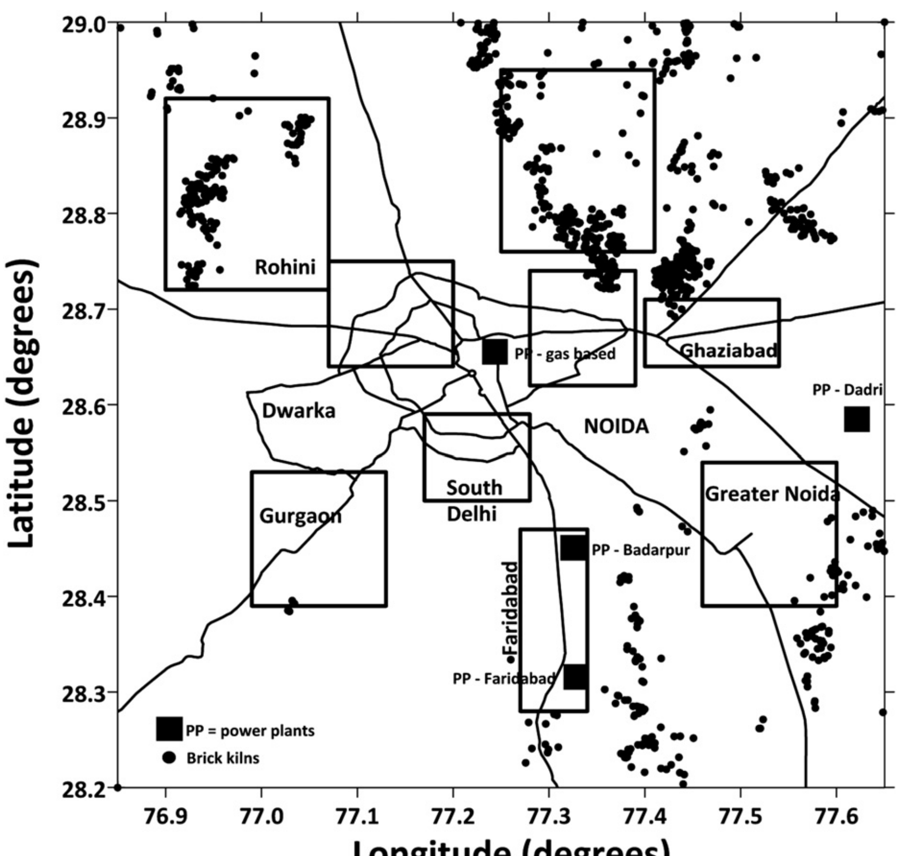

Fig. 1. Study domain over Delhi, along with location of, main highways, satellite cities, brick kiln clusters, and power plants.

added to the list of criteria pollutants in November, 2009. A map of all the monitoring stations in Delhi is presented in Supplementary material Fig. S1.

The annual average measured concentrations for 2009–10 ranged 130 ± 92 μg m^{-3} for $PM_{2.5}$ at ITO; 89 ± 50 μg m^{-3} for $PM_{2.5}$ at MM; 91 ± 51 μg m^{-3} for $PM_{2.5}$ at RK; 162 ± 97 μg m^{-3} for PM_{10} NSIT; 240 ± 155 μg m^{-3} for PM_{10} at IHBAS; and 205 ± 171 μg m^{-3} for PM_{10} at SHAD.

2.3. Multi-pollutant emissions inventory

We compiled an emissions inventory for base year 2010 based on fuel consumption data and emission factors for transport, industrial, and domestic sectors. We used the activity based method to estimate the emissions inventory for PM, SO_2, NO_x, CO and VOCs. The same method has been used for building regional and urban inventories published in Timilsina and Shrestha (2009) for Asia; Zhang et al. (2008) for Hangzhou, China; Kan et al. (2004) for Shanghai, China; Tung et al. (2011) for Hanoi, Vietnam; Reddy and Venkataraman (2002), Singh et al. (2008), Baidya and Borken-Kleefeld (2009) and Ramachandra and Shwetmala (2009) for India; and CPCB (2010) and Guttikunda and Jawahar (2012) for cities in India. We acknowledge the uncertainties involved in the use of available emission factors instead of us calculating or measuring emission factors for every activity, which is an expensive and time consuming process. Our method allows us to better understand the pollution data sources in the city and accordingly formulate methodology to improve the emissions inventory.

2.3.1. Vehicle exhaust

We used the ASIF methodology by Schipper et al. (2000) to calculate vehicle exhaust emissions. In this method total travel activity (A) and modal shares (S) describe how much people travel by mode (in vehicle-km traveled per day), modal energy intensity (I) represents energy use per kilometer, and the emission factor (F) is the emitted mass per vehicle-km traveled. Total number of registered vehicles in NCT is 6.7 million in 2010 and vehicle categories include passenger cars (30%), taxis (<1%), 2-wheelers (motorcycles and scooters, 61%), 3-wheelers (<1%), buses (urban and inter-state, 2%), and multi-utility and commercial vehicles (4%) (MoRTH, 2011). The average vehicle-km traveled and average trip lengths by mode are estimated from passenger travel surveys conducted in 30 big, medium, and small scale cities in India (MoUD, 2008). Annual average vehicle-km traveled is estimated as 10,000 for passenger cars; 20,000 for multi-utility vehicles; 36,000 for taxis and 3-wheelers; 50,000 for public transport buses; and 30,000 for the heavy duty and light duty vehicles. The age mix of on-road vehicles is calculated using data from the "pollution under check" (PUC) program, under which all passenger and para-transit vehicles are required to undergo emission tests and receive an inspection and maintenance certificate. For the passenger cars and motorcycles, a large portion (50%) of the fleet is less than 5 years. In 2010, before the Commonwealth Games, the public transport fleet was upgraded with newer CNG buses. We did not utilize the emission rate results from PUC tests, as they are based on free-acceleration tests conducted along the roadside for compliance and do not include a full driving cycle. We used emission factors for the Indian vehicle fleet by CPCB (2010) and integrated with DIESEL (2008) and GAINS (2010).

