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Anthropogenic Emission Inventory of Criteria Air Pollutants of an Urban Agglomeration - National Capital Region (NCR), Delhi

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ABSTRACT

This study aims to develop a spatial high-resolution emission inventory (2 km × 2 km) of criteria air pollutants (CO, NO_x, SO_2 and PM_{10}) for National Capital Region (NCR), Delhi. The inventory is centered at the metropolitan area of Delhi, and includes adjoining parts of the neighboring states of Haryana and Uttar Pradesh within an area of 70 km by 70 km for the year 2010. The bottom-up gridded emission inventory has been prepared taking into account land use pattern, population density as well as industrial areas which includes major emission sources of the region, namely vehicular exhaust, road-dust re-suspension, domestic, industrial, power plants, brick kilns, aircrafts and waste sectors. Data corresponding to various sectors along with related emission factors have been acquired from literature and various regulatory bodies for the study domain. The results reveal that total estimated emissions from vehicular exhaust, road dust and power plants contribute nearly 52%, 83%, 74% and 54% of PM_{10}, SO_2, NO_x and CO emission respectively. Transport sector has been found as the bulk contributor towards CO and NO_x emissions. Coal-fired power plants corresponds to the most polluting sector with regard to SO_2 contributing ~67%. Power plants Badarpur, Rajghat, Indraprastha and Faridabad power plant emerged as the primary hotspots for SO_2 and PM_{10} emissions. Further, Primary and secondary emission hotspots for each criteria pollutant has been identified and discussed in detail for the year 2010. In addition to it, forward trajectory analysis has been performed to assess the impact of emissions over the regional scale. Finally, a qualitative approach has been employed to assess the uncertainty in the emission estimates.

Keywords: Emission Inventory; Bottom-up approach; Criteria air pollutants; Emission hotspots; Trajectory analysis.

INTRODUCTION

Rapid urbanization and industrialization have resulted in the tremendous rise in population of Delhi, the capital city of India and its surrounding areas, which has further led to increase in energy consumption and remarkable increase in vehicle fleet, this has raised serious environmental concerns in the region. Variability of fine particulate ($PM_{2.5}$) concentration over the Indian subcontinent was very recently studied during the period of March 2000–February 2010 using Multi-angle Imaging Spectro-Radiometer (MISR) Level 2 aerosol product namely Aerosol Optical Depth (AOD) on board Terra satellite. Severe air pollution hotspots due to high $PM_{2.5}$ concentrations were observed in the western parts of the Indo-Gangetic Plain (IGP) i.e., Delhi and its surrounding areas. Further, Delhi registered the highest annual mean $PM_{2.5}$ (148.4 $\mu g/m^3$) concentration exceeding National Ambient air quality standard (NAAQS) of 25 $\mu g/m^3$ and World Health Organization (WHO) standard of 10 $\mu g/m^3$ among 46 urban centers of India considered by Dey *et al.* (2012). Delhi and its surrounding areas, as an important part of IGP, is one of the fastest growing economic centers of South Asia (Sahu *et al.*, 2011). Delhi, with a human population of ~16 million (Singh and Dey, 2012), is ranked among the top 20 most polluted cities in the world according to WHO Ambient Air Pollution Database Report, (2014). The number of vehicles registered in Delhi has already reached 6 million in 2010 (Delhi Statistical Handbook (DSH), 2012) and another 2.2 million vehicles mostly from the surrounding areas namely– Gurgaon, Faridabad, Ghaziabad, Noida, Greater Noida, Bahadurgarh and Sonipat contribute to total vehicular population (Sahu *et al.*, 2011), which are responsible for degrading the air quality (Sindhwani and Goyal, 2014). Vehicular pollution, contributed ~72% towards total air pollution load in 2000-2001 (Goyal *et al.*, 2006), which was only 23% in 1970–1971 (Central Pollution Control Board (CPCB), 2008a) over an area of 1483 km^2 of Delhi. The estimated emission of pollutants from automobiles in Delhi exceeds 1.3 kt every year (Goyal and Siddhartha, 2003) and contributed almost 64% to the total pollution in

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Delhi over an area 780 km^2 (Goyal *et al.*, 2013). The growing number of diesel vehicles in the region has further worsened the air quality scenario. The market share of diesel cars is more than 50 per cent (of sales), which is due to the growing differential between petrol and diesel prices. The diesel emission norms legally allow higher limits for NO_x and PM_{10} emissions compared to a petrol car (Centre for Science and Environment (CSE) Factsheet, 2012). Besides vehicular pollution, emissions from thermal power plants, industries including brick-kilns and construction activities in the vicinity are also contributing significantly towards CO, NO_x, SO_2 and PM_{10} pollution in Delhi. Apart from this, the dust transported from the Great Indian Desert (Singh *et al.*, 2005) and nearby regions also contribute (Singh and Dey, 2012) towards pollution in Delhi.

Air quality measurements undertaken by the regulatory authority, Central Pollution Control Board (CPCB) show that observed annual mean concentrations of coarse particles PM_{10} (particles with aerodynamic diameter less than or equal to 10 µm) was 150 µg/m^3 in 2006 (CPCB, 2009) nearly 7.5 times the acceptable World Health Organization standard of 20 µg/m^3. Post 2006, Air Quality trends reported by CPCB under National Air Quality Monitoring Programme (NAMP), Delhi's PM_{10} pollution continuously exceeded the annual National Ambient Air Quality Standards (NAAQS) of 60 µg/m^3 and rose up from 198 µg/m^3 in 2008 to 243 µg/m^3 in 2009 and 261 µg/m^3 in 2010. Air pollution in Delhi's satellite city, Ghaziabad has been rising since 2007, and annual average PM_{10} concentration reached 290 µg/m^3 in 2010, in comparison to 240 µg/m^3 and 258 µg/m^3 in 2008 and 2009 respectively and thereby surpassing the ambient annual average PM_{10} concentration in Delhi (Environmental Information System (ENVIS), 2014). High PM_{10} pollution is reported by CPCB for satellite cities Faridabad, Gurgaon and Noida.

Nitrogen dioxide (NO_2) also exceeded the annual NAAQS standard of 40 µg/m^3 from 2003 onwards, till 2010. Carbon monoxide (CO) concentrations at ITO (a major traffic intersection), violated 8-hourly NAAQS of 2 mg/m^3 during 1999 to 2008 (State of Environment Report (SOE), 2010). Apart from it, studies conducted by the pollution regulatory authority in India reported that high pollution levels in Delhi are found to be positively associated with lung function deficits and respiratory ailments (CPCB, 2008a, b). Gurjar *et al.* (2010) estimated that urban air pollution caused ~10,500 premature deaths per year in Delhi. Kandlikar and Ramachandran (2000) illustrated an increase in the incidences of respiratory diseases among urban population and reported that about 30% of Delhi's population suffers from respiratory disorders.

