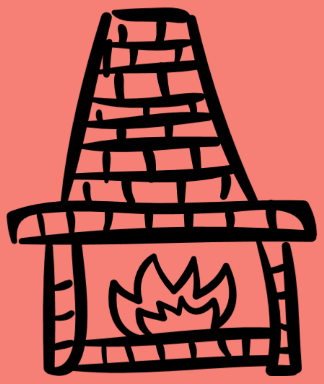
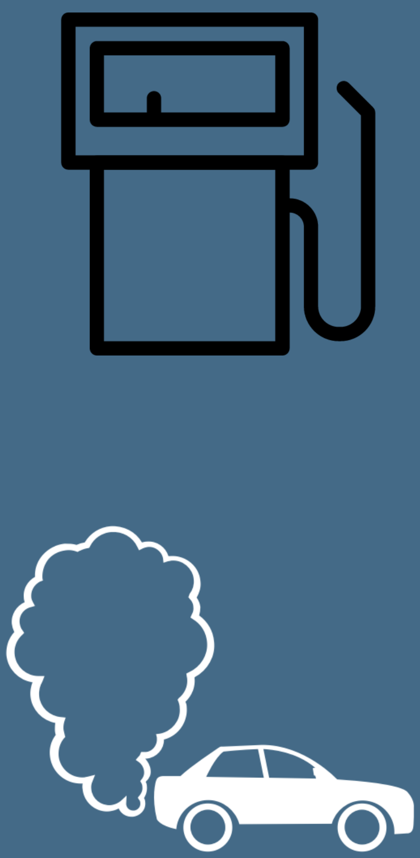
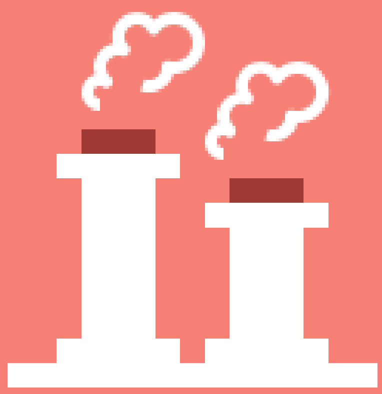


Multi-pollutant Emissions Inventory for the National Capital Region of Delhi



Dr. Sarath Guttikunda
Dr. Giuseppe Calori

URBAN emissions .info



SIM-air working paper series # 38-2012

(UEinfo) was founded in 2007 with the vision to be a repository of information, research, and analysis related to air pollution. There is a need to scale-up research applications to the secondary and the tertiary cities which are following in the footsteps of the expanding mega-cities. Advances in information technology, open-data resources, and networking, offers a tremendous opportunity to establish such tools, to help city managers, regulators, academia, and citizen groups to develop a coordinated approach for integrated air quality management for a city.

UEinfo has four objectives: (1) sharing knowledge on air pollution (2) science-based air quality analysis (3) advocacy and awareness raising on air quality management and (4) building partnerships among local, national, and international airheads.

This report was conceptualized, drafted, and designed by the members of UEinfo.

All the working papers and more are accessible @ www.urbanemissions.info/publications

Send your questions and comments to simair@urbanemissions.info

Multi-Pollutant Emissions Inventory for the National Capital Region of Delhi

Dr. Sarath Guttikunda, UrbanEmissions.info, New Delhi, India
Dr. Giuseppe Calori, AriaNet srl., Milano, Italy

Delhi (India), host city for the 2010 Commonwealth Games, covers an area of ~2,500 square kilometers including parts of the neighboring states of Haryana, Uttar Pradesh, and Rajasthan. The area is collectively referred as the National Capital Region of Delhi (NCR). The region has grown rapidly over the past 20 years -- in 1990, the total population of NCR stood at ~8.6 million and in 2011 at ~22 million (*Census-India, 2012*). As India's capital, Delhi has grown across all sectors - industry, transport, and housing – that have contributed to an increase in air pollution (*Bose, 1996; Gurjar et al., 2004; Narain and Bell, 2006; Kandlikar, 2007; Mohan et al., 2007; Guttikunda, 2009; Firdaus and Ahmad, 2011; Guttikunda and Gurjar, 2011*). This, in turn, has increased health risks, reflected by an increase in respiratory ailments (*Chhabra, et al., 2001; Pande et al., 2002; Khaturia and Khan, 2007*).

Fig.01: Mail Today, March 3rd, 2009

Capital has more toxic particles in its air than other major Indian metros

DELHI IS INDIA'S ASTHMA CAPITAL

By Meenal Dubey in New Delhi

DELHI has the highest levels of Respirable Suspended Particulate Matter (RSPM) among the four metros, exposing its residents to a greater risk of asthma than people elsewhere in the country.

Acceptable levels of RSPM should not be more than 60 microgram (mg) per cubic meter (cu m) annually. In 2008, Delhi's RSPM was recorded at a shocking 149 mg/cu m, according to a report published by the Central Pollution Control Board (CPCB) with the help of data collected between January and August 2008.

This is well above Mumbai's RSPM mark of 118 mg/cu m, Kolkata's 104 mg / cu m and Chennai's 54 mg/cu m.

It is no secret that India's capital is highly

Turn to Page 6

Over the past decade, a number of green initiatives have been introduced to address city's pollution problem, including

- The largest ever compressed natural gas (CNG) switch for more than 100,000 public transport vehicles (buses, three wheelers, and taxis) (*DTC, 2010*). In the early 2000's this resulted in significant decrease in PM pollution, with the largest improvement coming from retrofitting approximately 3,000 diesel buses (*DTE, 2002; Kathuria, 2005; Kumar and Foster, 2007; Chelani and Devotta, 2007*).
- Before the 2010 Commonwealth Games, a large part of the retrofitted fleet was replaced with newer CNG buses and the fleet size increased to around 5,000; along with implementation of special transport corridors during the Games, which succeeded as a pilot for future bus rapid transport application.
- The city also benefitted from the completion of the Metro Phase-II, increasing the coverage from 65 km in Phase I to 180 km, including an express line from the city center to the International Airport. This resulted in a drop in on-road vehicle density towards the satellite cities of Gurgaon and Noida.
- Conversion of coal based thermal power plants within Delhi to gas based power plants (*SoE-Delhi, 2010*) and relocation of the coal and fuel oil based industries, including brick kilns, to the city outskirts, following the Supreme Court orders, (*Narain and Bell, 2006*).
- While these initiatives helped improve the quality of air in the city and thus the respiratory health for the citizens of Delhi, they have nevertheless fallen short in keeping up with the daunting challenges posed by the growing sources of air pollution. The benefits of leapfrogging to alternative fuels like CNG is outdone by the increasing number of passenger vehicles on road, lack of enough public transport buses, growing demand for electricity leading to use of in-situ generator sets, and industrial growth.

Fig.02: Old Bus

Fig.03: New Bus

Fig.04: Metro System

For the period of 2008 and 2011, at the seven monitoring stations in the city PM2.5 averaged 123 ± 87 μg/m^3 and PM10 averaged 208 ± 137 μg/m^3. PM10 refers to particulate matter with aerodynamic diameter < 10μm and PM2.5 refers to particulate matter with aerodynamic diameter < 2.5μm, and the annual ambient air standards for PM10 and PM2.5 are 60 μg/m3 and 40 μg/m3 respectively. The pollution levels are worse in the winter months with concentrations at least double the annual averages, due to increased emissions from heating, and meteorological conditions (*Guttikunda and Gurjar, 2011*). In December 2011, the daily average PM2.5 was 267 ± 105 μg/m^3 and PM10 was 368 ± 116 μg/m^3 at four stations in Delhi.

Fig.05: $PM_{2.5}$ Measurements in December 2011

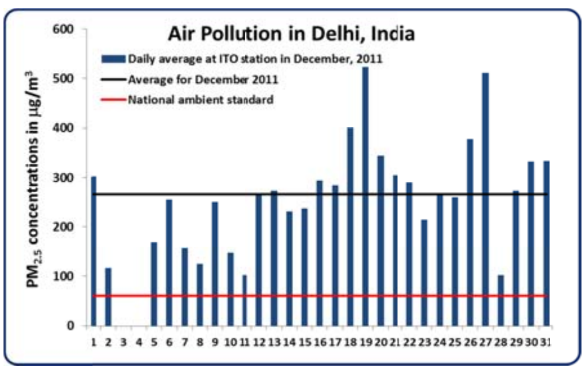
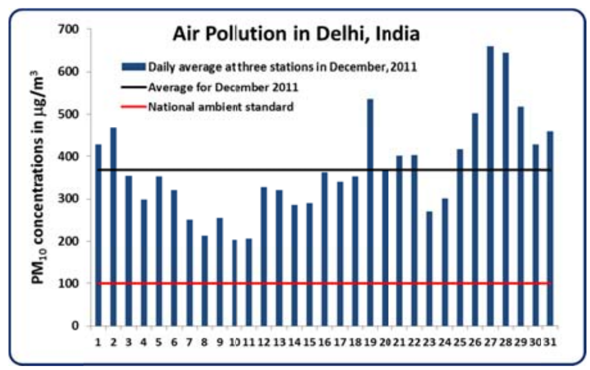


Fig.06: PM_{10} Measurements in December 2011



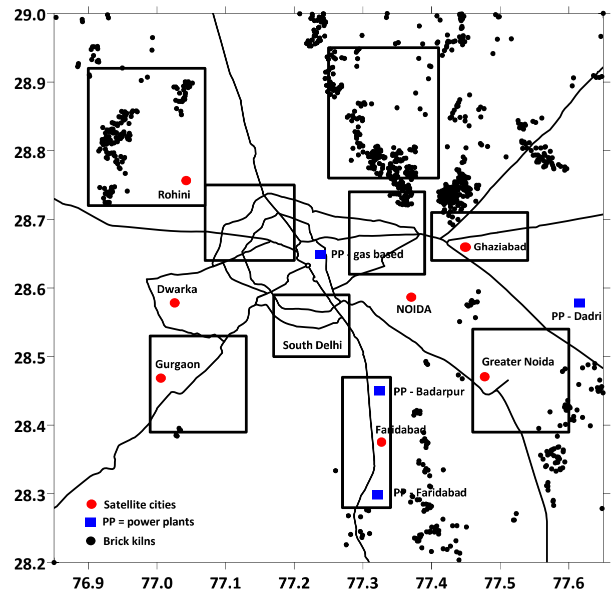
Apte et al., (2011) highlighted the risks of exposure to air pollutants on the roads of Delhi, which can be ~1.5 times the ambient levels for PM2.5. Enriched trace elements are also reported in urban and rural environments (*Chowdhury et al., 2007; Shridhar et al., 2010*). While the health impacts of air pollution are known (*Chhabra, et al., 2001; Pande et al., 2002; HEI (2004 and 2010)*), relatively few studies have developed a comprehensive emissions inventory for the criteria pollutants and investigated the source contribution for the city as a whole. The Central Pollution Control Board (CPCB) of India published sector contributions based on established PM pollution source apportionment methodologies, highlighting the role of vehicle exhaust emissions, re-suspension of road dust, diesel generator sets, domestic fuel burning, and industrial emissions and discussed an emissions inventory for areas surrounding the monitoring sites, where the source apportionment sampling was conducted (*CPCB, 2010*). However, these are not for the city as a whole. Knowledge about the spatial spread of emissions across the city is necessary to assess their impacts on the ambient pollution levels and health (*Johnson et al., 2011*).