2.3.2. Road dust

Re-suspension of road dust is a significant source of coarse PM and contributes as much as 30% to the ambient PM_{10} concentrations in Delhi, particularly along the transport corridors and residential areas (Srivastava et al., 2009; Shridhar et al., 2010; CPCB, 2010). The source apportionment studies also established empirical functions that estimate re-suspension rates (Abu-Allaban et al., 2003; Etyemezian et al., 2003; Gillies et al., 2005; USEPA, 2006; Berger and Denby, 2011). We estimated re-suspension of dust on roads using the USEPA AP-42 methodology (USEPA, 2006), which suggests its application for average road speeds less than 55 mph (which is 2 times more than those observed on Delhi roads (Apte et al., 2011)). The average road dust re-suspension rates of 5.6 g per vehicle-km traveled for feeder roads, 5.9 for arterial and ring roads, and 10.4 for main roads, are calculated based on the vehicle density, mix of vehicles, silt loading, and vehicle speeds, for each road type. Heavy duty trucks are known to re-suspend more dust than the light weight vehicles (Kupiainen, 2007) and their presence on the main roads and highways led to higher re-suspension rates for ring and main roads. We used vehicle density figures from studies by the Central Road Research Institute (CRRI, New Delhi, India). The density figures account for type of vehicles on the road, for instance heavy duty trucks primarily travel on the highways and ring roads and the light duty commercial vehicles, buses, and passenger cars ply on a mix of roads.

2.3.3. Industrial and construction activities

NCR has several commercial areas where smelters, tanning, textiles, manufacturing, chemicals, paper, and pharmaceuticals operate. These clusters (Fig. 1) are located in Faridabad (in the south), Ghaziabad (in the east), Janakpuri (in the west), and Gurgaon (in the south). SoE-Delhi (2010) lists ~6000 individual units located in these clusters. The total energy consumption is approximately 43 PJ and fueled by coal and coke (25%), fuel oil (35%), gas (7%), and diesel (33%) (GAINS, 2010; CPCB, 2010). We used emission factors from previous studies (Reddy and Venkataraman, 2002; Gurjar et al., 2004; GAINS, 2010; CPCB, 2010).

The construction sector is rapidly growing in India. This includes brick and cement manufacturing. In case of NCT, the brick kilns are located mostly along the border. The dots in Fig. 1 show the location of 1000 kilns, with a production capacity of 25,000 bricks per day, using a mix of coal and biomass. The area covered by the black boxes drawn north of the outer ring road contains most of the kilns (60%). Brick manufacturing in northern India is dominated by small individual operators, each consisting of 200–300 daily wage workers per kiln, employed on a seasonal basis (Gupta, 2003). Most of the installations are conventional fixed chimney bull trench kilns that are more polluting and energy-inefficient as compared to the newer, cleaner technologies, such as Hoffmann, high draught or vertical shaft brick kilns (CAI-Asia, 2008; World-Bank, 2010; Maithel et al., 2012). Similar kilns are found in most of Northern India, along the Indo-Gangetic plain and closer to the cities in South India (Isabelle et al., 2007; Guttikunda and Jawahar, 2012). We calculated emissions of this sector based on brick production rates for the manufacturing season (non-monsoonal months) and used the following emission factors (in grams per brick produced) of 3.4 for $PM_{2.5}$; 4.6 for PM_{10}; 1.5 for SO_2; 2.5 for NO_x; 64.0 for CO; and 420 for CO_2 (Maithel et al., 2012). These rates are lower than those observed at the brick kilns in Dhaka, operating under similar conditions and utilizing similar technology, primarily due to differences in fuel mix (Guttikunda et al., 2012). We also include construction activities to estimate re-suspension of dust that has an impact on PM emissions.

2.3.4. Electricity generation

Six major power plants are located within the modeling domain of this study (Fig. 1). A summary of their location, fuel consumption, and flue gas characteristics is in SoE-Delhi (2010). The power plants located in the city (Indraprastha, Rajghat, and Pragati) are natural gas based and while those outside (Faridabad, Badapur, and Dadri) are coal based. Their combined generation capacity is 2700 MW, with an average fuel consumption rate of 800 kg of coal and 250 m^3 of natural gas per MW-hour (Kansal et al., 2009).

While most of the electricity needs are met by the power plants, areas such as Gurgaon, Noida, Faridabad, and Ghaziabad, supplement their power needs using in-situ diesel generator sets. Large capacity generators in hotels, hospitals, malls, markets, large institutions, apartment complexes, cinemas, and farm houses are a source of emissions. These are estimated using on-site surveys for fuel consumption. For example, a five-star hotel or a big hospital is estimated to consume 30,000 L of diesel per month and a campus like the Indian Institute of Technology consumes 80,000 L per month. The total diesel consumption in the in-situ generator sets is estimated at 60 PJ.

Emissions factors for power plants and diesel generators are from GAINS (2010).

2.3.5. Domestic sector

We estimate domestic emissions from the distribution of population in the city. The 2001 Census data has information on mix of fuels and daily use at the sub-district level (IFMR, 2011). We segregated emissions from cooking activities into urban and rural areas based on the population density, per grid – with high density areas utilizing mostly liquefied petroleum gas (LPG) and low density areas utilizing a mix of fuels including coal, biomass, cow dung, wood, kerosene, and LPG. During the winter months (November to February) the domestic sector also includes emissions from heating that uses biofuels, coal, and wood. We obtain activity based emissions factors for various fuels used for cooking and heating from Zhang et al. (1999), Bhattacharya et al. (2000), Zhang et al. (2000), and GAINS (2010).