In the light of above, it would be useful to identify and estimate emissions from the various polluting sources, which would further aid the regulating and planning authorities in the decision making process for improving the air quality of the study region. For the same, emission inventories have become critical tool for estimating ambient air quality of a region as it comprises of description of air pollutant-emitting sources, along with the estimated pollutant emission quantities, which supplies the essential information to understand regional and sectorial emission sources, and provide guidance to air pollutants control management authorities to formulate policies to improve air quality (Qui *et al.*, 2014). Data from source-specific emission tests or continuous emission measurements are usually preferred for estimating quantities of emissions. However, such data from individual sources is generally not always available. Thus, estimation of emissions by using emission factor approach as suggested by Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006) has been the most preferred method used in the literature (Elbir and Muezzinoglu, 2004; Dincer and Elbir, 2007; Zarate *et al.*, 2007; Elbir, 2008; Zheng *et al.*, 2009; Droge *et al.*, 2010; Elbir *et al.*, 2010; Wang and Fu, 2010; Aleksandropoulou *et al.*, 2011). Therefore, knowledge of various types of air pollutants and their emission rates is of fundamental importance (Elbir and Muezzinoglu, 2004) because these rates, together with the prevailing meteorological conditions and topographical factors, determine the air quality of a region. Moreover, it is also observed that long-range transport of air pollutants from polluted areas can affect regional and global regions with high pollutant concentration (Gurjar *et al.*, 2004; Wang *et al.*, 2006). Kerschbaumer and Lutz (2008) also showed about 40% of urban PM_{10} concentrations in Berlin city were related to local emissions while 60% was due to transport processes from outside the city.

Summing up, the present study deals with the preparation of gridded bottom-up emission inventory of criteria pollutants namely carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter (PM_{10}) for Delhi and its surrounding areas (Gurgaon, Faridabad, Bahadurgarh, Ghaziabad, Noida, Greater Noida, Sonipat) together known as National Capital Region (NCR) at a 2km × 2 km spatial resolution between 76.76°E to 77.46°E longitude and 28.30°N to 29.0°N latitude centered at metropolitan area, Delhi. This study further, helps to identify the primary and secondary emission hotspots over the study domain. Finally, this study has also tries to show implications of emissions generated by the study domain on regional and global scale using HYSPLIT model.

METHODOLOGY

Study Domain and Source Characterization

The study domain extends from 28.3°N to 29.0°N and 76.76°E to 77.46°E, ~238 m above mean sea level, which includes megacity Delhi and its neighboring cities- Gurgaon, Ghaziabad, Faridabad, Noida, Greater Noida, Sonipat and Bahadurgarh (Fig. 1). Delhi is one of the most densely populated cities in Asia (with about 10,400 persons per km^2), located in a semi-arid region at ~1100 km away from the nearest coast on the North Arabian Sea and lies between the Indo-Gangetic Basin to the east and arid tracts of Thar and Margo desert at ~160 km to the west and south-west (Lodhi *et al.*, 2013). Delhi, with its human population of ~16 million (Singh and Dey, 2012) along with the additional ~13 million population from different states has been considered for the study domain (Census of India, 2011).

The climatic conditions of the study domain are extreme in nature with very hot summers (the temperature rises even beyond 45°C) and cold winters (with temperatures as low as 3°C). The year can be broadly divided into four distinct seasons, namely winter (December–February), summer (March–June), monsoon (July–September), and post-monsoon (October–November). The present study focuses on emissions from power plants (PP), industrial sources (IS), brick kilns (BK), domestic sources (DS), on-road vehicular sources (VS), waste and open burning sources (WS), Landing and Take-off cycle Aircraft emissions (LTO) and road dust (RD).

Data Sources

The emissions estimated are based on activity data of each source category and appropriate emission factors selected from the literature for the base year 2010. The same method has been used for developing emission inventories in different scales such as urban (Gurjar *et al.*, 2004; Goyal *et al.*, 2013), regional scale (Sahu *et al.*, 2011; Guttikunda and Calori, 2013), national (Reddy and Venkataraman, 2002; Ramachandra *et al.*, 2009). The various emission-producing sources have been discussed briefly below.

Emissions from Vehicles

The study domain is predominantly dependent on road transport for the movement of people and goods. Delhi and its satellite cities, together known as NCR has the largest number of vehicles compared to any other Indian city. The vehicle population growth has sharply increased at an average annual rate 7.40% for private vehicles and 9.15% for commercial vehicles (SOE, 2010). The number of vehicles per kilometer of road in Delhi has gone up from 128 to 191 between 2003 and 2009 (Goyal *et al.*, 2013).

Emission load from vehicles has been calculated using the following equation (IPCC, 2006; Sahu *et al.*, 2011) (Eq. (1)).

$$E_i = \sum(\text{Veh}_j \times D_j) \times EF_{i,j,km} \quad (1)$$

E_i: Emission of pollutant (i); Veh_j: Number of vehicles per type (j); D_j: Distance travelled by per vehicle in per year or vehicle utilization factor (j); $EF_{i,j\ km}$: Emission of pollutant (i) for vehicle type (j) per driven kilometer.

Vehicle population data for various vehicle types has been obtained from the Statistical Abstract of Delhi, (2012) and Ministry of Road Transport and Highways Report (MoRTH, 2011). Six vehicle categories have been considered in the present study which includes two-wheelers (2W), three wheelers (or auto-rickshaws) (3W), passenger cars (PCs), Buses, Light commercial vehicles (LCV) and Heavy commercial Vehicles (HCV). Annual average vehicle-kilometer travelled is estimated as 10,000 for passenger cars; 36,000 for taxis and auto-rickshaws; 50,000 for buses and 30,000 for HCV and LCV (Guttikunda and Calori, 2013) and 27,000 for 2-wheelers (2W) (Sahu *et al.* 2011). Buses and 3W have been assumed to use only compressed natural gas (CNG) as fuel. On the basis of engine type, 2W vehicles have been classified as 2-Stroke (2S) and 4-Stroke (4S) and use gasoline (or petrol) as fuel. Amongst the total 2W, 72% are motorbikes, and while the rest 28% are scooters. Since 4S-2W emits less pollution load in comparison to 2S-2W, thus a ratio of 72:28 has been considered for 4S-2W and 2S-2W (CPCB, 2010). The age-wise distribution of vehicular population of Delhi has been taken from CPCB (2010).

The numbers of vehicles monitored on different types of roads in the year 2008–2009 has been used from Goyal *et al.* (2013). According to Integrated Mobility Plan for Gurgaon-Manesar Urban Complex, on an average about 0.3 million vehicles are entering and exiting Gurgaon, including NH-8 expressway each day. The maximum number of vehicles entering/exiting Gurgaon are through NH-8 (from Delhi side), followed by Mehrauli-Gurgaon road and NH-8 from Rewari side. About 0.5 million vehicles commute between Delhi and Noida and vice-versa, on daily basis. In addition, major congestion points in Noida were also identified which included Agarsen Marg, Kalindi Kunj, Filmcity to Mahamaya Flyover (Keelor, 2011). Also, traffic characteristics at various locations in NCR have been taken from CES primary survey (2007). Thus, nearly 2.2 million vehicles from all surrounding areas of Delhi contribute to the total vehicular population (Sahu *et al.* 2011).

Emission factors (EFs) developed by The Automotive Research Association of India (ARAI) (2007) and CPCB (2010) according to the age, engine technology, type of fuel for the different vehicles categories has been used in the present study. EFs for SO_2 are based on reports of United Nations Environment Programme (UNEP) (UNEP, 1999) and The Energy and Resources Institute (TERI) (TERI, 2006).