Sources of Air Pollution in Delhi

In this paper, we present results of a bottom-up emissions inventory, an analysis of source-receptor relationships for PM10 and PM2.5 for residential and industrial areas in the region, and implications of sector based interventions on the air pollution control policy, for the city of Delhi.

The study domain, presented in **Fig.07** 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 highways, locations of brick kilns (mostly located north and east of the city limits), power plants, and some points of interest.

Fig.07: Study domain over the NCR Delhi



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 is estimated using a well established activity based methodology. The same method has been used for building similar regional and urban inventories (*Timilsina and Shrestha, 2009; Zhang et al., 2008; Kan et al., 2004; Tung et al., 2011; EEA, 2002 and 2010; Ramachandra and Shwetmala, 2009; Reddy and Venkataram, 2002; Garg et al., 2006; Singh et al., 2008; Baidya and Borken-Kleefeld, 2009; Majumdar and Gajghate, 2011*). Recently, similar methodology was utilized in India for the cities of Delhi, Mumbai, Pune, Bangalore, Kanpur, and Chennai for the base year 2006-07 (*CPCB, 2010)*. We acknowledge the uncertainties involved in the use of available emission factors instead of us calculating emission factors for every activity which is an expensive and time consuming process. Our method allows us to better understand the pollution sources in the city and the accordingly formulate policy to improve air quality (*Schwela et al., 2006; Johnson et al., 2011*).

Vehicle Exhaust

We used the ASIF methodology by *Schipper et al., (2000)* to calculate vehicular 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 travelled. **Table 1** lists a summary of registered vehicles in the NCR. The types of vehicles included are 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%). We obtained passenger travel statistics from **MoUD (2008)**. The Ministry of Urban Development (MoUD, Government of India) studied these patterns in 30 big, medium, and small scale cities in India. The age mix of on-road vehicles is calculated using data from the "pollution under check" program, under which all passenger and para-transit vehicles are required to undergo emission tests and receive an inspection and maintenance certificate. We did not utilize the emission rate results from these tests, as they are based free-acceleration tests conducted along the road-side for compliance and do not include a full driving cycle. We used emission factors for the Indian vehicle fleet by *ARAI (2007)* and *CPCB (2010)*. In this work, we mostly refer to the latest studies of *Reynolds et al. (2011)* which measured emissions factors between CNG, petrol, and diesel based 3-wheelers on Delhi roads, integrated with *DIESEL (2008)* and *GAINS (2010)*.

Table 1: Number of registered vehicles in 2007, 2008, 2009, and 2010 in the national capital region of Delhi, India

	March, 2007	March, 2008	March, 2009	March, 2010
Cars	1,536,900	1,668,900	1,802,300	1,946,450
MUV (Passenger) [a]	77,850	78,750	78,900	81,300
Two Wheelers [b]	3,377,100	3,616,450	3,846,750	4,126,500
LMV (Passenger) [c]	193,300	212,000	230,050	244,750
Buses [d]	127,850	129,000	130,550	134,850
HDV (Goods) [e]	87,800	89,100	89,650	92,250
LMV (Goods) [f]	91,700	105,350	124,200	141,600
Total	5,493,000	5,900,000	6,303,000	6,768,000

*Source: Ministry of Road Transport and Highways, Government of India (**MoRTH, 2011**)*

MUV = multiple utility vehicles; LMV = light motor vehicle; HDV = heavy duty vehicle; (a) includes jeeps, vans, and sport utility vehicles; (b) includes mopeds, scooters, and motorcycles; (c) includes three and four wheeler passenger vehicles, which can carry three to seven passengers per trip, and local and radio taxis; (d) includes public transport, contract, school, and private stage carriers; (e) includes trucks, lorries, ambulances, and police and other state owned vehicles; (f) includes three and four wheeler goods vehicles.

Road Dust

Fig.08: Dust on roads

Re-suspension of road dust is a significant source of air pollution in most Asian cities (Johnson et al., 2011) and contributes as much as 30% to the ambient PM10 concentrations in Delhi, particularly along the transport corridors and residential areas (*Balachandran et al., 2004; Srivastava et al., 2009; Shridhar et al., 2010; CPCB, 2010*). A few monitoring and source apportionment studies established empirical functions that estimate re-suspension rates in the United States, Europe, and China (*Abu-Allaban et al., 2003; Etymezian et al., 2003; Gillies et al., 2005; USEPA, 2006; EEA, 2009; Amato et al., 2011; 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 (this is however 2 times more than the observed speeds in Delhi (*Apte et al., 2011*)). The average road dust re-suspension rates of 4.8 grams per vehicle km traveled for feeder roads, 5.8 for arterial roads, and 10.5 for main roads, are calculated based on the vehicle density and mix of vehicles, silt loading, and vehicle speeds, on each of these road types. We used vehicle density figures from studies by the Central Road Research Institute (CRRI, New Delhi, India). The density figures account for type of vehicle, for instance heavy duty trucks primarily travel on the highways and ring roads and the light duty commercial vehicles, buses, and passenger cars plying on a mix of roads.

Industrial and Construction Activities

NCR has several commercial areas where smelters, tanning, textiles, manufacturing, chemicals, paper, and pharmaceuticals operate. These clusters (**Fig.07**) are located in Faridabad (in the south), Ghaziabad (in the east), Janakpuri (in the west), and Gurgaon (in the south). *SoE (2010)* lists ~6,000 individual units located in these clusters and the location information is gathered from the EICHER mapping division in New Delhi, India. The total energy consumption is approximately ~43 PJ, 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 et al., 2002; Gurjar et al., 2004; GAINS, 2010; CPCB, 2010*).

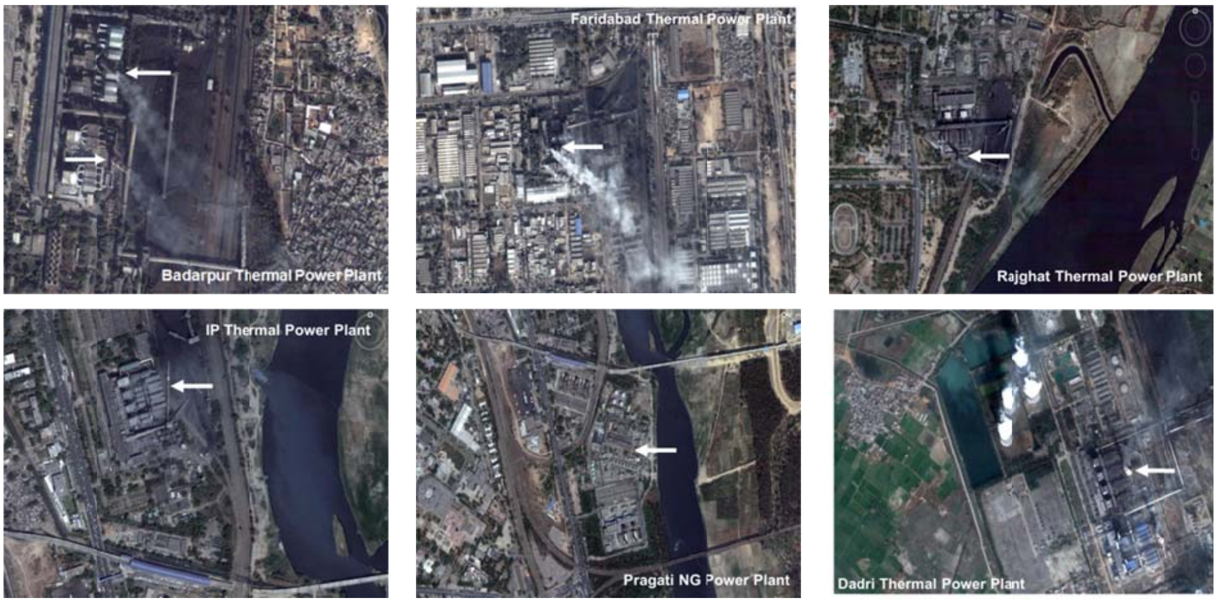
The construction sector is rapidly growing in India. This includes brick and cement manufacturing. In case of NCR, the brick kilns are located just outside the Delhi city limits, mostly along the border. The black dots in **Fig.07** show the location of ~1,000 kilns in the study domain, with a production 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 to 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, as Hoffmann, high draught or vertical shaft brick kilns (CAI-Asia, 2008; World Bank, 2010). Similar kilns are found in most of Northern India, along the Indo-Gangetic plain, and around the cities of Bangalore, Chennai, and Hyderabad (in South India) (*Isebelle et al., 2007*). 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 (*World Bank, 2007; Guttikunda et al., 2012*). We also included construction activities to estimate re-suspension of dust that has an impact on PM emissions.

Fig.09 Brick kilns around NCR Delhi

Electricity Generation

Six major power plants are located within the modeling domain of this study (**Fig.07**). A summary of their location, fuel consumption, and flue gas characteristics is presented 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 2,700 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*).

Fig.10 Power Plants in the modeling domain of NCR Delhi



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 liters of diesel per month and a campus like the Indian Institute of Technology consumes ~80,000 liters per month. The total diesel consumption in the in-situ generator sets is estimated at ~60 PJ.

Fig.11 Diesel generators in use

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

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)*.