2.3.6. Waste management sector

There are three active landfills in Delhi at Okhla Phase I, Jhangir puri, and Ghazipur, with a combined processing capacity of 5000 tons per day. However, the total garbage generation for NCR is estimated at 9000 tons per day (SoE-Delhi, 2010). A portion of the collected garbage is regularly burnt in the residential areas, collection sites, roadside sites, and in some cases, at the landfill site. Garbage burning emissions are estimated for varying collection efficiencies based on the population density at the sub-district level. The sectors with the highest population density often experience the highest waste collection rates (World-Bank, 2006; CPCB, 2010).

2.3.7. Air traffic

The domestic and international airports in Delhi handle approximately 650 flights daily. The landing and take-off data for a week was collected from the flight status information available in the public domain. The inventory also includes emissions from bus operations for shuttling passengers to and from the aircrafts and a fraction of idling emissions at the arrival and departure sections from the passenger cars.

2.4. Spatial allocation of emissions

We developed the emissions inventory on a GIS platform to spatially disaggregate the emissions for further use in atmospheric dispersion modeling. Hence we subdivided the domain (Fig. 1) into 80 cells in each direction at 0.01° resolution, corresponding to 1 km. We used spatial proxies to allocate the emissions for each sector to the grid. Similar methodology was utilized for six cities in India (Guttikunda and Jawahar, 2012) and summarized in Supplementary material Fig. S2.

The population density data is obtained from GRUMP (2010) at 30″ spatial resolution (Supplementary material Fig. S3). The average population density is more than 5000 per km^2 in the main districts. We purchased the GIS maps from EICHER Pvt. Ltd. (New Delhi, India) for roads (including information on bus stops, bus depots, traffic signals, and landmarks), industries, hotels, hospitals, markets, malls, cinemas, apartment complexes, large institutions, and farm houses. A summary of these layers is presented in the Supplementary material Fig. S4. In case of the transport sector, we used grid based population density, road density (defined as number of km per grid), and commercial activity density from the EICHER GIS layers, and vehicle density surveys conducted by CRRI (New Delhi) to distribute emissions on feeder, arterial, and main roads.

Emissions from power plants, industries, and brick kilns were directly assigned to their respective locations. The scattered garbage burning emissions were distributed using the population density and land-use data.

2.5. Temporal allocation of emissions

The winters in Delhi are foggy and more polluted than any other season (Guttikunda and Gurjar, 2012; Guttikunda, 2012). The recurring impacts include heavy and persistent smog and fog in the months of November to February, higher pollution levels for all criteria pollutants, frequent delays or cancellations of flights (domestic and international), and reduced visibility causing minor and major accidents along the roads.

To capture the seasonality of emissions and pollution, the emission inventory includes sector-specific temporal profiles for dispersion model-ready input preparation. The six power plants experience peaks in summer months requiring air conditioning and winter months requiring heating. The winter months also experience an increase in the biomass burning, which is mostly open burning in the residential and industrial areas. The brick manufacturing is mostly operational during the non-monsoonal months (October to May).

In Fig. 2, we present the diurnal variation of $PM_{2.5}$ and SO_2 concentrations over one year from the monitoring station at ITO. This is a junction with heavy traffic transiting between central and east Delhi and is close to the industrial clusters of Ghaziabad (East Delhi). Besides the rush hour bumps (8:00–10:00 AM and 6:00–9:00 PM) the steady increase and higher pollution levels can be attributed to the exhaust emissions from trucks, which are allowed to pass through the city only after 9:00 PM. The influence of the truck emissions is more evident in the direct correlation of $PM_{2.5}$ and SO_2 concentrations, mostly from the diesel combustion in trucks. The importance of the freight transport via trucks in the night is not negligible, since the high concentrations observed at night, tend to linger during the rush hours (through 11:00 AM) combined with the passenger traffic and further exacerbating the exposure times and related health concerns along the major

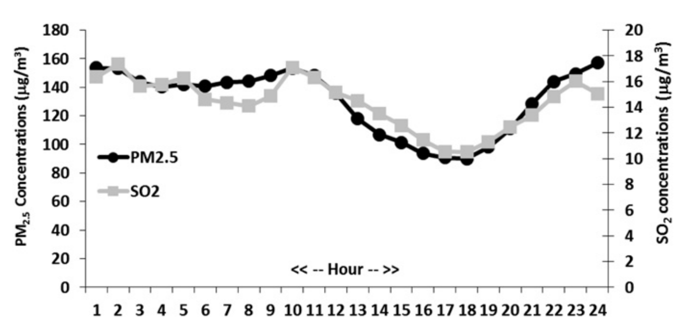

Fig. 2. Annual average diurnal variation of $PM_{2.5}$ and SO_2 concentrations measured at the monitoring station near Income Tax Office, Delhi, India.

corridors. Combined with these measurements, we have incorporated in the emissions inventory the diurnal cycles for the transport sector to distinguish between the rush and non-rush hours for all modes, operational hours for the industries, flight landing and take-offs, cooking hours for the domestic sector, and winter heating. A summary of the diurnal cycles utilized in this study for transport sector is presented in Supplementary material Table S1.

2.6. Atmospheric dispersion modeling

We applied the Atmospheric Transport Modeling System (ATMoS) version 3.4 – a forward trajectory Lagrangian Puff-transport dispersion model, to model PM concentrations (Calori and Carmichael, 1999). This version is modified from the USA National Oceanic Atmospheric Administration, Branch Atmospheric Trajectory (BAT) model (Heffter, 1983). The layers include a surface layer, boundary layer (designated as the mixing layer height) and a top reservoir layer. The multiple layers allow the model to differentiate the contributions of near-ground diffused area sources, like transport and domestic combustion emissions and of elevated sources like industrial, brick kilns, and power plant stacks. The model also includes first order chemical reactions for SO_2 and NO_x emissions to estimate the secondary contributions in the form of sulfates and nitrates, added to the total $PM_{2.5}$ concentrations (Guttikunda et al., 2001; Holloway et al., 2002). The model has flexible temporal and spatial resolution and can run for periods ranging from one day to a year and from regional to urban scales (Guttikunda et al., 2001; Holloway et al., 2002; Kan et al., 2004; Guttikunda and Jawahar, 2012).