Emissions from Power Plants

Three coal-fired (i.e., Badarpur, Indraprastha and Rajghat) and two gas-fired (i.e., Gas Turbine (G.T.) station and Pragati–Gas Station) power plants are located in Delhi whereas Faridabad power plant located outside Delhi is coal based. These power plants are located in the heart of the study domain. The amount of fuel consumed is calculated using equations given by Gurjar *et al.* (2004).

$$\text{Gross Generation (GWH)} = \text{PLF (\%)} \times \text{capacity} \times 24 \times 365 \quad (2)$$

$$\text{Fuel use (kt)} = \text{Gross Generation} \times \text{fossil fuel use per GWH} \quad (3)$$

Plant Load Factor (PLF) of different power plants is taken from performance review report of thermal power plants issued by Central Electricity Authority (CEA). Emission factors (EFs) for PM_{10} are based on Sahu *et al.* (2011) whereas EFs for SO_2 and CO are taken from CPCB (2010) and for NO_x (as NO_2) from Kansal *et al.* (2011).

Emissions from Industries, Construction Activities and Brick-Kilns

Rapid urban development has led to formation of isolated industrial pockets in Delhi. The industrial sector, which is segregated into small and medium scale industries, creates significant yearly emissions. According to CPCB (2010), there are about 33 small industrial estates and 8 medium scale industries in Delhi itself. In addition to it, there are nearly 25,000 industries located in the rest of the study domain (Haryana State Pollution Control Board (HSPCB) Report, 2011). Ghaziabad and Gurgaon, mostly use coal, petro-coke, wood, fuel oil, Light Diesel Oil (LDO) and Low Sulphur Heavy Stock (LSHS) diesel oil as fuel in its industries (Uttar Pradesh Pollution Control Board (UPPCB), 2010). Emission from industries has been calculated using Eq. (4) defined below.

$$E_i = \sum(\text{Fuel}_j \times \text{EF}_{i\,j}) \quad (4)$$

where, E_i: emission per pollutant (i) (tons); Fuel_j: consumption of fuel per fuel type (j) (kt); $\text{EF}_{i,j}$: emissions of pollutant (i) per unit of energy (j) (g/kg).

Apart from this, a lot of construction activities have been taking place in Delhi and its satellite cities. Construction of flyovers, roads, shopping malls and housing projects contribute majorly towards PM_{10} emissions. In Gurgaon, Noida and Greater Noida, a lot of construction activities are going on, as major residential projects have come up for rising population, which contributes to higher pollution levels. Land clearing, operation of diesel trucks, demolition waste, burning of toxic materials generates very high levels of dust (Rao, 2013).

Bricks, are used as walling material in residential and commercial buildings. Stack emissions from brick kilns are a major source of air pollution in the study domain. Bull's trench kilns (BTKs) and clamps are two prominent firing technologies used for brick making. The BTK is a continuous type kiln and has higher production capacities (15,000–50,000 bricks per day) and account for 70% of the total brick production. Coal is the main fuel used in BTKs. The specific energy consumption in firing bricks in BTKs ranges between 1.1 and 1.6 MJ/kg of fired brick (UNEP, 2012). Brick kilns are primarily associated with PM_{10}, CO, SO_2, volatile organic compounds (VOC), nitrogen oxides (NO_x), and heavy metals emissions depending on the type of fuel burnt. In case of NCR, ~850 brick kilns are located along the border, with a production capacity of more than 20,000 bricks per day. Emissions from this sector were calculated only for the manufacturing season and the emission factors for this sector have been taken from Maithel *et al.* (2012).

Emissions from Diesel Generator Sets in Residential and Telecom Sector

Emissions from generator sets (gensets) are major source of emissions. In Delhi, power failure occurs approximately 100 hours per month during summer season and occasionally during rest of the year. During power cut hours, generators sets are operated in residential co-operative societies as well as in commercial shops (CPCB, 2010). In Gurgaon, the demand for electricity is increasing at the rate of 15% per annum. According to a Haryana Pollution Control Board, nearly two-third of Gurgaon's power demand is met by diesel generator sets due to frequent power outages of about 10–12 hours. A shopping mall during such time uses nearly 2500 liters of diesel per day. The data corresponding to the registered number of diesel generators operating in the study has been taken from CPCB (2010). Recent technological development has resulted in rising telecom sector as major contributor due to use of gensets near telecommunication towers (Small Industries Development Bank of India (SIDBI), 2012; Shankar, 2014).

Emissions from gensets is calculated using the following Eq. (4) given by Shankar (2014)

$$E_i = \sum P_j \times E_{ij} \quad (5)$$

where, E_i: emission per pollutant (i) ; P_j: Power rating of the Genset (kw) and E_{ij}: Emission factor (g/kwh)

Emissions from Residential Sector

Kulshreshtha and Khare (2011) study revealed that economic status of the inhabitants influenced the choice and type of fuel use. According to slum Department of Delhi nearly 14.1% of Delhi's total population is living in slum areas of Delhi. Liquefied Petroleum Gas (LPG) is the most commonly used cooking fuel (68.4%) followed by kerosene (24.4%) while biomass is also used in 3.9% households in Delhi (SOE, 2010). About 9.4% of PM_{10} is contributed by domestic sources in Delhi (CPCB, 2010). Emissions from the domestic sources are distributed on the grid system with respect to the population density. The use of LPG was majorly concentrated in urban area with high population density, whereas the rural as well as slum areas use coal, wood, kerosene, cow-dung and biomass as cooking fuel. The slum areas in Delhi are identified from Centre for Global Development Research (CGDR) report (2010). Emission factors for various fuels used for cooking and heating purposes are taken from Sahu *et al.* (2011), CPCB (2010) and Gurjar *et al.* (2004). Emissions from fuel consumption in domestic sector are calculated as

$$E_i = \sum(\text{Fuel}_j \times \text{EF}_{i\,j}) \quad (6)$$

where, E_i: emission per pollutant (i) (tons); Fuel_j: consumption of fuel per fuel type (j)(kt); $\text{EF}_{i,j}$: emissions of pollutant (i) per unit of energy (j) (g/kg).

Waste and Open Burning Emissions

Solid waste management remains the most neglected sectors in Delhi and one of the most important sources of anthropogenic emissions especially for greenhouse gases in fast urbanizing cities. Municipal Corporation of Delhi (MCD) along with the Cantonment Board and the New Delhi Municipal Corporation (NDMC) is responsible for the disposal of municipal solid waste collected within the periphery of National Capital Territory (NCT) of Delhi. About 80% of the collected municipal solid waste (MSW) is disposed in landfills, and the remainder is composted (Sharma *et al.*, 2002). Latest estimates indicate that about 6500–7000 tons of MSW is generated each day which includes nearly 10% of plastic waste in Delhi (Economic Survey of Delhi (ESD), 2008–09) with per capita generation rate of 0.47 kg per day in urban Delhi (Chakraborty *et al.*, 2011).