Fig.12 Winter heating and waste burning

Waste Management Sector

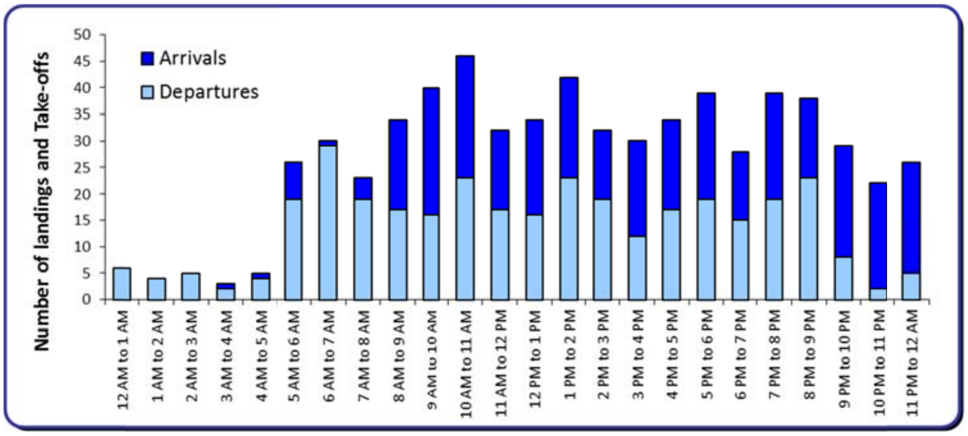
There are three active landfills in Delhi at Okhla Phase I, Jhangir puri, and Ghazipur, with a combined processing capacity of ~5,000 tons per day. However, the total garbage generation for NCR is estimated at ~9,000 tons per day (*SoE-Delhi, 2010*). A portion of the collected garbage is regularly burnt 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*).

Fig.13 Landfills in Delhi

Air Traffic

The domestic and international airports in Delhi operate ~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 at the domestic terminal and a fraction of idling emissions at the arrival and departure sections from the passenger cars.

Fig.14 Flight statistics for Delhi



Emissions Inventory and Sector Contributions

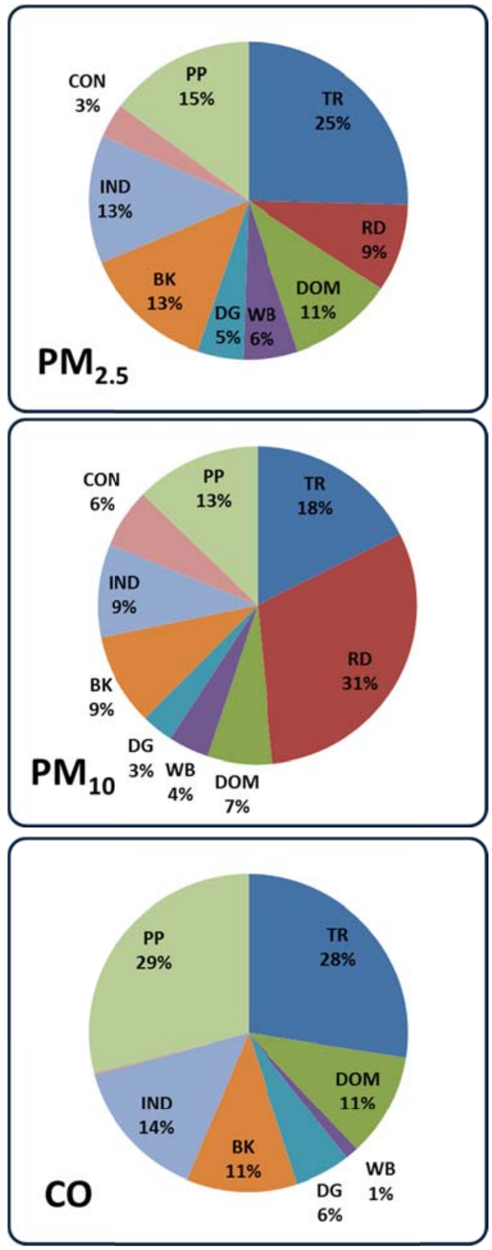
A summary of the total emissions resulting for year 2010 for the National Capital Region is presented in **Table 2**, along with sector contributions. Total emissions are estimated as 69,050 tons of PM2.5, 133,900 tons of PM10, 37,000 tons of SO2, 492,250 tons of NOx, 1.52 million tons of Carbon Monoxide (CO), and 332,700 tons of volatile organic compounds (VOCs**)**.

Table 2: An activity based emissions inventory (tons/year) by sector for the national capital region of Delhi, India, in 2010

	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC
Transport (TR)	17,750 (26%)	23,800 (18%)	950 (3%)	329,750 (67%)	421,450 (28%)	208,900 (63%)
Domestic (DOM)	7,300 (11%)	8,800 (7%)	2,050 (6%)	2,350 (1%)	161,200 (11%)	18,300 (6%)
Diesel Gen Sets (DG)	3,200 (5%)	4,300 (3%)	1,050 (3%)	81,300 (17%)	85,100 (6%)	31,600 (9%)
Brick Kilns (BK)	9,250 (13%)	12,400 (9%)	4,000 (11%)	6,750 (1%)	171,850 (11%)	24,200 (7%)
Industries (IND)	9,000 (13%)	12,650 (9%)	8,500 (23%)	41,500 (8%)	219,600 (14%)	13,250 (4%)
Construction (CON)	2,450 (4%)	8,050 (6%)	100 (1%)	2,150 (1%)	2,700 (1%)	50 (1%)
Waste Burning (WB)	3,850 (6%)	5,450 (4%)	250 (1%)	1,450 (1%)	20,050 (1%)	1,600 (%)
Road Dust (RD)	6,300 (9%)	41,750 (31%)				
Power Plant (PP)	10,150 (15%)	16,850 (13%)	20,250 (55%)	27,200 (6%)	442,150 (29%)	34,900 (10%)
Total	**69,050**	**133,900**	**37,000**	**492,250**	**1,524,050**	**332,700**

Overall, road transport sector remains one of the major sources of all the emissions, either directly from the vehicle exhaust or indirectly from the re-suspension of dust on the roads. For PM_{10} emissions, road dust (31%) and vehicle exhaust (18%) remain the major source, followed by the power plant (13%), industries (9%), and brick kilns (9%). For $PM_{2.5}$ and CO emissions, diesel and biomass based sectors are the dominant sources, with substantial contributions from vehicle exhaust (26% and 28%), power plants (15% and 29%), brick kilns (13% and 11%), industries (13% and 14%), and the domestic sector (11% and 11%) respectively. For NO_x emissions, vehicle exhaust (67%) remains the dominant source. For SO_2, power plants (55%) and industries (23%), the largest coal users in the region, are the dominant sources.

Fig.15: Sector Contributions



In the transport sector, freight movement via heavy duty and light duty trucks is the largest contributor. Most of these, except for some light duty vehicles, operate on diesel. During the CNG shift in the early 2000's, some of the light duty vehicles were retrofitted to operate on CNG. However, the benefits of converting the buses, taxis, and 3-wheelers to CNG based vehicles are now lost, due to an increase in the sales of diesel based passenger vehicles. An increase in the diesel based passenger vehicle sales is primarily driven by the diesel subsidy program (*SIAM, 2012*).

The six power plants in the modeling domain, dominate the total SO_2 (54%) and CO (29%) emissions. Diesel consumption for in-situ power generation from diesel generator sets in the hotels, hospitals, large institutions, markets, malls, and apartment complexes, is estimated to contribute about 5% of $PM_{2.5}$. Although, the overall percentage of these emissions is small, when spatially segregated, these low lying emissions are substantial, especially in the densely populated areas.

The brick kilns operate only between November and May. Due to the recent boom in the construction industry, the production rates and the number of kilns have increased in the vicinity of the city and estimated to account for 13% of annual $PM_{2.5}$, 11% 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.07** that these kilns are located close to the border and a major contributor to the air pollution levels in Delhi.

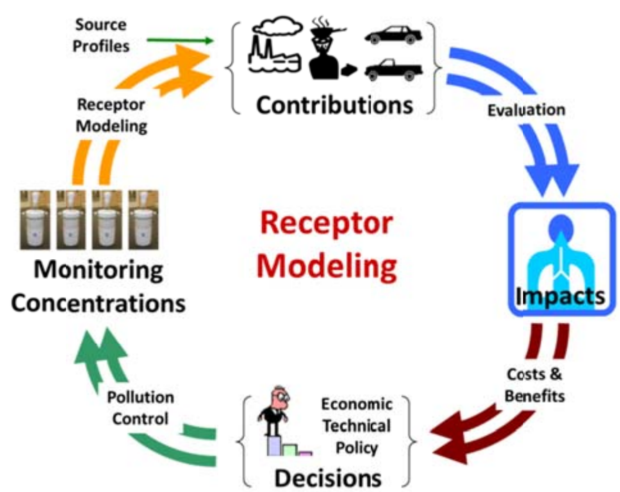
The emission inventory also includes sector-specific profiles for dispersion model-ready input preparation; such as diurnal cycles for the transport sector to distinguish between the rush and non-rush hours for all modes, operational hours for the industrial sector, and cooking and heating hours for the domestic sector.

Previous studies

An earlier emissions inventory for Delhi, prepared by *Gurjar et al. (2004)* and updated by *Mohan et al. (2007)* for the time period of 1990 to 2000, concluded that power plants are the primary sources for SO_2 (68%) and total suspended particles (80%), while NOx, CO and VOC emissions came from the transport sector. Additionally, agriculture was the major contributor for ammonia (70%) and nitrous oxide (50%), and solid waste disposal the main source of methane CH4 (80%). The modeling domain in *Gurjar et al., (2004)* was much smaller than the one used in the current study; another change is that since 2000-05, the power plants located in Delhi have been converted from coal to CNG, and the vehicle fleet for passenger and commercial activities has at least doubled (*SoE-Delhi, 2010*).

The Ministry of Environment and Forests (MoEF) of India and CPCB, carried out particulate pollution source apportionment study in six cities: Delhi, Kanpur, Chennai, Mumbai, Pune, and Bangalore (*CPCB, 2010*). This study for Delhi estimated ~147 tons PM10 per day, ~460 tons per day of NOx, and ~268 tons per day of SO2. Since, these figures are below the estimates from our study, it is important to note the differences in the methodologies. *CPCB (2010)* is for the base year of 2006-07 and represents only the main city, covering an area of 32 km x 32 km; which is ~25% of the area covered in our study. The inventories were primarily estimated for an area of 2 km x 2 km around the monitoring site selected for the source apportionment study and then extrapolated to the city district area. This does not include the areas surrounding the main district where the industrial activity is generally larger than the in-district activities. In case of Delhi, the largest missed contribution seems to arise from brick kiln emissions, with clusters located ~20 km away from the city district boundaries (**Fig.07**), yet they make a definite contribution to air pollution concentrations over the whole NCR. *Sahu et al. (2011)* published a gridded inventory for the region at 1.67km x 1.67km grid resolution, also fails to distinguish the brick kiln sector.