We derived meteorological data (3D wind, temperature, pressure, surface heat flux, and precipitation fields) from the National Center for Environmental Prediction (NCEP) global reanalysis (NCEP, 2012) and interpolated to the model grid. The mixing heights are as high as 2500 m during the summer days and as low as 50 m during the winter nights. A summary of daily average mixing heights, total monthly precipitation, and monthly windrose functions are presented in Supplementary material Fig. S5 and for multiple years in Guttikunda and Gurjar (2012). We utilized the model results for particulate pollution to compare with the monitoring data and further validate the emissions inventory.

3. Results and discussion

3.1. Emission budgets and sector contributions

Total emissions for year 2010 along with sector contributions are summarized in Table 1.

For PM_{10} emissions, though shares of power plants, industries, and brick kilns (15%, 11%, and 11% respectively) are higher, they are elevated point sources, because of which their pollution is dispersed farther distances. While the vehicle exhaust, road dust, and diffused domestic sources (with shares of 13%, 22%, and 12% respectively) are at the ground level and exacerbate exposure levels and exposure times.

For $PM_{2.5}$ and CO emissions, we estimated shares of 17% and 18% for vehicle exhaust, 16% and 31% for power plants, 15% and 12% for brick kilns, 14% and 15% for industries, and 12% and 14% for domestic, respectively. For both $PM_{2.5}$ and CO, diesel and biomass combustion account for major shares in the respective sectors. In the transport sector, freight movement via heavy duty and light duty trucks are the largest contributors. All the heavy duty trucks are diesel operated and most of the light duty trucks are CNG operated. For NO_x emissions, vehicle exhaust remains the dominant source (53%).

For SO_2, power plants (55%) and industries (23%), the largest coal users in the region, are the dominant sources. Diesel consumption for in-situ power generation from diesel generator sets in the mobile phone towers, hotels, hospitals, large institutions, markets, malls, and apartment complexes, contributes about 6% of $PM_{2.5}$. Although, the overall percentage of these emissions is small, when spatially segregated, these low lying emissions are substantial, especially since they are located in densely populated areas.

The production rates and the number of kilns outside Delhi have increased, with an increasing growth in the construction sector and estimated to account for 15% of annual $PM_{2.5}$, 12% of CO and 11% of SO_2 emissions. Following an ordinance by the Supreme Court, kilns are not allowed to operate within the city limits. However, it is evident from Fig. 1 that these kilns are located close to the border and a major contributor to the air pollution levels in Delhi.

3.1.1. Previous studies

Gurjar et al. (2004) presents an emissions inventory for 1990–2000 period and concluded that the power plants account for 68% of SO_2 (113,000) and 80% of the total suspended particles (141,000), the transport sector dominates NO_x (131,000 tons), CO (361,000) and VOC (148,000) emissions. The numbers in brackets are total emissions for 1990. This study did not account for $PM_{2.5}$ and PM_{10}. The city grew in area, population, activity, and emissions, at least doubling in every category since 1990.

CPCB (2010) estimated 147 tons of PM_{10} per day, 460 tons of NO_x per day, and 268 tons of SO_2 per day. Since, these figures are below our estimates for PM_{10} and NO_x (312 and 1030 respectively) and higher for SO_2 (101), it is important to note the differences in the methodologies. CPCB (2010) estimates for the base year 2006–07 and covers only the metropolitan area of 32 km × 32 km; which is 16% of the area covered in our study. The inventories were primarily estimated for an area of 2 km × 2 km around the monitoring site selected for the source apportionment analysis and then extrapolated to 32 km × 32 km. This does not include the areas where the industrial activity is generally larger and missed brick kiln contributions, with clusters outside their selected modeling

Table 1
An activity based emissions inventory (tons/year, rounded to 00's) by sector (% total by pollutant) for NCT of Delhi, India, in 2010.

	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC
Transport	10,900 (17%)	14,600 (13%)	700 (2%)	198,900 (53%)	256,200 (18%)	132,200 (51%)
Domestic	7500 (12%)	9000 (8%)	2100 (6%)	2900 (1%)	204,700 (14%)	17,300 (7%)
Diesel Gen sets	3800 (6%)	5000 (4%)	1300 (4%)	94,000 (25%)	98,500 (7%)	36,600 (14%)
Brick Kilns	9300 (15%)	12,400 (11%)	4000 (11%)	6800 (2%)	171,900 (12%)	24,200 (9%)
Industries	9000 (14%)	12,700 (11%)	8500 (23%)	41,500 (11%)	219,600 (15%)	13,300 (5%)
Construction	3300 (5%)	10,800 (9%)	100 (%)	2900 (1%)	3600 (%)	100 (%)
Waste burning	5300 (8%)	7600 (7%)	400 (1%)	2000 (1%)	27,800 (2%)	2300 (1%)
Road dust	3900 (6%)	25,500 (22%)				
Power plant	10,200 (16%)	16,900 (15%)	20,300 (55%)	27,200 (7%)	442,200 (31%)	34,900 (13%)
Total	63,000	114,000	37,000	376,000	1,425,000	261,000

domain. While not including the external sources of emissions understated the total emissions for PM_{10} and NO_x, we feel that the same extrapolation procedure resulted in overestimation of the SO_2 emissions.

Sahu et al. (2011) present an inventory for 70 km × 65 km area developed for the air quality forecasting and research program and estimated a total of 236,000 tons of PM_{10} and 94,000 tons of $PM_{2.5}$ for 2009–10. The largest contributor to total PM_{10} is road dust re-suspension (55%) and mixed sources for $PM_{2.5}$. These totals are larger than our PM total estimates and we find the following as major differences in methodologies. The brick kiln sector is not distinguished in the inventory and is not clear if this included in the overall industrial sector. The daily average vehicle-km traveled for passenger vehicles and public transport is higher. This combined with higher road re-suspension rates is the possible reason for higher estimates for road dust in PM_{10}. Before the Commonwealth Games, a number of flyovers and roads were under maintenance and the metro rail system was still under construction, during which time any measurements for silt loading are bound to result in higher rates.