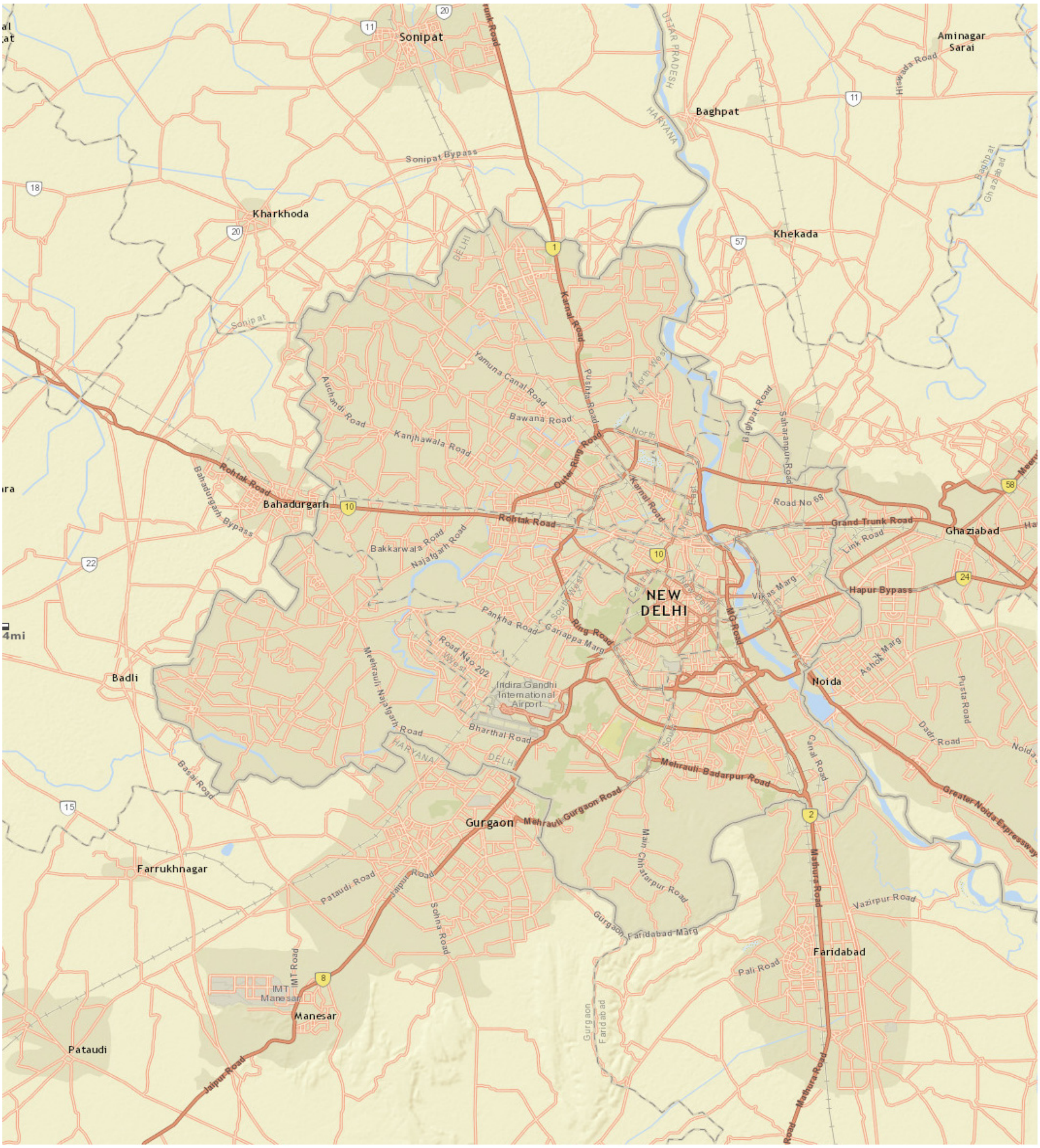

Fig. 1. Map of the Study Domain.

All the MSW generated in the city is transported to landfill sites in Ghazipur (GL; in East Delhi), Bhalswa (BL; in North Delhi) and Okhla (OL; in South East Delhi) landfill sites. The satellite city Gurgaon, on the other hand, generates 600 tons of solid waste per day. The majority of waste is generated by residential, commercial and institutional sources and municipal activities such as street sweeping and drain cleaning. MSW in Gurgaon, as per Indian scenario, is expected to comprise of 50–52% biodegradable, 12–15% dry recycles and 30–35% inert component (Bandyopadhyay, 2013). Ghaziabad generates nearly 550 tons/day of solid waste. Amount of waste generated in Faridabad, Noida, Greater Noida have been taken from National Capital Region Planning Board (NCRPB), (2012) report. Moreover, out of 700 tons/day of MSW generated by Faridabad 12% is plastic waste (Federation of Indian Chambers of Commerce and Industry (FICCI), 2009, CPCB, 2010). However, total garbage generation from NCR is estimated to be greater than 9000 tons/day approximately (SOE, 2010).

Guttikunda and Calori (2013) stated that a major portion of waste collected is burnt in residential areas, collection sites, and roadsides. With the rapid technological development, there has been tremendous rise in the e-waste generated in the region. Apart from this, the major area of e-waste burning is located close to the northern border of Delhi namely Hazipur, Loni, Mandoli, Karwal Nagar, Seelampur (International Resource Group (IRG), 2004; Malik, 2004). Nearly, 3150 kg of cables and 8750 kg of printing wiring boards (PWBs) are burned daily on the eastern borders of Uttar Pradesh and Delhi (http://www.empa.ch/plugin/temp ate/empa/*/59242). Nearly 0.04 tons/year in Delhi and ~1.73 tons/year of crop residue is burnt in the remaining parts of study area (Gargava *et al.*, 2014). Air pollutant emissions as a result of open solid waste burning has been calculated using the formula given by Kansal *et al.* (2011)

$$P_j = \sum(650 \times 0.1 \times p \times EF_j/86400) \quad (7)$$

where, P_j is the emission of pollutant j (g/s); p is the human population; EF_j is the emission factor of pollutant j (g/kg). According to Waste-to-Energy Research and Technology Council (WTERT), about 650 g/capita/day of waste is generated by NCR and approximately 10% of the municipal solid waste generated is burned in the open (Pachauri and Batra, 2001)

Aircraft Emissions (LTO Cycle)

Aircraft movement at Indira Gandhi International Airport (IGI) rose from 81587 in 2000 to 229227 in 2009 registering a growth of 180% during the past decade (Airport Authority of India (AAI), 2010). Emissions of air pollutants due to aircrafts occur by burning of fuel in the main engines and in auxiliary engines, powering the auxiliary power units. The Landing and Take-off (LTO) cycle includes all activities near the airport that take place below the altitude of 3000 feet (1000 m). This therefore includes taxi-in and out, take-off, climb-out, and approach, landing. The average LTO cycle in 2005 was 520 per day, which rose to 675 in 2008. The landing and take-off data was collected from flight status information available in public domain. The present study deals with the estimation of LTO emissions at IGI airport. The calculation of emission from aircrafts was done by using the following formula:

$$E_i \text{ (in kg)} = \sum_{\text{All Aircrafts}} (\text{Number of LTO cycles of aircraft j}) \times (EF_i) \quad (8)$$

$$\text{Fuel Consumption (in kg)} = \sum_{\text{All Aircrafts}} (\text{Number of LTO cycles of aircraft j}) \times (\text{Fuel Consumption}) \quad (9)$$

Time in each operation mode (Table 1) of the LTO cycle has been taken from the International Civil Aviation Organisation (ICAO)-Engine emissions data bank.