Fig.16: Receptor modeling schematics

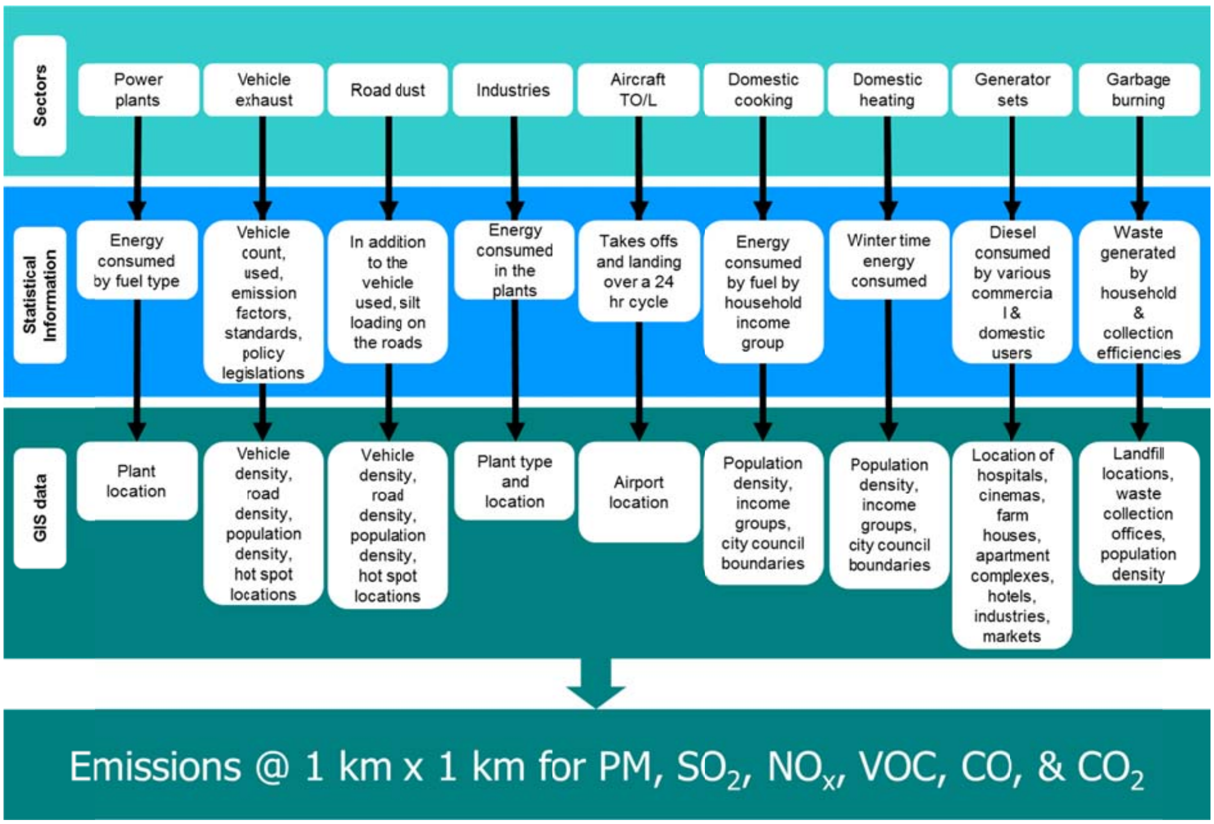


A number of receptor modeling studies have been conducted in Delhi (*Balachandran et al., 2000; Khillare et al., 2004; Chowdhury et al., 2007; Srivastava and Jain, 2007a; Srivastava and Jain, 2007b; Srivastava et al., 2009; Tiwari et al., 2009; Chelani et al., 2010; CPCB, 2010; Mönkönnen et al., 2004; Shridhar et al., 2010*). Key contributors to PM pollution in Delhi have been identified as road dust, vehicle exhaust, coal and biomass combustion, open refuse burning, secondary aerosols, and construction activities. Interestingly, among other sources, LPG gas was identified as a key contributor to $PM_{2.5}$ in residential areas by *CPCB (2010)*, which no other studies have reported in the past (*Pant and Harrison, 2012*). Although the contributions estimated from the receptor models varied from study to study, depending on the season and location of monitoring site, these studies provide a scientific background and a method to validate the source-receptor relationships at the monitoring sites. However, the rigorous methodology is financially and technically demanding to repeat the experiment for many locations, in which case the source modeling studies such as this study can be complimentary (*Johnson et al., 2011*).

Spatial Distribution of Emissions

We developed the emissions inventory on a GIS based platform to spatially segregate emissions for further use in atmospheric modeling. Hence we subdivided the domain under study (**Fig.07**) 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 on the grid - summarized below.

Fig.17: Schematics utilized for spatial segregation of total emissions over NCR Delhi



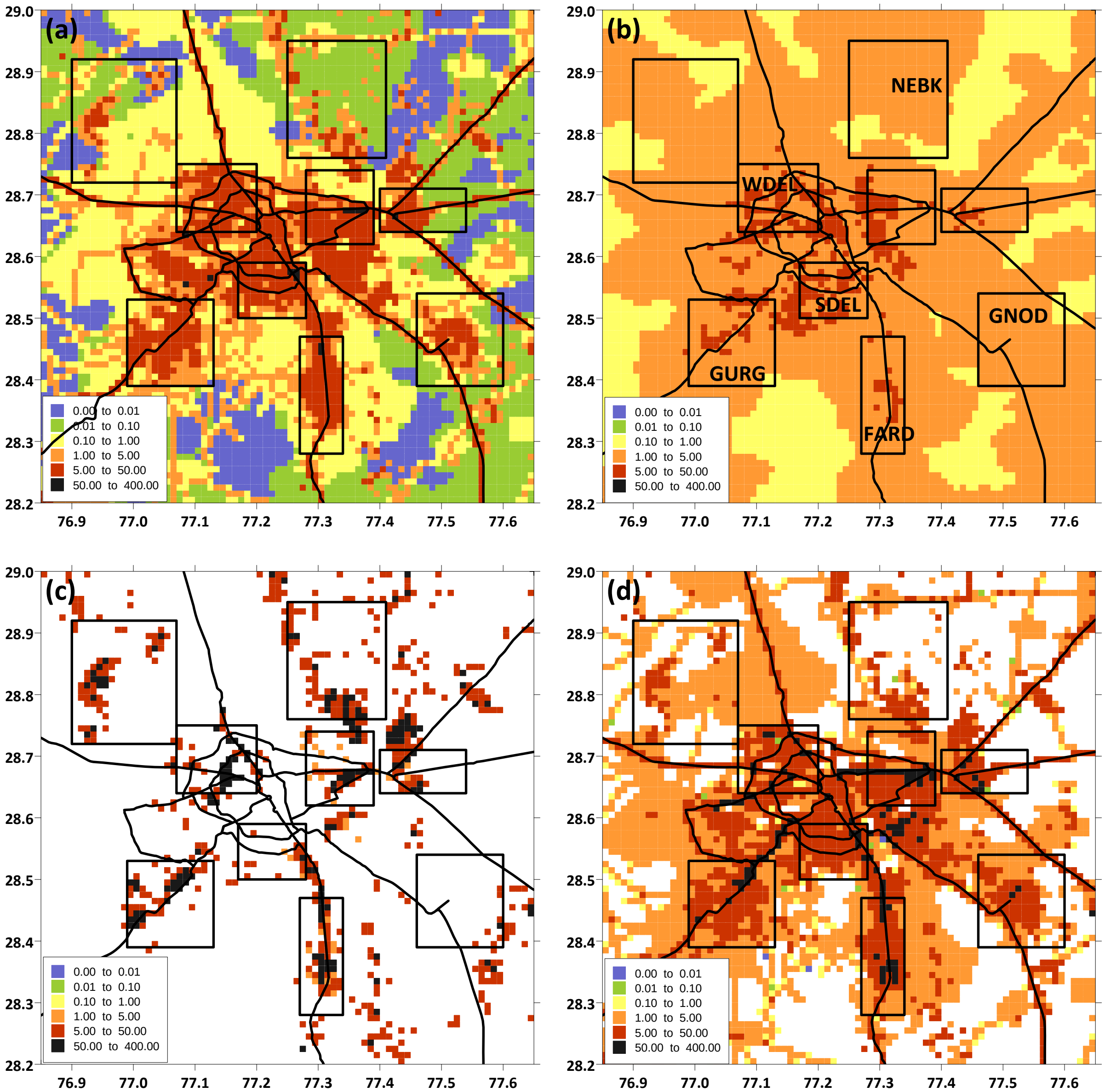
For the population density maps, we used data from *GRUMP (2010)* at 30” spatial resolution. The average population density is more than 5,000 per km^2 in the main districts.

We used GIS data from EICHER (New Delhi, India) to map roads (including information on bus stops, bus depots, traffic signals, and landmarks), industries, brick kilns, hotels, hospitals, markets, malls, cinemas, apartment complexes, large institutions, and farm houses. In case of the transport sector, we used grid based population density and vehicle density surveys conducted by CRRI (New Delhi) to distribute emissions on feeder, arterial and main roads.

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

Four panels for gridded PM_{10} emissions (in tons/year/grid) for vehicles, industries (including the brick kilns), domestic (including heating, waste burning, and winter heating), and dust (including road dust and construction activities) are presented below. 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 below. However, gridded fields were also developed for $PM_{2.5}$, SO_2, NO_x, CO and VOC.

Fig.18: Schematics utilized for spatial segregation of total emissions over NCR Delhi



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 3 presents the percentage contributions by sector to total annual $PM_{2.5}$ emissions for six select regions evidenced in Figure 3. Note that the other pollutants are not presented in this graph. The regions are selected with equal areas, so that we can compare the mix of 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.

Table 3: Contributions to total $PM_{2.5}$ emissions in select residential and industrial regions for year 2010 in Delhi, India						
	SDEL	**FARD**	**GNOD**	**NEBK**	**WDEL**	**GURG**
Total $PM_{2.5}$ (tons/year)	2,080	3,700	1,680	2,700	5,360	4,700
Transport	48%	35%	40%	10%	31%	27%
Domestic	7%	5%	16%	12%	5%	5%
Diesel Gen Sets	13%	6%	2%		6%	6%
Brick Kilns			8%	68%		1%
Industries	10%	35%			45%	43%
Construction	2%	3%	10%	1%		6%
Waste Burning	5%	4%	6%	4%	4%	3%
Road Dust	14%	13%	17%	5%	9%	10%

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 Northeast 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), also linked to the lack of paved roads in the area. Road dust re-suspension and waste burning are uniformly present in all the regions. It is important to note that 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 PM10 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 hours a day.