3.2. Spatial distribution of emissions contributions

All the emissions are spatially disaggregated into grids at 0.01° resolution and four panels for gridded PM_{10} emissions (in tons/year/grid) for vehicles exhaust, industries (including the brick kilns), domestic (including heating, waste burning, and winter heating), and dust (including road dust and construction activities) are presented in Fig. 3. In case of vehicle exhaust, the highest density of emissions is observed along the major road intersections, which is linked to the density of the feeder roads in the grid. A combination of vehicle, road, industrial, and population density is used to assign weights for congestion emissions. For convenience, only PM_{10} emissions are presented in this paper. The gridded fields were also developed for $PM_{2.5}$, SO_2, NO_x, CO and VOC.

While it is important to know the footprint of total emissions for a city, it is also important to understand the hotspots and their pollution loads in residential and industrial regions. Table 2 presents the percent sector contributions to total annual $PM_{2.5}$ emissions for six select regions identified in Fig. 3. The regions are selected with equal areas, so that we can compare the mix of

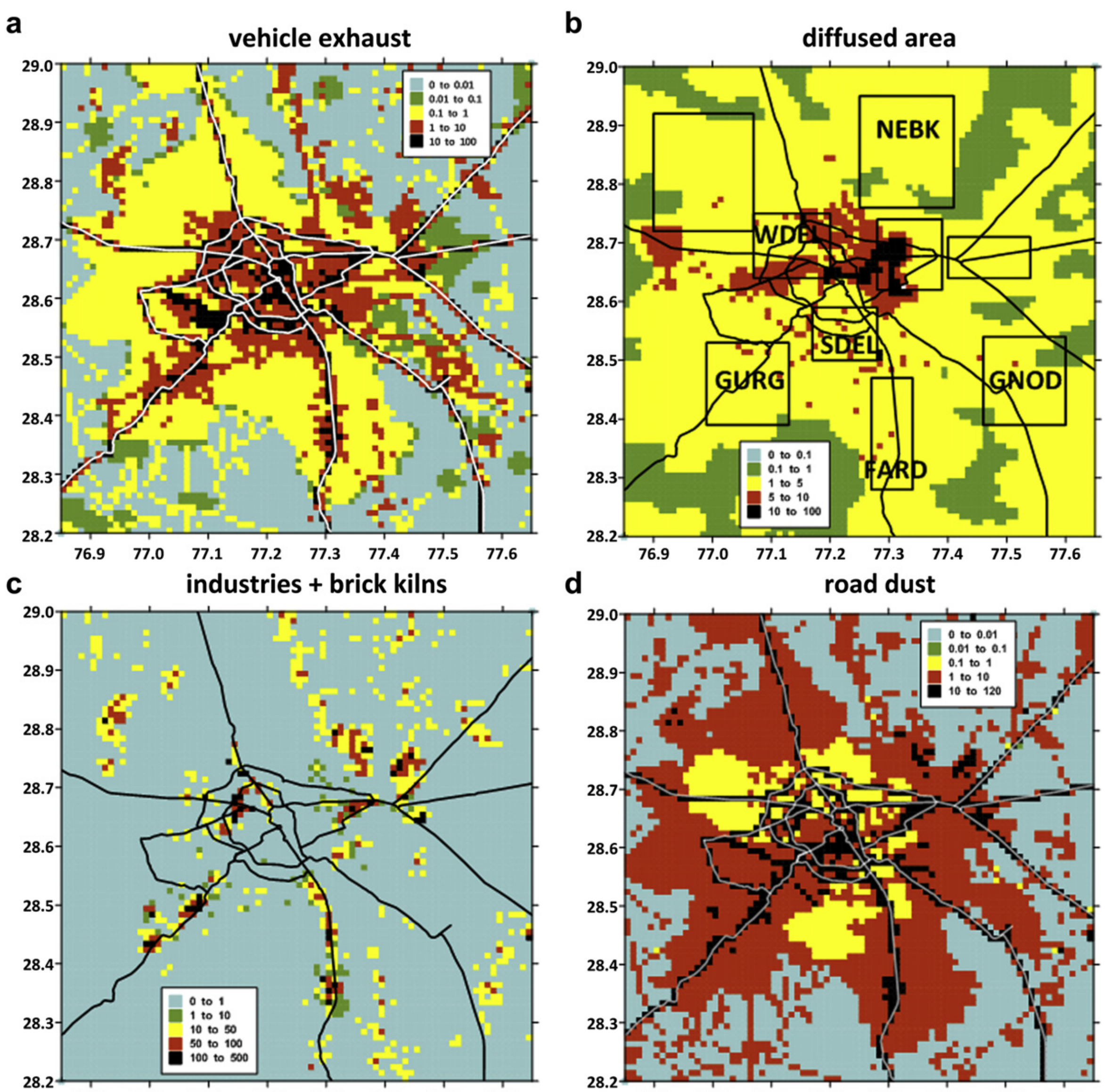

Fig. 3. Gridded emissions inventory of PM_{10} in tons/year/grid for year 2010.

Table 2
Sector contributions to total $PM_{2.5}$ emissions and modeled annual average $PM_{2.5}$ and PM_{10} for select residential and industrial regions for year 2010 in Delhi, India.