Road Dust Emissions

In NCR, apart from emissions from vehicles, re-suspension of road dust due to traffic movement is also an important source of PM_{10} emissions to an extent of 52% of total PM_{10} emissions (CPCB, 2010). Guttikunda and Calori (2013) estimated road-dust re-suspension emission rates based on United States Environment Protect Agency (USEPA, 2006) AP-42 methodology, which have been used in the present study. Vehicle density on various types of roads has been taken from Central Road Research Institute (CRRI), New Delhi as well as from CPCB (2010). A major contribution of road dust emissions are observed during night-time due to movement of heavy vehicles and in the morning due to frequent street sweeping in morning (Tandon *et al.*, 2008).

RESULTS AND DISCUSSION

Emissions of CO, NO_x, SO_2 and PM_{10} were estimated for the year 2010 in NCR Delhi. The total emissions of CO, NO_x, SO_2 and PM_{10} were 1290.134 kt/yr, 342.304 kt/yr, 83.168 kt/yr and 107.655 kt/yr respectively. Fig. 2 shows the contribution of each sector towards total emissions. Transport, road dust and domestic sources together contribute nearly 47% of PM_{10} emissions. The share of power plants, industries, construction and brick kilns towards PM_{10} emissions is 13%, 10%, 9% and 11% respectively. Contribution of PM_{10} from the highly industrialized areas like west Delhi, Okhla, Loni, Faridabad and Gurgaon is majorly due to the use of diesel generators to meet their electricity demands. In addition to it, areas with high population density like south Delhi, east Delhi, west Delhi and Gurgaon use diesel generators due to large number of institutions, shopping malls, hospitals, hotels and offices located in these areas.

Power plants and industries together (76%) are largest contributors of SO_2 emissions in the study region. Contribution of road traffic in SO_2 emissions has greatly reduced after implementation of CNG in public transport but still it shares 14% of SO_2 emissions.

With the rise in construction activities, brick kilns have come up as a dominant sector, contributing about 12% towards CO emissions. Brick-kilns located in North-east Delhi and its nearby areas in Uttar Pradesh contribute

Table 1. Time and thrust setting in operation phase.

LTO Mode	Time-in-mode (minutes)	Thrust setting (%)
Approach	4.0	30
Taxi in and ground idle	7.0	7
Taxi out and ground idle	19.0	7
Take-off	0.7	100
Climb	4.2	85

*Source: ICAO emission data bank.

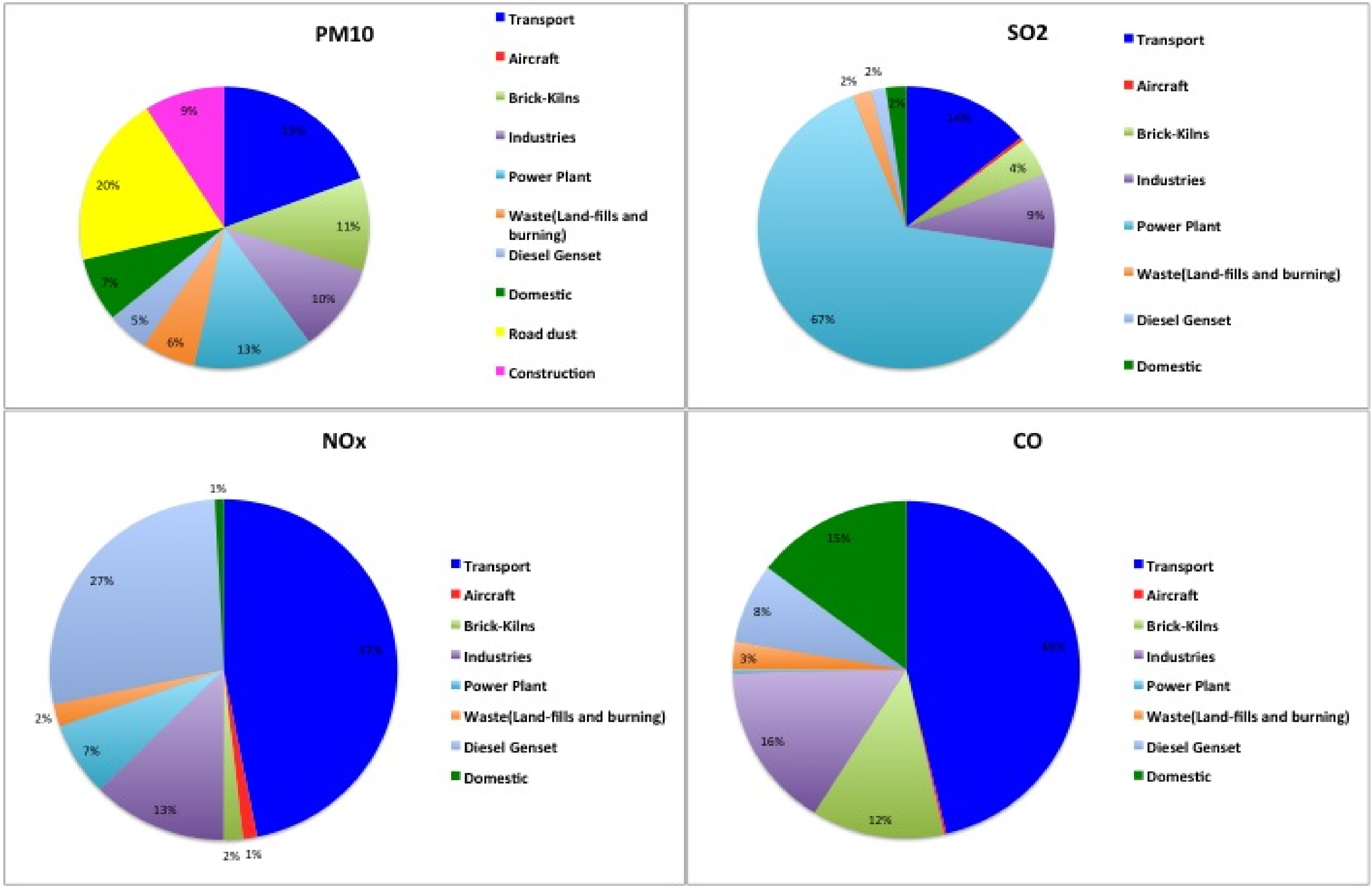

Fig. 2. Contribution of various sectors towards PM_{10}, SO_2, NO_x and CO emissions.

significantly towards CO emissions. Emissions of CO from domestic and industries are 15% and 16% respectively due to use of coal, biomass, coke and petro-products being used in industries located in satellite cities. Vehicles contributing nearly 46%, emerged as the largest emitter of CO.

In the present study, transport sector (47%), power plants and industries together (20%) and diesel generators (27%) emerged as the major contributors towards NOx emissions. Transport sector of Delhi alone has been found to be contributing ~54% towards total NO_x emissions (161 kt/yr) from NCR. Sindhwani and Goyal (2014) also reported that ~85 kt/yr of NO_x emissions are emitted by Delhi itself.