Particulate Matter Concentrations

We used the Atmospheric Transport Modeling System (ATMoS) dispersion model - a meso-scale three-layer forward trajectory Lagrangian Puff-transport model (*Calori and Carmichael, 1999*) to model PM concentrations for the base year 2010. This model was previously utilized in pollution management studies in Asia at a regional scale (*Arndt et al., 1998; Streets et al., 2000; Guttikunda et al., 2001; Holloway et al., 2002; Carmichael et al., 2008*) and urban scale (*Kan et al., 2004; Guttikunda et al., 2003; Guttikunda and Gurjar, 2011*). The ATMoS model is a modified version of 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. The model has flexible temporal and spatial resolution and can run for periods ranging from one month to a year and from regional to urban scales.

Input meteorological data for Delhi analysis (3D wind, temperature, and pressure, as well as surface heat flux and precipitation fields) is derived from the National Center for Environmental Prediction (NCEP) global reanalysis (*Kalnay et al. 1996*), interpolated on the model grid. The summer time mixing heights are estimated to be as high as 2,500 meters during the daytime compared to the lows of less than 100 meters in the winter months (*Guttikunda and Gurjar, 2011*).

Fig.19 Mixing layer height in 2008 over NCR Delhi, estimated from NCEP Reanalysis data (thick line indicates a 15 day moving average)

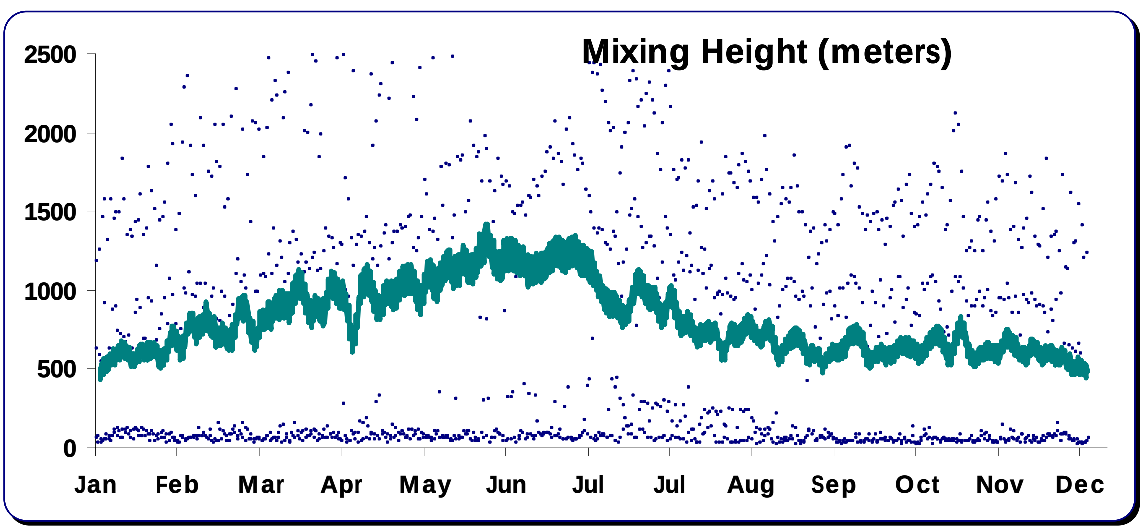
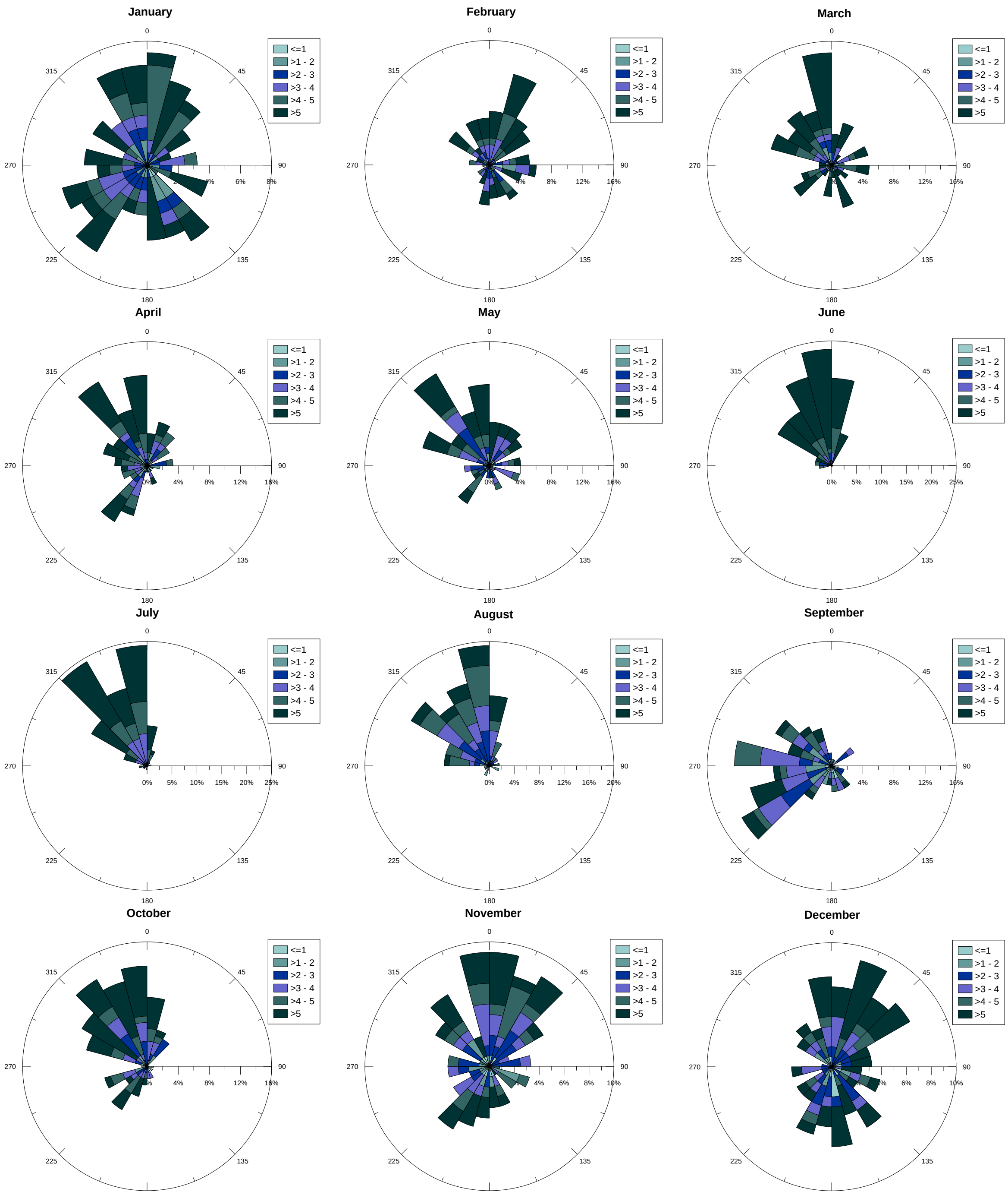
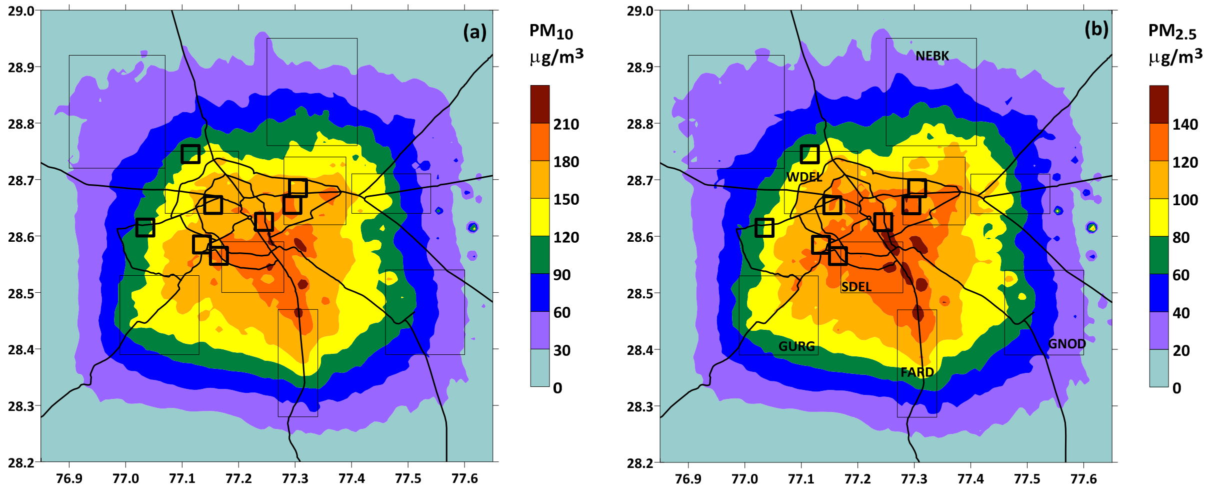


Fig. 20: Wind speed and wind direction for the Delhi domain @ 6 hour interval, estimated from NCEP reanalysis data for year 2008



We present below the modeled annual average concentrations for $PM_{2.5}$ and PM_{10}. We ran the dispersion model by sector and then aggregated the total $PM_{2.5}$ and PM_{10} bins. These totals include primary PM and contributions from chemical transformation of SO_2 and NO_x emissions in the form of sulfates and nitrates (*Guttikunda et al., 2001; Holloway et al., 2002*) and do not include any effects of long-range transport from the regions outside modeling domain.

Fig.21 Modeled annual average (a) PM_{10} and (b) $PM_{2.5}$ concentrations over the NCR of Delhi



For most of NCR the estimated concentrations exceeded the national ambient standards for yearly averages, 60 $\mu g/m^3$ for PM_{10} and 40 $\mu g/m^3$ for $PM_{2.5}$. The resulting modeled annual average concentration for the main Delhi district (the area inside outer ring road) is ~120 $\mu g/m^3$ for $PM_{2.5}$ and ~160 $\mu g/m^3$ for PM_{10}. For the regional boxes designated in Figure 3, the estimated annual average $PM_{2.5}$ concentrations are - 131 $\mu g/m^3$ for SDEL, 88 $\mu g/m^3$ for GURG, 50 $\mu g/m^3$ for GNOD, 89 $\mu g/m^3$ for FARD, 102 $\mu g/m^3$ for WDEL, 46 $\mu g/m^3$ around the brick kiln clusters in the Northeast (NEBK).