	SDEL	FARD	GNOD	NEBK	WDEL	GURG
Total $PM_{2.5}$ (tons/year)	2080	2860	1020	2500	5000	3980
Transport	42%	17%	26%	6%	24%	15%
Domestic	10%	7%	22%	11%	8%	5%
Diesel Gen Sets	16%	9%	2%		6%	8%
Brick Kilns			13%	73%		1%
Industries	10%	45%			48%	51%
Construction	3%	8%	14%	1%		8%
Waste burning	8%	7%	11%	5%	6%	6%
Road dust	12%	7%	12%	2%	7%	6%
Modeled $PM_{2.5}$ ($\mu g\ m^{-3}$)	122 ± 10	77 ± 11	42 ± 10	93 ± 23	93 ± 26	90 ± 20
Modeled PM_{10} ($\mu g\ m^{-3}$)	218 ± 21	144 ± 19	86 ± 19	167 ± 38	158 ± 42	164 ± 32

activities in the main district and in the satellite cities. Gurgaon (GURG) and West Delhi (WDEL) experience the most in terms of the total emissions, due to the large contribution of industries (>40%). Industries account for (35%) in nearby Faridabad (FARD). In the industrial regions, vehicular emissions are attributed to movement of heavy duty and light duty trucks. In South Delhi (SDEL), an area with high population density, vehicle exhaust emissions are the largest contributors (48%), while in less dense parts of the city like North-east Delhi (NEBK), brick kilns contribute about 68% of the emissions. In addition, most of the vehicle exhaust emissions are related to freight movement, originating or ending either at the brick kilns or at the industries. Among satellite cities, Gurgaon and Greater Noida (GNOD) experience the most significant contribution from construction activities (6% and 10% respectively). Road dust re-suspension and waste burning are uniformly present in all the regions. The road dust particles are predominantly in the coarse size range (particle diameter between 2.5 and 10 μm), so the percent contribution to total PM_{10} emissions is much larger than those estimated for total $PM_{2.5}$ emissions. The use of diesel generator sets is the highest in the densely populated areas (>6% in SDEL, WDEL, FARD, and GURG), due to the high number of hotels, hospitals, malls, and institutions. The industrialized areas (WDEL, FARD, and GURG) cannot meet all the demand for electricity and there are instances when large institutions operate on diesel generators for more than 12 h a day.

3.3. Temporal distribution of emissions contributions

An important input into the dispersion model is also the diurnal variation in the emission rates for each sector. Gridded vehicle exhaust emissions inventory for $PM_{2.5}$ for 2 h (12:00 – daytime noon and 00:00 – midnight) is presented in Fig. 4, using the total emissions presented in Table 1, gridding procedures in Supplemental material Fig. S1, and hourly variation rates in Supplementary material Table S1. The night time emissions are dominated by the heavy duty trucks and the day time emissions by a mix of passenger, public, and freight vehicles. For convenience, only the $PM_{2.5}$ vehicle exhaust emission results are presented in this paper. However, the same fields are available for all sectors and other pollutants – PM_{10}, SO_2, NO_x, CO, and VOCs.

3.4. Particulate matter concentrations

We present the modeled annual average concentrations for $PM_{2.5}$ and PM_{10} in Fig. 5. The modeled annual average $PM_{2.5}$ and PM_{10} concentrations for select residential and industrial areas (Fig. 3) are summarized in Table 2. The variations indicate standard deviation among the averages for grid cells covering those regions. All the concentrations exceed the national annual standards.

Similar to the annual average concentration maps, monthly average concentration maps for $PM_{2.5}$ for the months of December–January and July–August are presented in Fig. 6. The winter time pollution levels are at least three times higher than those observed in the summer months. Results from tracer model simulations (for the period of 2001–2008) concluded that irrespective of the emissions over each month, the observed concentrations are invariably 40–80 percent higher in the winter months (November, December, and January) and 10–60 percent lower in the summer months (May, June, and July) compared to the annual averages (Guttikunda and Gurjar, 2012).

3.4.1. Comparison with monitoring data

We compare the modeled concentrations against monitoring data from six continuous monitoring stations. We account for the

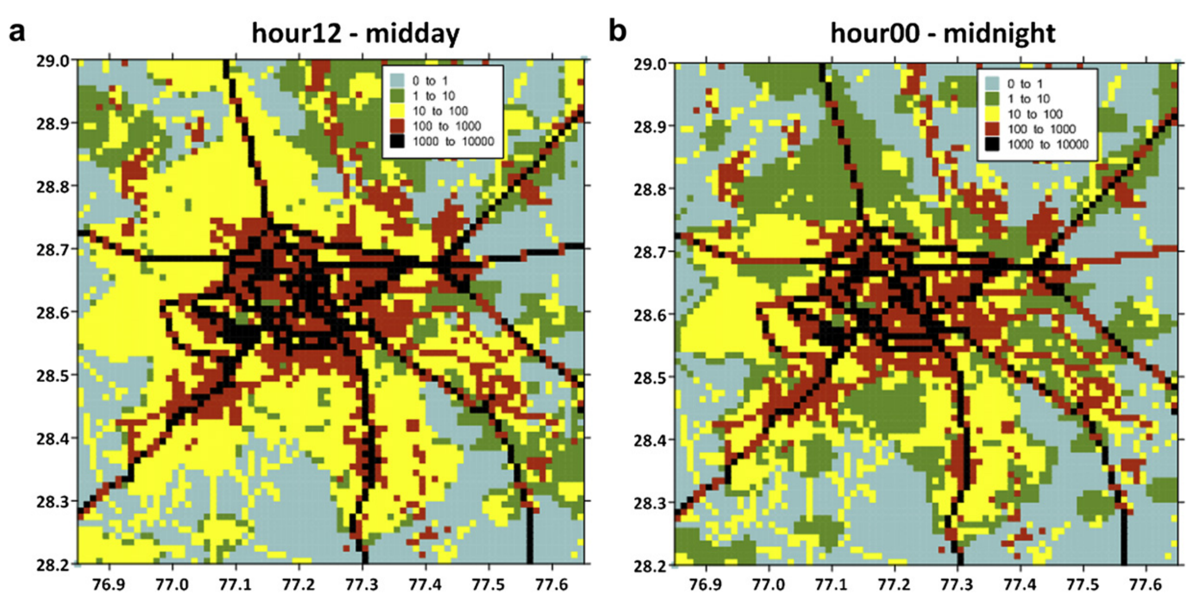

Fig. 4. Gridded $PM_{2.5}$ vehicle exhaust emissions in g/h/grid for year 2010.