Comparison with Previous Studies

Table 2 presents emissions estimated by the present study as well as from various studies available in the literature. Gurjar *et al.* (2004) presented sector-wise emission inventory of administrative region of Delhi, based on emission factor approach. The total emissions estimated were 502 kt/yr, 160 kt/yr, 112 kt/yr and 149 kt/yr of CO, NO_x, SO_2 and PM_{10} respectively. The major drawback of the study was that it did not include emissions from biomass burning, vehicular emissions commuting from nearby towns, re-suspension of road-dust, construction activities, brick kilns. Secondly, although the transport sector of Delhi was illustrated in detail, a lot of uncertainty was reported due to unavailability of source specific emission factors for Delhi domain.

CPCB (2010) estimated emission loads over the metropolitan area (32 km × 32 km = 1024 km^2) of Delhi, for the base year 2006–2007. CO, NO_x, SO_2 and PM_{10} emissions were found to be 374.1 tons/day, 460 tons/day, 268 tons/day and 147 tons/day respectively. This study estimated average total daily re-suspended road dust PM_{10} emissions from arterial, main and feeder roads to be 252.56 kg/day, 111.6 kg/day and 134.43 kg/day respectively. Also, road and building construction activities contributed 12 tons/day towards PM_{10} emissions. The major drawback of this study includes exclusion of vehicular emissions from some parts Delhi as well as its surrounding areas. Since, the city almost doubled its population, activity and emissions since 1990 (Guttikunda and Calori, 2013), and the domain area considered was nearly 69% of the total area of Delhi thus; it doesn't provide the clear picture of emissions even from whole of Delhi (1483 km^2).

Sahu *et al.* (2011) presented a high-resolution gridded emission inventory (1.67 km × 1.67 km) centered about metropolitan city Delhi for the year 2010. The domain area (70 km × 65 km = 4550 km^2) covered Delhi and its surrounding regions Ghaziabad, Faridabad, Gurgaon and Noida. Major sectors considered in this study included transport, residential and commercial cooking, industries and power plants. This study reported only PM_{10} and $PM_{2.5}$ emissions, whereas no estimation was given for CO, NO_x and SO_2 in this study. Total PM_{10} and $PM_{2.5}$ emissions estimated were 236 kt/yr (which includes contribution from road dust as well as from commercial cooking (131 kt/yr)) and 94 kt/yr respectively. This study emphasized that nearly 2.2 million vehicles from surrounding areas of Delhi contributed majorly towards emissions from transport sector of Delhi. Higher VKT and road re-suspension rates may be one of the possible reasons of higher PM_{10} emissions (Guttikunda and Calori, 2013). However, CO, NO_x and SO_2 emissions have been taken from Marrapu (2012, 2014) which reported rest of the emissions from detailed emissions inventory prepared by Indian Institute of Tropical Meteorology (IITM) Pune, Maharastra for the Delhi area at a resolution of 1.67 km. However, Sahu *et al.* (2011) omitted a major chunk of emissions by not considering the emissions contributed by the diesel generators, brick kilns, waste and open burning emissions lying in Delhi and in its fringing area. This could be one of the prominent reasons for the underestimation of CO, NO_x and SO_2 emissions in comparison to Guttikunda and Calori (2013) and present study.

Guttikunda and Calori (2013) estimated emissions for the National Capital Territory of Delhi covering Delhi and its satellite cities over an area of 6400 km^2 for the base year 2010. The emission inventory of 0.01° (1 km × 1 km) spatial resolution included contributions from vehicle exhaust, re-suspended road-dust, domestic cooking and heating, power plants, industries including brick kilns, diesel generators and waste burning. Nearly 37% of PM_{10} emissions are contributed by elevated point sources (power plants, industries and brick kilns) and about 35% contribution was made by vehicle exhaust and road dust. This study highlighted brick kiln sector located outside Delhi, as an important contributor towards air pollution in Delhi but it didn't distinguish whether emissions from diesel generators from telecom sector, e-waste burning, and construction waste mainly responsible PM_{10} emissions from the surrounding areas have been included or not.

The present study demonstrates contribution from road dust towards total PM_{10} emissions, which is about 20% whereas Sahu *et al.* (2011) and Guttikunda and Calori (2013) estimated that road dust contributed ~55% and ~22% respectively. The main difference of present study with respect to Sahu *et al.* (2011) arises due to the consideration

Table 2. Comparison of emission estimates of various studies and present study.

Year	Study	Area (km^2)	Tons/day			
			CO	NO_x	SO_2	PM_{10}
2000	Gurjar *et al*. (2004)	1483	1378	441	309.5	410.9*
2007	CPCB (2010)	1024	374.1	460	268	147
2010	Sahu *et al*. (2011)	4550	1320#	598.5#	81#	646
2010	Guttikunda and Calori (2013)	6400	3904.1	1030.1	101.36	312.3
2010	Present Study	4900	3534.6	937.81	227.85	294.45

* TSP emissions; # Marappu (2012).

of higher road dust re-suspension rate in the latter. Also a significant difference can be seen between SO_2 emissions estimated by Sahu *et al.* (2011) in Table 2. This can be attributed to exclusion of waste and open burning emissions, e-waste and genset emissions along with the brick kilns. However, the emissions generated by commercial cooking done by small hotels and street vendors who use coal or kerosene in open air, is an important aspect highlighted in Sahu *et al.* (2011). The present study has emphasized and included emission contribution from the gensets used in the flourishing telecommunication sector, burning of e-waste which were not included in the Guttikunda and Calori (2013).

Spatial Distribution of Emissions and Emission Hotspots Identification

Figs. (3)–(6) presents spatial distribution of emissions of criteria pollutants (CO, NO_x, SO_2 and PM_{10}) over the study domain. The spatial distribution of emissions helps in the identification of primary and secondary emission hotspots over the study domain. Primary hotspots are the places with maximum emission loads whereas secondary hotspots are the places that have a prominent contribution to emissions next to primary ones (Mohan *et al.*, 2007). Emission Range considered for defining hotspots corresponding to each pollutant over the study domain is given in Table 3.

Major primary emission hotspots for SO_2 and PM_{10} are found to be located at Rajghat, Badarpur Indraprastha and Faridabad power stations whereas secondary emission hotspots of PM_{10} have been found to be at major traffic intersections in CP (Connaught Place), ITO (Income Tax Office), IGI (Indira Gandhi International) Airport, Civil lines and Kanjhawala in Delhi. Apart from these, NH-1, NH-8 and NH-24 have been identified major traffic induced