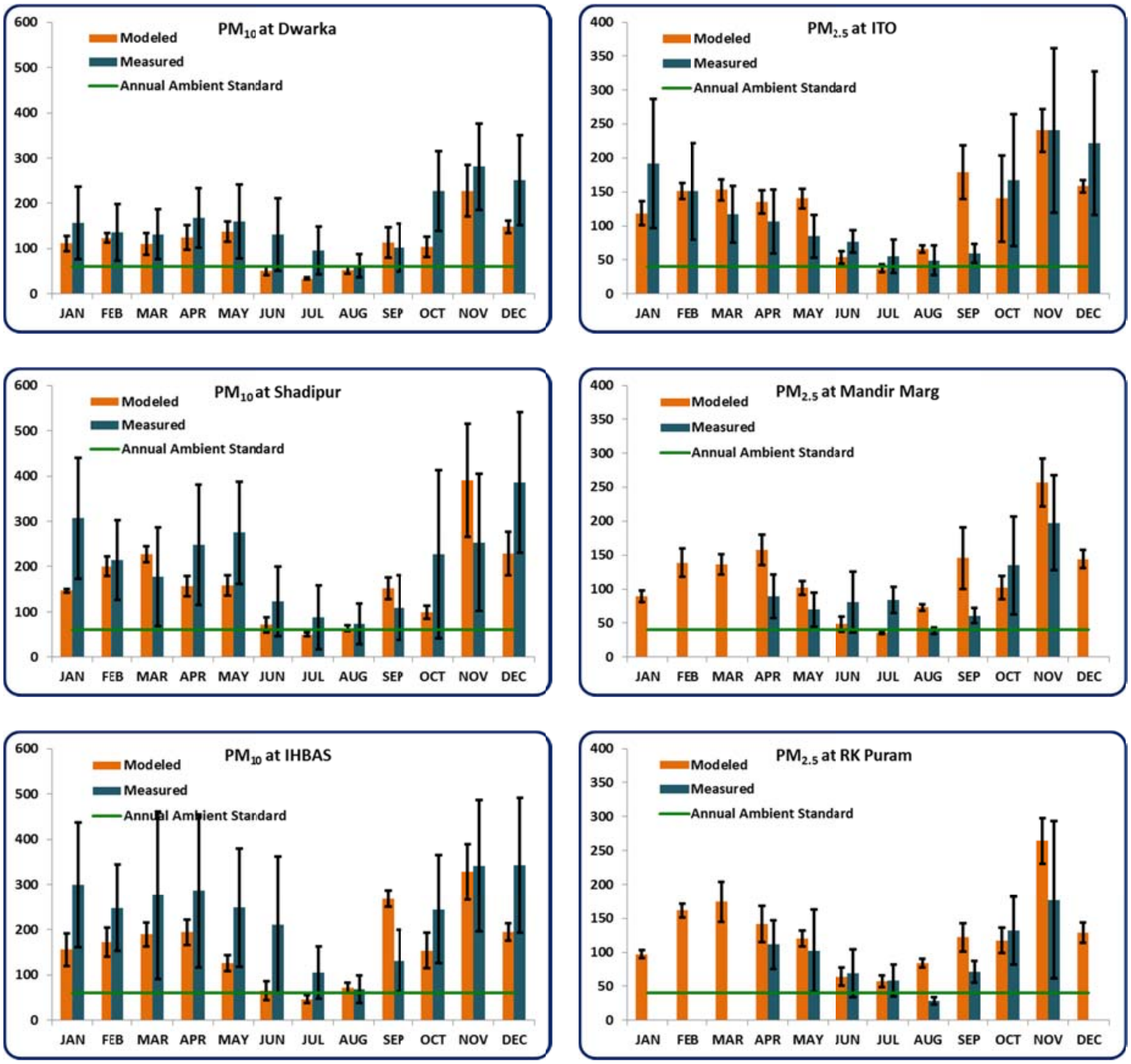
Comparison with Monitoring Data

We also compare the modeled concentrations against monitoring data from six continuous monitoring stations (presented below). The monitoring data analyzed in this paper is from the continuous air monitoring stations operated by CPCB and the Delhi Pollution Control Committee. This data is from (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 (mixed residential, industrial, and traffic) (5) Institute of Human Behaviour & Allied Sciences (IHBAS, mixed residential and traffic) (6) Mandir Marg (mixed traffic and industrial) (7) RK Puram (mixed traffic and residential) and is available in the public domain. These stations measure SO_2, NO_x, and CO, not all stations measure both $PM_{2.5}$ and PM_{10}. Ozone and $PM_{2.5}$ were added to the list of criteria pollutants in November, 2009.

The uncertainties in measured and in modeled data are not undermined and these results are presented to ensure that the emission estimates and the dispersion model schematics are representative of the geographical and meteorological conditions prevalent in the region. All the stations measure only one fraction of PM (either $PM_{2.5}$ or PM_{10}) and the data collection efficiencies are lower than 40% in a year. So, the measurements are an average of all the data available during the period of 2009 to 2011. The stations at Mandir Marg (MM) and RK Puram (RK) both measuring $PM_{2.5}$ are new and operational since April, 2011; while the station at the income tax office (ITO) is operational since 2006. However, for PM10, stations at IHBAS, Shadipur (SHAD), and in Dwarka (NSIT) are operational since 2009. The annual average measured concentrations ranged 130 ± 92 $\mu g/m^3$ for $PM_{2.5}$ at ITO; 89 ± 50 $\mu g/m^3$ 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.

Fig.22 Comparison of PM_{10} and $PM_{2.5}$ measurements from six stations in Delhi with the modeled monthly average concentrations over a 3km x 3km area covering the monitoring station

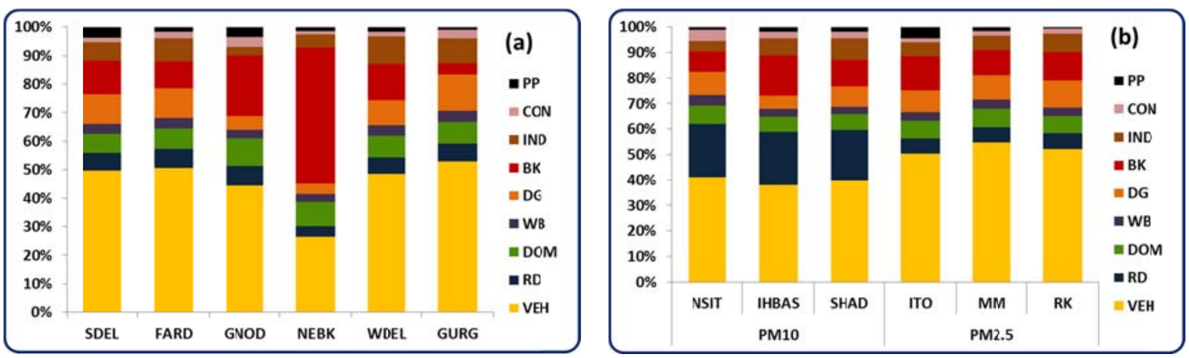


The graph, also presents the variations in the measured and the modeled concentrations: the variation of the daily averages over each month for the measurements and the variation over 9 cells surrounding the monitoring station for the modeled results. It is in fact to be considered that the station measurements are mostly representative of the monitoring location and the surrounding sources; while the modeled concentrations are inherently grid averages. From the comparison it seems that the levels observed at the different sites are reasonably captured, as well the main features in their monthly behaviors, with maxima in the cold season as a combined result of the increased emissions and the unfavorable dispersion conditions during these months (*Guttikunda and Gurjar, 2011*). The differences between the measured and the modeled numbers can be explained further by (a) uncertainty in the emissions inventory estimation (b) uncertainty in the spatial disaggregation of the emissions inventory into grids, and (c) uncertainty in the dispersion modeling results.

Source-Receptor Relationships by Region

Due to prevalent meteorological conditions determining the role of emissions from surrounding areas, the source contributions to ambient concentrations are not necessarily the same as those estimated for emissions at the same location. As presented in **Table 3** with total emissions by region, Figure below shows the sector contributions to the modeled ambient concentrations over the same regions. Similar information is presented for six monitoring stations used for comparisons, using the modeled data from 3x3 grid cells, centered on the location of the station. For convenience and because of the higher health impact factor (*HEI, 2010*), percent shares for only $PM_{2.5}$ concentrations are presented here.

Fig.23: Contributions to total $PM_{2.5}$ and PM_{10} concentrations over select regions in Delhi, India because of emissions from power plants (PP), construction activities (CON), industries (IND), brick kilns (BK), diesel generator sets (DG), waste burning (WB), domestic (DOM, including winter burning), road dust (RD), vehicle exhaust (VEH) for (a) six select residential and industrials (b) around the monitoring stations



Area and diffused sources contribute the most to the $PM_{2.5}$ concentrations, dominated by vehicle exhaust (up to 50%) and followed by road dust, diesel generator sets, and domestic emissions, including open waste burning. While the brick kilns are limited to certain pockets of the city, due to their stack height and intensity of emissions, the effects are felt farther from their locations. For example, SDEL, with a population density of ~10,000 people per km^2, is approximately 30km away from any of the clusters presented in Figure 1 and yet experiences 10% of fine $PM_{2.5}$ pollution originating from these kilns. The monitoring stations are often located closer to the traffic junctions and thus capturing a higher proportion of vehicle exhaust.

Implications to Air Pollution Control in Delhi

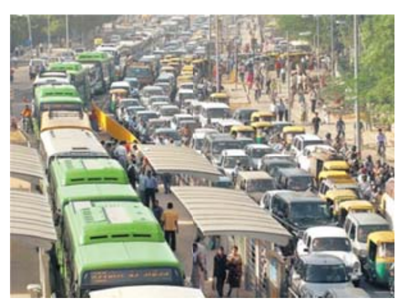
For the national capital region, the total emissions for 2010 are estimated as 69,050 tons of $PM_{2.5}$, 133,900 tons of PM_{10}, 37,000 tons of SO_2, 492,250 tons of NO_x, 1.52 million tons CO, and 332,700 tons of VOCs; and further spatially segregated into 80x80 grids at 0.01° resolution for each of the contributing sectors. The monitoring data from the stations and the dispersion modeling results further emphasize the deteriorating PM pollution levels in the region, from a mix of sources.

From this study (and previously published studies), we know the areas that need action, 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.

Our study highlights the low hanging fruit in terms of policy changes that can be made to improve air quality and better public health. The urban clusters of small-scale manufacturers, such as leather tanneries, brick kilns, smelters, and metalworking shops account for a large portion of pollution in Delhi. Moreover, it is easier to inspect and maintain 1,000 brick kilns or 6,000 other industries, compared to the 6 million vehicles plying on the roads. While relocation of industries proved beneficial in the past, with the growing population and city size, a more promising approach would be to introduce emerging technologies that reduce the emission rates at the brick kilns and the industrial boilers, followed by the enforcement of an inspection and maintenance program.