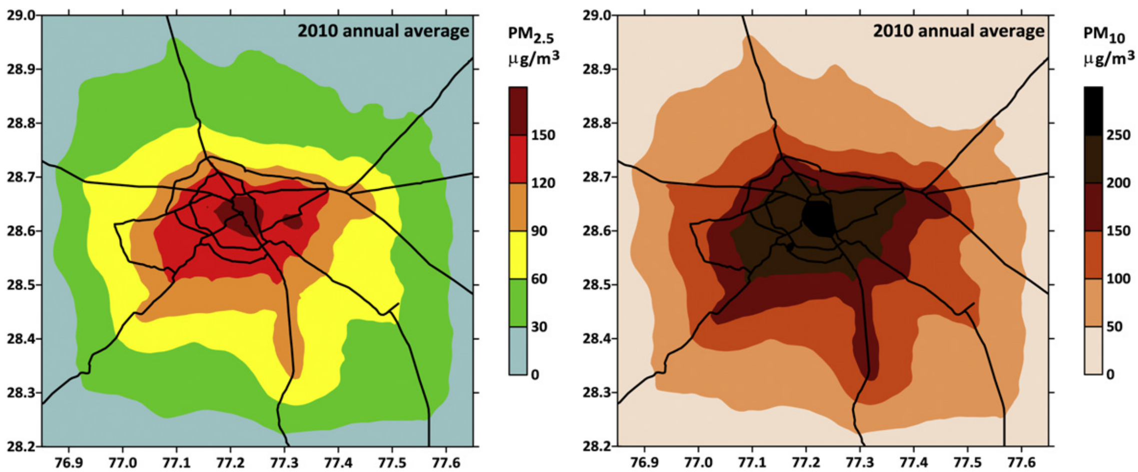

Fig. 5. Modeled annual average $PM_{2.5}$ and PM_{10} concentrations for year 2010 in Delhi, India.

uncertainties in measured and in modeled data and the results are presented in Fig. 7 to ensure that the emission estimates and the dispersion model are representative of the regional geography and meteorological conditions. The station measurements are mostly representative of the surroundings of the monitoring location and the modeled concentrations are grid averages. The variation in the measured data represents the standard deviation in daily averages over each month and the variation in the modeled data is over 9 one km^2 model grids surrounding the monitoring station.

The comparisons are reasonably captured, along with the seasonal variation. The monitoring stations are often located closer to the traffic junctions and thus capture a higher proportion of vehicle exhaust. For all the stations, the differences between the measured and the modeled numbers can be explained further by

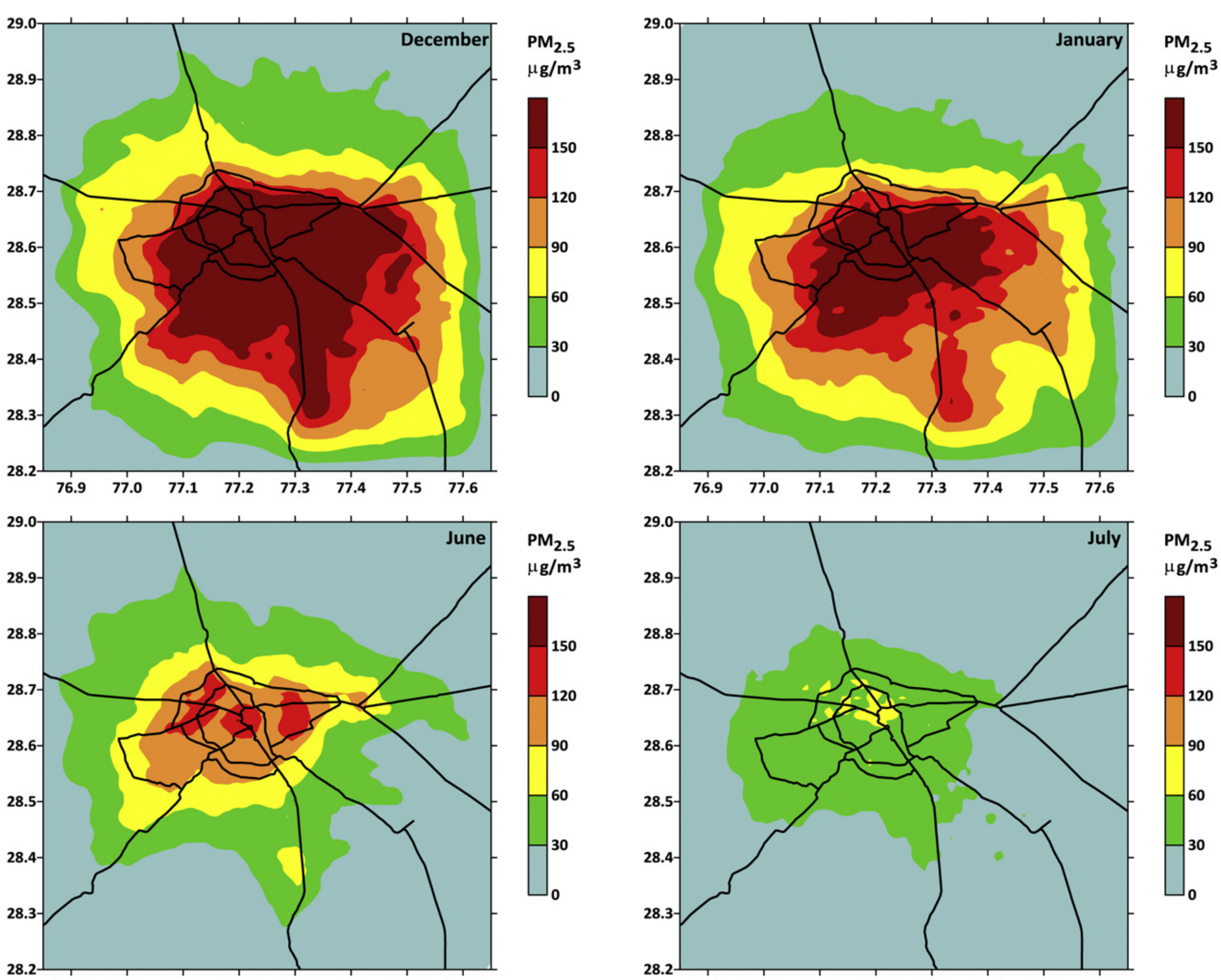

Fig. 6. Modeled monthly average $PM_{2.5}$ concentrations for year 2010 in Delhi, India.