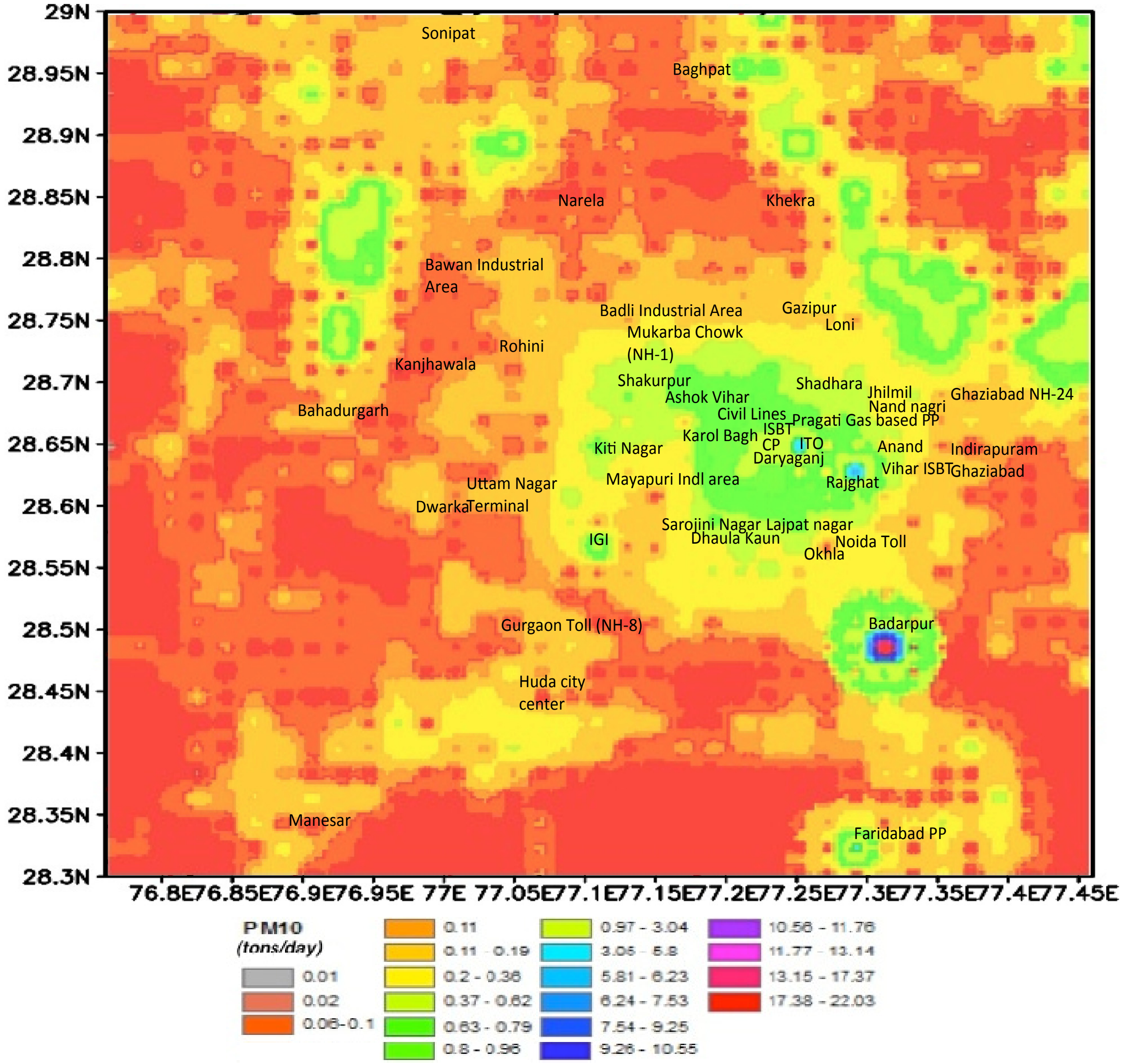

Fig. 3. Spatial distribution of PM_{10} over the study domain (tons/day).

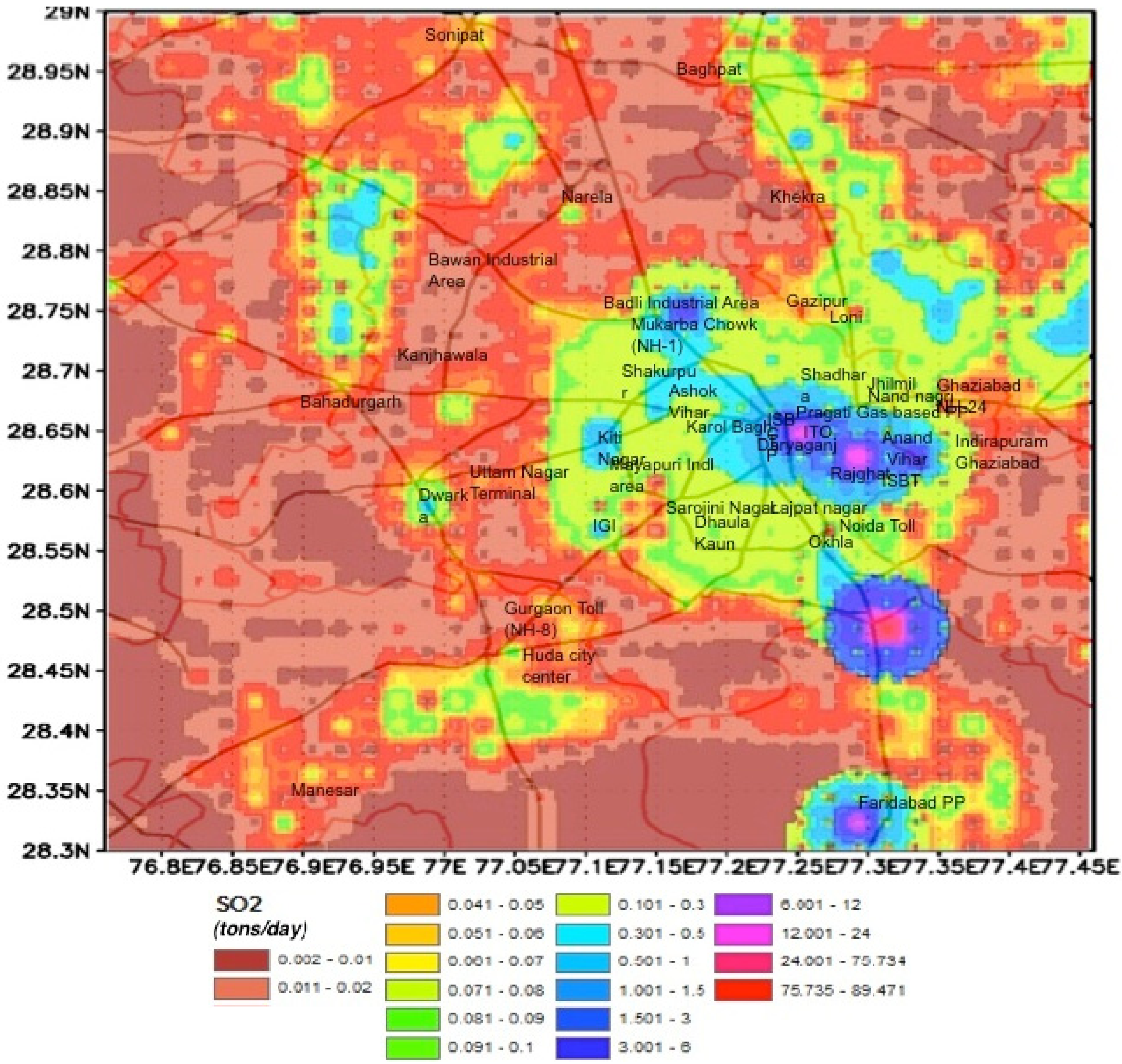

Fig. 4. Spatial distribution of SO_2 over the study domain (tons/day).

pollution sources of secondary emissions. Emissions from brick kilns have resulted in identifying Loni, Baghpat area near State Highway 57 and area near State Highway 18 in Uttar Pradesh as well as Sohati, Qutabgarh, in Haryana as major secondary emission hotspots.