The passenger and commercial vehicles are responsible for an increasing portion of the energy consumption, emissions, and harmful exposure. In dense traffic zones of Delhi, large populations are exposed to the vehicle exhaust and the road dust pollution, sometimes double the ambient pollution (*Apte et al., 2011*). A number of interventions are in place or being promoted for the passenger transport. After only a 6 km pilot for bus rapid transport (BRT) corridor in 2008, the implementation of special bus corridors for the CWG covering 80 km between venues, Games village, and major residential areas, succeeded as a good pilot for future BRT application. The interventions introduced during the 2010 CWG in Delhi were not as stringent as those observed in Beijing during the 2008 Olympic Games (*UNEP, 2009*), but served as an example for public awareness on air quality issues in the city. The public transport sector got a boost from doubling of fleet, along with the introduction of air conditioned buses and an extension of the metro lines.

Fig.24 Special lanes during the 2010 Commonwealth Games and BRT in 2008



The para-transit sector, 3-wheelers and taxis have also benefitted from the expansion of their fleets and from the expansion of metro by linking the feeding lanes to the residential points. The commercial heavy duty trucks are banned from entering the city limits between 6AM and 9PM, to reduce the emission loads and exposure levels during the day time. However, the density of these vehicles carrying raw and finished products, construction debris, sand, and bricks, has increased, resulting in more emissions, and this pollution tend to linger even after the trucks have stopped operating at 6AM. The debris and sand, which is often carried without any covers, tend to add to the silt loading on these roads.

Another major source of pollution in most Indian cities is road dust (*CPCB, 2010*), including that from the construction activities. This source, a large part of the coarse PM_{10} pollution, is often difficult to quantify as it depends on the vehicle movement on the roads, road types, silt loading on roads and at construction sites, and meteorological conditions. However, this source can be managed with measures like wet sweeping of street roads, promoting vegetation in dry areas, paving roads and completing road work that often time results in ditches and pavements that are left as is after the concerned department (telephone, sewer, electricity, and gas) has finished their work.

Fig.25: Sweeping on roads

A source which needs further attention is waste management and garbage burning. Considerable knowledge of best practices to improve the waste collection and management exists. The basic problem has been in adapting these practices to specific local conditions. In Delhi and other cities, waste management is highly labor intensive, and promises basic employment opportunities for large numbers of people, which means we need a consolidated effort between the communities and management, to reduce the garbage burning emissions.

The electricity demand in the domestic, commercial, and industrial sectors is fueling the need for in-situ diesel generator sets and related emissions. This is a sector which cannot be addressed by simply setting up new power plants in the region and requires a consented dialogue between power, petroleum, energy, and environment ministries.

It is often observed that emission inventories are never complete and require refinements and updates that can be made by building monitoring capacity, continued identification of pollution sources, and use of source and receptor modeling studies. The emissions inventory presented in this paper is in-use for an operational air quality forecasting system for NCR, launched before the 2010 Commonwealth Games (CWG), now maintained, updated, and validated by CPCB (Guttikunda et al., 2011). These modeling systems while advantageous for mega events like CWG, which benefited from 48-hour short term health alert notices, also provided better understanding of the influencing sources for long term planning to control air pollution.

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 as an Excel file. The remaining 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.

References

Abu-Allaban, M., Gillies, J.A., Gertler, A.W., Clayton, R., Proffitt, D., 2003. Tailpipe, resuspended road dust, and brake-wear emission factors from on-road vehicles. Atmospheric Environment 37, 5283-5293.

Amato, F., Pandolfi, M., Moreno, T., Furger, M., Pey, J., Alastuey, A., Bukowiecki, N., Prevot, A., Baltensperger, U., Querol, X., 2011. Sources and variability of inhalable road dust particles in three European cities. Atmospheric Environment In Press, Accepted Manuscript.

Apte, J.S., Kirchstetter, T.W., Reich, A.H., Deshpande, S.J., Kaushik, G., Chel, A., Marshall, J.D., Nazaroff, W.W., 2011. Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. Atmospheric Environment 45, 4470-4480.

ARAI, 2007. Emission Factor development for Indian Vehicles. Central Pollution Control Board, New Delhi, India.

Arndt, R.L., Carmichael, G.R., Roorda, J.M., 1998. Seasonal source-receptor relationships in Asia. Atmospheric Environment 32, 1397-1406.

Baidya, S., Borken-Kleefeld, J., 2009. Atmospheric emissions from road transportation in India. Energy Policy 37, 3812-3822.

Balachandran, S., Meena, B.R., Khillare, P.S., 2000. Particle size distribution and its elemental composition in the ambient air of Delhi. Environment International 26, 49-54.

Berger, J., Denby, B., 2011. A generalised model for traffic induced road dust emissions. Model description and evaluation. Atmospheric Environment 45, 3692-3703.

Bhattacharya, S.C., Abdul Salam, P., Sharma, M., 2000. Emissions from biomass energy use in some selected Asian countries. Energy 25, 169-188.

Bose, R.K., 1996. Energy demand and environmental implications in urban transport — Case of Delhi. Atmospheric Environment 30, 403-412.

CAI-Asia, 2008. Clean brick making technology—success of VSBK in Kathmandu. Clean air initiative for Asia cities, Manila, Philippines.

Calori, G., Carmichael, G.R., 1999. An urban trajectory model for sulfur in Asian megacities: model concepts and preliminary application. Atmospheric Environment 33, 3109-3117.

Carmichael, G.R., Sakurai, T., Streets, D., Hozumi, Y., Ueda, H., Park, S.U., Fung, C., Han, Z., Kajino, M., Engardt, M., Bennet, C., Hayami, H., Sartelet, K., Holloway, T., Wang, Z., Kannari, A., Fu, J., Matsuda, K., Thongboonchoo, N., Amann, M., 2008. MICS-Asia II: The model intercomparison study for Asia Phase II methodology and overview of findings. Atmospheric Environment 42, 3468-3490.

Census-India, 2012. Census of India, 2011. The Governement of India, New Delhi, India.

Chelani, A., Devotta, S., 2007. Air Quality Assessment in Delhi: Before and After CNG as Fuel. Environmental Monitoring and Assessment 125, 257-263.

Chelani, A.B., Gajghate, D.G., ChalapatiRao, C.V., Devotta, S., 2010. Particle Size Distribution in Ambient Air of Delhi and Its Statistical Analysis. Bulletin of Environmental Contamination and Toxicology 85, 22-27.

Chhabra, S.K., Chhabra, P., Rajpal, S., Gupta, R.K., 2001. Ambient air pollution and chronic respiratory morbidity in Delhi. Archives of Environmental Health 56, 8.

Chowdhury, Z., Zheng, M., Schauer, J.J., Sheesley, R.J., Salmon, L.G., Cass, G.R., Russell, A.G., 2007. Speciation of ambient fine organic carbon particles and source apportionment of PM2.5 in Indian cities. J. Geophys. Res. 112, D15303.

CPCB, 2010. Air quality monitoring, emission inventory and source apportionment study for Indian cities, Central Pollution Control Board, Government of India, New Delhi, India.

Das, D., Sharfuddin, A., Datta, S., 2009. Personal Vehicles in Delhi: Petrol Demand and Carbon Emission. Int. J. Sustain. Transp. 3, 122-137.

DIESEL, 2008. Developing Integrated Emissions Strategies for Existing Land-Transport (DIESEL) in Bangkok, Thailand. UNDP/World Bank Energy Management Assistance Programme, Washington DC, U. S. A.

DTC, 2010. Largest CNG Based Fleet in the World, Delhi Transport Corporation, New Delhi, India.

DTE, 2002. The Supreme Court not to budge on CNG issue, Down to Earth Magazine, New Delhi, India.

EEA, 2002. National and central estimates for air emissions from road transport, European Environment Agency, Brussels, Belgium.

EEA, 2009. Air pollutant emission inventory guidebook, European Environmental Agency, Brussels, Belgium.

EEA, 2010. Annual European Union greenhouse gas inventory 1990–2008 and inventory report 2010, European Environment Agency, Brussels, Belgium.

Etyemezian, V., Kuhns, H., Gillies, J., Chow, J., Hendrickson, K., McGown, M., Pitchford, M., 2003. Vehicle-based road dust emission measurement (III):: effect of speed, traffic volume, location, and season on PM10 road dust emissions in the Treasure Valley, ID. Atmospheric Environment 37, 4583-4593.

Firdaus, G., Ahmad, A., 2011. Changing air quality in Delhi, India: determinants, trends, and policy implications. Regional Environmental Change 11, 743-752.

GAINS, 2010. Greenhouse Gas and Air Pollution Interactions and Synergies - South Asia Program. International Institute of Applied Systems Analysis, Laxenburg, Austria.

Garg, A., 2011. Pro-equity Effects of Ancillary Benefits of Climate Change Policies: A Case Study of Human Health Impacts of Outdoor Air Pollution in New Delhi. World Dev. 39, 1002-1025.

Gillies, J.A., Etyemezian, V., Kuhns, H., Nikolic, D., Gillette, D.A., 2005. Effect of vehicle characteristics on unpaved road dust emissions. Atmospheric Environment 39, 2341-2347.

Goswami, P., Baruah, J., 2008. Simulation of daily variation of suspended particulate matter over Delhi: Relative roles of vehicular emission, dust, and domestic appliances. Mon. Weather Rev. 136, 3597-3607.

GRUMP, 2010. Gridded Population of the World and Global Rural and Urban Mapping Project. Center for International Earth Science Information Network (CIESIN) of the Earth Institute, Columbia University, New York, U. S. A.

Gupta, J., 2003. Informal Labour in Brick Kilns: Need for Regulation. Economic and Political Weekly 38, 3282-3292.

Gurjar, B.R., van Aardenne, J.A., Lelieveld, J., Mohan, M., 2004. Emission estimates and trends (1990-2000) for megacity Delhi and implications. Atmospheric Environment 38, 5663-5681.

Guttikunda, S., Gurjar, B., 2011. Role of meteorology in seasonality of air pollution in megacity Delhi, India. Environmental Monitoring and Assessment, 1-13.

Guttikunda, S.K., 2009. Air Quality Management in Delhi, India: Then, Now, and Next, in: UrbanEmissions.Info (Ed.), SIM-air Working Paper Series, 22-2009, New Delhi, India.

Guttikunda, S.K., Bilkis, B., Wadud, Z., 2012. An Evaluation of Particulate Pollution from Brick Kiln Clusters in the Greater Dhaka Region, Bangladesh. Atmospheric Environment, under review.