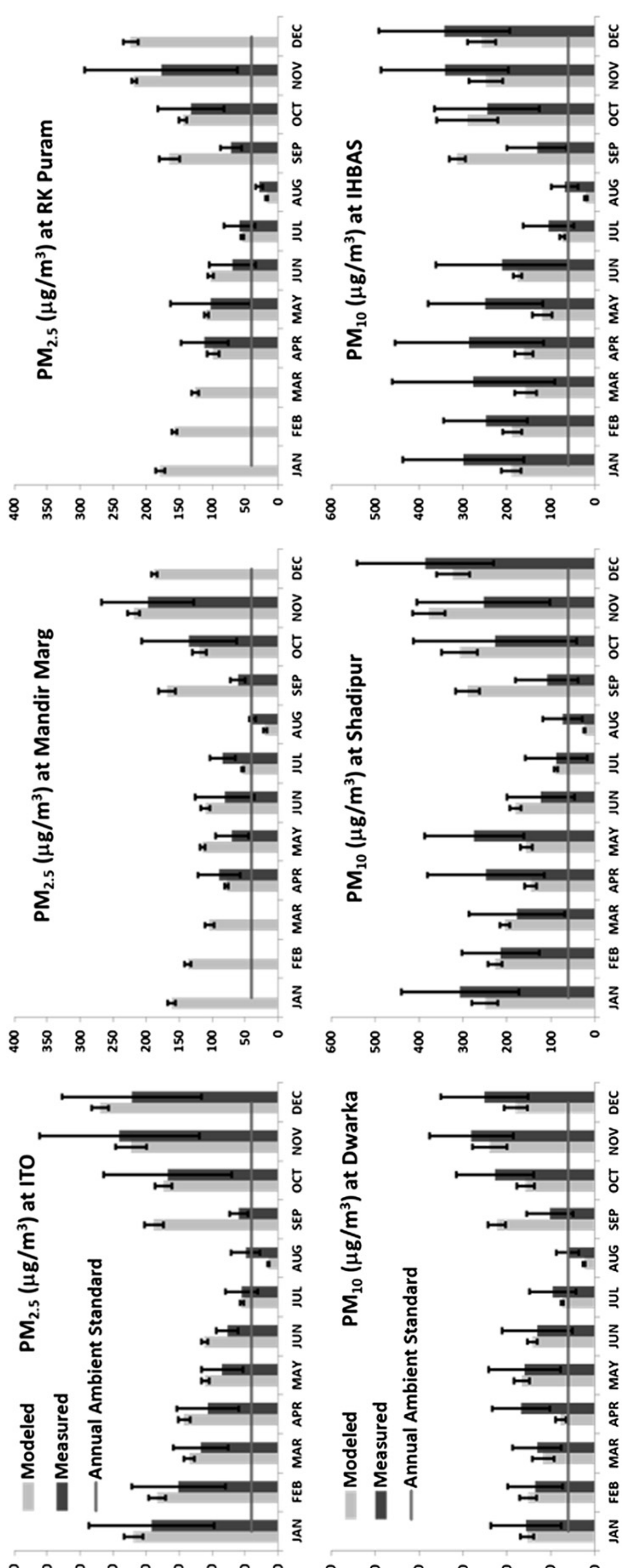

Fig. 7. Comparison of modeled and measured $PM_{2.5}$ and PM_{10} concentrations for the base year 2010 in Delhi, India.

(a) Less than 50% data collection efficiency at the monitoring stations. The measurements are an average of all the data available during the period of 2009–2011. This fact particularly affected the results for the month of September, for which the modeled results were consistently higher than the measured values (b) Uncertainty in the emissions inventory estimation, spatial disaggregation to one km^2 grids, and dispersion modeling.

Overall, the emissions inventory estimation and dispersion modeling has an uncertainty of $\pm$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, Asia, and global databases, it is difficult to accurately measure the uncertainty in our estimates. In the transport sector, the largest margin is in vehicle-km 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 re-suspension, 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 surveys to hotels, hospitals, large institutions, and apartment complexes, with an uncertainty of $\pm$30%. The fuel consumption data with the least uncertainty is from the power plants.

4. Summary and conclusions

For Delhi and its satellite cities, we estimated the total emissions for base year 2010 and spatially disaggregated into 80×80 grids at 0.01° grid resolution using GIS data fields for each of the sectors. It is often observed that these inventories are never complete and require refinements and updates that can be made by building monitoring capacity, continued identification of pollution sources, regular surveys for fuel consumption patterns, and receptor modeling studies. The emissions inventory presented in this paper is in-use for an operational air quality forecasting system for NCT, launched before the 2010 Commonwealth Games, now maintained, updated, and validated by CPCB (Guttikunda et al., 2011). These modeling systems while advantageous for mega events like these, which benefited from 48-h short term health alert notices, also provided better understanding of the influencing sources for long term planning to control air pollution.

From this study (and previously published studies), we know the sectors and regions that need further pollution control measures, but at the end of the day – pollution is an externality (a public bad) that cannot be addressed without concerted action from the city and national authorities – such as setting emission and ambient standards, monitoring the emissions and pollution, implementation of necessary interventions, and enforcement of inspection and maintenance. This applies to all sectors – industry, public transport, personal transport, freight transport, traffic management, waste management, road maintenance, and domestic.

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

Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2012.10.040.

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