Guttikunda, S.K., Calori, G., Velay-Lasry, F., Ngo, R., 2011. Air Quality Forecasting System for Cities: Modeling Architecture for Delhi, in: UrbanEmissions.Info (Ed.), SIM-air Working Paper Series, 36-2011, New Delhi, India.

Guttikunda, S.K., Carmichael, G.R., Calori, G., Eck, C., Woo, J.-H., 2003. The contribution of megacities to regional sulfur pollution in Asia. Atmospheric Environment 37, 11-22.

Guttikunda, S.K., Thongboonchoo, N., Arndt, R.L., Calori, G., Carmichael, G.R., Streets, D.G., 2001. Sulfur deposition in Asia: Seasonal behavior and contributions from various energy sectors. Water Air and Soil Pollution 131, 383-406.

Heffter, J.L., 1983. Branching atmospheric trajectory (BAT) model, NOAA Tech. Memo. ERL ARL-121, Air Resources Laboratory, Rockville, MD USA.

HEI, 2004. Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review, Special Report 15, Health Effects Institute, Boston, USA.

HEI, 2010. Outdoor Air Pollution and Health in the Developing Countries of Asia: A Comprehensive Review, Special Report 18, Health Effects Institute, Boston, USA.

Holloway, T., Levy Ii, H., Carmichael, G., 2002. Transfer of reactive nitrogen in Asia: development and evaluation of a source-receptor model. Atmospheric Environment 36, 4251-4264.

IFMR, 2011. Atlas of Household Energy Consumption and Expenditure in India, The Institute for Financial Management and Research, Chennai, India.

Isabelle, G., Augendra, B., Parthasarthy, Venkatasubramanian, G., 2007. Labour in Brick Kilns: A Case Study in Chennai. Economic and Political Weekly 42, 599-606.

Johnson, T.M., Guttikunda, S.K., Wells, G., Bond, T., Russell, A., West, J., Watson, J., 2011. Tools for Improving Air Quality Management. A Review of Top-down Source Apportiontment Techniques and Their Application in Developing Countries. ESMAP Publication Series, The World Bank, Washington DC, USA.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society 77, 437-471.

Kan, H., Chen, B., Chen, C., Fu, Q., Chen, M., 2004. An evaluation of public health impact of ambient air pollution under various energy scenarios in Shanghai, China. Atmospheric Environment 38, 95-102.

Kandlikar, M., 2007. Air pollution at a hotspot location in Delhi: Detecting trends, seasonal cycles and oscillations. Atmospheric Environment 41, 5934-5947.

Kansal, A., Khare, M., Sharma, C.S., 2009. Health benefits valuation of regulatory intervention for air pollution control in thermal power plants in Delhi, India. Journal of Environmental Planning and Management 52, 881-899.

Kathuria, V., 2005. Vehicular Pollution Control in Delhi: Impact of Compressed Natural Gas. Economic and Political Weekly 40, 1907-1916.

Khillare, P.S., Balachandran, S., Meena, B.R., 2004. Spatial and Temporal Variation of Heavy Metals in Atmospheric Aerosol of Delhi. Environmental Monitoring and Assessment 90, 1-21.

Kumar, N., Foster, A.D., 2007. Have CNG Regulations in Delhi Done Their Job? Economic and Political Weekly 42, 48-58.

Maithel, S., Uma, R., Bond, T., Baum, E., Thao, V.T.K., 2012. Brick Kilns Performance Assessment, Emissions Measurements, & A Roadmap for Cleaner Brick Production in India, Study report prepared by Green Knowledge Solutions, New Delhi, India.

Majumdar, D., Gajghate, D.G., 2011. Sectoral CO2, CH4, N2O and SO2 emissions from fossil fuel consumption in Nagpur City of Central India. Atmospheric Environment 45, 4170-4179.

Mohan, M., Dagar, L., Gurjar, B.R., 2007. Preparation and validation of gridded emission inventory of criteria air pollutants and identification of emission hotspots for megacity Delhi. Environmental Monitoring and Assessment 130, 323-339.

Mönkkönen, P., Uma, R., Srinivasan, D., Koponen, I.K., Lehtinen, K.E.J., Hämeri, K., Suresh, R., Sharma, V.P., Kulmala, M., 2004. Relationship and variations of aerosol number and PM10 mass concentrations in a highly polluted urban environment—New Delhi, India. Atmospheric Environment 38, 425-433.

MoRTH, 2011. Road Transport Year Book, Ministry of Road and Highway Transport, Government of India, New Delhi, India.

MoUD, 2008. Traffic and transportation policies and strategies in urban areas in India, Ministry of Urban Development, Government of India, New Delhi, India.

Mukherjee, N., Mukherjee, A., Jayaswal, M., Ray, S., Jena, B., 2001. Air Pollution, Farming Systems and Livelihoods: Evidence from Haryana. Economic and Political Weekly 36, 526-527.

Narain, U., Bell, R.G., 2006. Who Changed Delhi's Air? Economic and Political Weekly 41, 1584-1588.

Pande, J.N., Bhatta, N., Biswas, D., Pandey, R.M., Ahluwalia, G., Siddaramaiah, N.H., Khilnani, G.C., 2002. Outdoor air pollution and emergency room visits at a hospital in Delhi. Indian J Chest Dis Allied Sci 44, 9.

Pant, P., Harrison, R.M., 2012. Critical review of receptor modelling for particulate matter: A case study of India. Atmospheric Environment.

Ramachandraiah, C., 2007. Public Transport Options in Hyderabad. Economic and Political Weekly 42, 2152-2154.

Reddy, M.S., Venkataraman, C., 2002. Inventory of aerosol and sulphur dioxide emissions from India: I--Fossil fuel combustion. Atmospheric Environment 36, 677-697.

Reynolds, C.C.O., Grieshop, A.P., Kandlikar, M., 2011. Climate and Health Relevant Emissions from in-Use Indian Three-Wheelers Fueled by Natural Gas and Gasoline. Environmental Science & Technology 45, 2406-2412.

Sahu, S.K., Beig, G., Parkhi, N.S., 2011. Emissions inventory of anthropogenic PM2.5 and PM10 in Delhi during Commonwealth Games 2010. Atmospheric Environment 45, 6180-6190.

Schipper, L., Marie-Lilliu, C., Gorham, R., 2000. Flexing the link between transport and greenhouse gas emissions: A path for the World Bank, International Energy Agency, Paris, France.

Schwela, D., Haq, G., Huizenga, C., Han, W., Fabian, H., Ajero, M., 2006. Urban Air Pollution in Asian Cities - Status, Challenges and Management. Earthscan Publishers, London, UK.

Shridhar, V., Khillare, P.S., Agarwal, T., Ray, S., 2010. Metallic species in ambient particulate matter at rural and urban location of Delhi. Journal of Hazardous Materials 175, 600-607.

SIAM, 2012. Passenger and commercial vehicle sales data, Society of Indian Automotive Manufacturers (SIAM), Delhi, India.

Singh, A., Gangopadhyay, S., Nanda, P.K., Bhattacharya, S., Sharma, C., Bhan, C., 2008. Trends of greenhouse gas emissions from the road transport sector in India. Science of The Total Environment 390, 124-131.

SoE-Delhi, 2010. State of the Environment Report for the National Capital Region of Delhi 2010, Government of Delhi, New Delhi, India.

Srivastava, A., Gupta, S., Jain, V.K., 2009. Winter-time size distribution and source apportionment of total suspended particulate matter and associated metals in Delhi. Atmospheric Research 92, 88-99.

Srivastava, A., Jain, V.K., 2007a. Size distribution and source identification of total suspended particulate matter and associated heavy metals in the urban atmosphere of Delhi. Chemosphere 68, 579-589.

Srivastava, A., Jain, V.K., 2007b. Seasonal trends in coarse and fine particle sources in Delhi by the chemical mass balance receptor model. Journal of Hazardous Materials 144, 283-291.

Streets, D.G., Guttikunda, S.K., Carmichael, G.R., 2000. The growing contribution of sulfur emissions from ships in Asian waters, 1988-1995. Atmospheric Environment 34, 4425-4439.

Timilsina, G.R., Shrestha, A., 2009. Transport sector CO2 emissions growth in Asia: Underlying factors and policy options. Energy Policy 37, 4523-4539.

Tiwari, S., Srivastava, A.K., Bisht, D.S., Bano, T., Singh, S., Behura, S., Srivastava, M.K., Chate, D.M., Padmanabhamurty, B., 2009. Black carbon and chemical characteristics of PM(10) and PM(2.5) at an urban site of North India. Journal of Atmospheric Chemistry 62, 193-209.

Tung, H.D., Tong, H.Y., Hung, W.T., Anh, N.T.N., 2011. Development of emission factors and emission inventories for motorcycles and light duty vehicles in the urban region in Vietnam. Science of The Total Environment 409, 2761-2767.

UNEP, 2009. Independent environmental assessment - Beijing 2008 Olympic Games, United Nations Environmental Program (UNEP), Nairobi, Kenya.

USEPA, 2006. Clearinghouse for Inventories & Emissions Factors - AP 42 (fifth ed.), United States Environmental Protection Agency, Washington DC, USA.

World-Bank, 2006. Improving Management of Municipal Solid Waste in India - Overview and Challenges. Report No. 37070, Environment Publication Series, South Asia Region, The World Bank, New Delhi, India.

World-Bank, 2007. Small Study on Air Quality of Impacts of the North Dhaka Brickfield Cluster by Modeling of Emissions and Suggestions for Mitigation Measures including Financing Models. Consultant report prepared by Bangladesh University of Engineering and Technology for the World Bank, Washington DC, USA.

World-Bank, 2010. Vertical Shaft Brick Kiln - Design Manual. ESMAP Publication Series, The World Bank, Washington DC, USA.

Zhang, J., Smith, K.R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M.A.K., Rasmussen, R.A., Thorneloe, S.A., 2000. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmospheric Environment 34, 4537-4549.

Zhang, J., Smith, K.R., Uma, R., Ma, Y., Kishore, V.V.N., Lata, K., Khalil, M.A.K., Rasmussen, R.A., Thorneloe, S.T., 1999. Carbon monoxide from cookstoves in developing countries: 1. Emission factors. Chemosphere - Global Change Science 1, 353-366.

Zhang, Q., Xu, J., Wang, G., Tian, W., Jiang, H., 2008. Vehicle emission inventories projection based on dynamic emission factors: A case study of Hangzhou, China. Atmospheric Environment 42, 4989-5002.

www.urbanemissions.info