Sahu *et al.* (2011) identified eastern, central and some parts of southeastern Delhi as the major contributors toward PM_{10} emissions due to high vehicular emissions. Guttikunda and Calori (2013) also identified six regions corresponding to high emission loads of $PM_{2.5}$ in NCR namely South Delhi, Faridabad, Gurgaon, West Delhi, Greater Noida and North-east Delhi.

Primary emission hotspots of CO and NOx are found at ITO, Kashmere Gate ISBT, Daryaganj, CP, Karol bagh, Uttam Nagar Terminal, Shahadra in Delhi. Baghpat near Sonipat, Narela-Kundli crossing at NH-1, Huda city center in Gurgaon, Fatiyabad Nihaura in UP, Rajniganda chowk in Noida, Noida toll are among the primary areas located outside Delhi. These locations are major traffic intersections. Secondary emission hotspots of CO and NO_x are found to be located near the industrial clusters at Mayapuri phase–III, Okhla Phase-II, Patparganj, Loni, Badli industrial area, Kirti nagar and areas near Faridabad Power plant.

Mohan *et al.* (2007) presented spatial distribution of CO, NO_x, SO_2 and PM for the years 1990, 1996 and 2000 over urban area of Delhi (780 km^2). The spatial distribution of emissions presented in the present study for the year 2010 showed similar pattern over the urban area but with increased emission loads, which can be attributed to rapidly rising population of Delhi, which has resulted in the tremendous increase in vehicle population in and around Delhi (Sindhwani and Goyal, 2014). In addition to this, majority of primary and secondary hotspots have been found in and around Delhi.

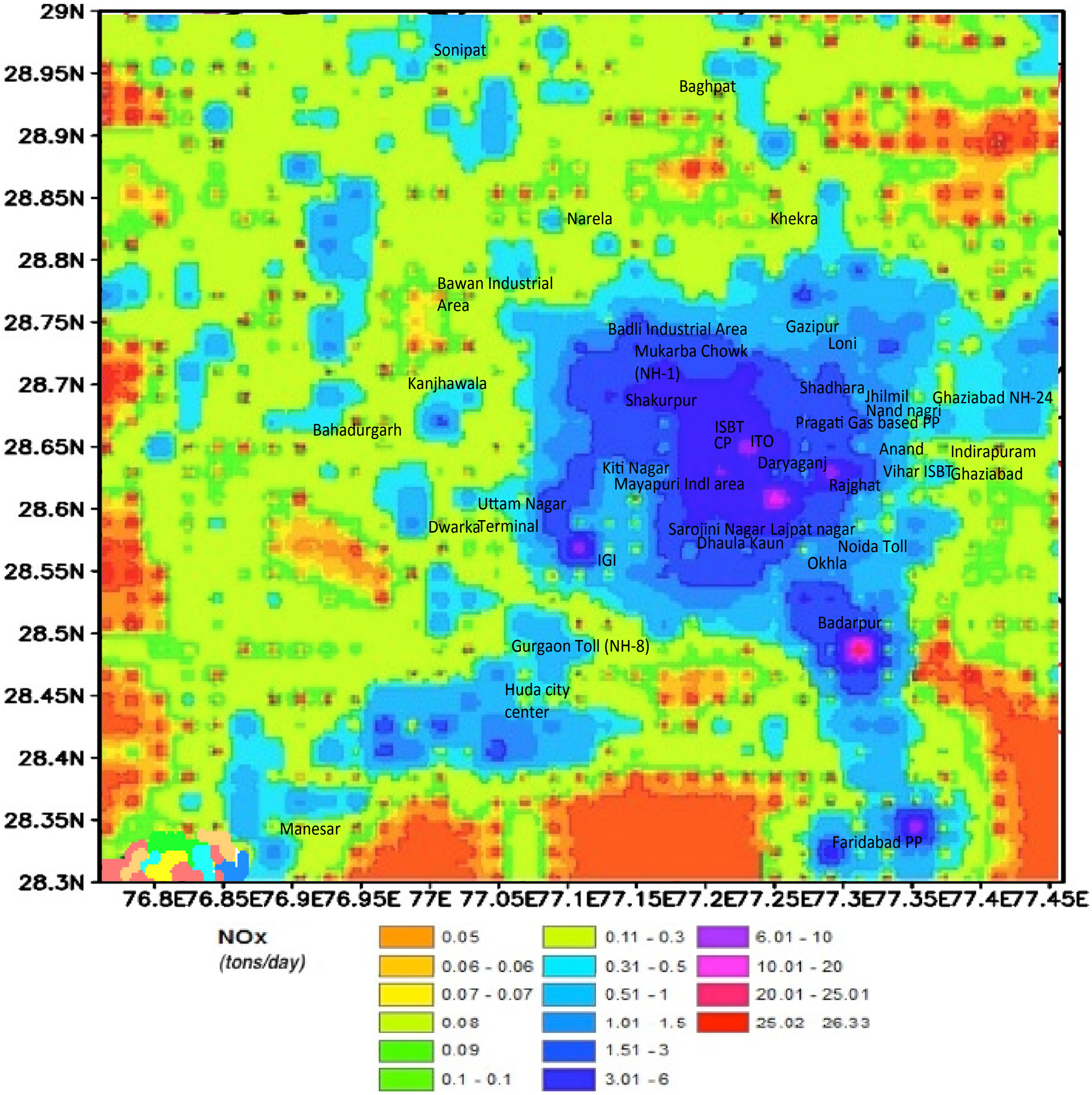

Fig. 5. Spatial distribution of NO_x over the study domain (tons/day).

Implications of Emissions on Regional and Global Scale

Air quality measurements undertaken by the Indian Pollution Regulatory Authority- CPCB at IGI Airport and Civil lines during 1st Nov 2010 to 15th Nov 2010 reveal that 8-hourly ozone concentrations exceeded NAAQS of 100 µg/m^3. Average concentration observed during the time-period was 120 µg/m^3 and 193 µg/m^3 respectively. Nagpure *et al.* (2011) estimated maximum emission rate of 0.78 g/km for NO_x emissions in Delhi, which being a strong ozone precursor causes higher ozone concentrations in the study region. There is a distinctive possibility of enhancement of ozone concentration in downwind rural areas due to rising NO_x emissions in Delhi, particularly significant during dry winter season when transport of air mass is mostly confined to the lower troposphere (Lelieveld *et al.*, 2001). Wang (2006) further stated that long range transport of air pollutants from highly polluted areas bring in high pollutant concentration in regional areas and impact the ground level concentration. Thus, ten days forward trajectories estimated during November 2010 reveal that air mass remain confined to the lower troposphere and travel towards the Indian Ocean (Fig. 7). During summer season, long-range transport takes place in the free atmosphere and air mass may cross the entire continent and reach the pacific (Fig. 8). Thus, it can be concluded that air pollutant emissions emitted by the study domain results in the increase in air pollutant concentration in the surrounding areas as well on the global scale. Mayer *et al.* (2000) and Akimoto (2003) have reported similar studies in the past.

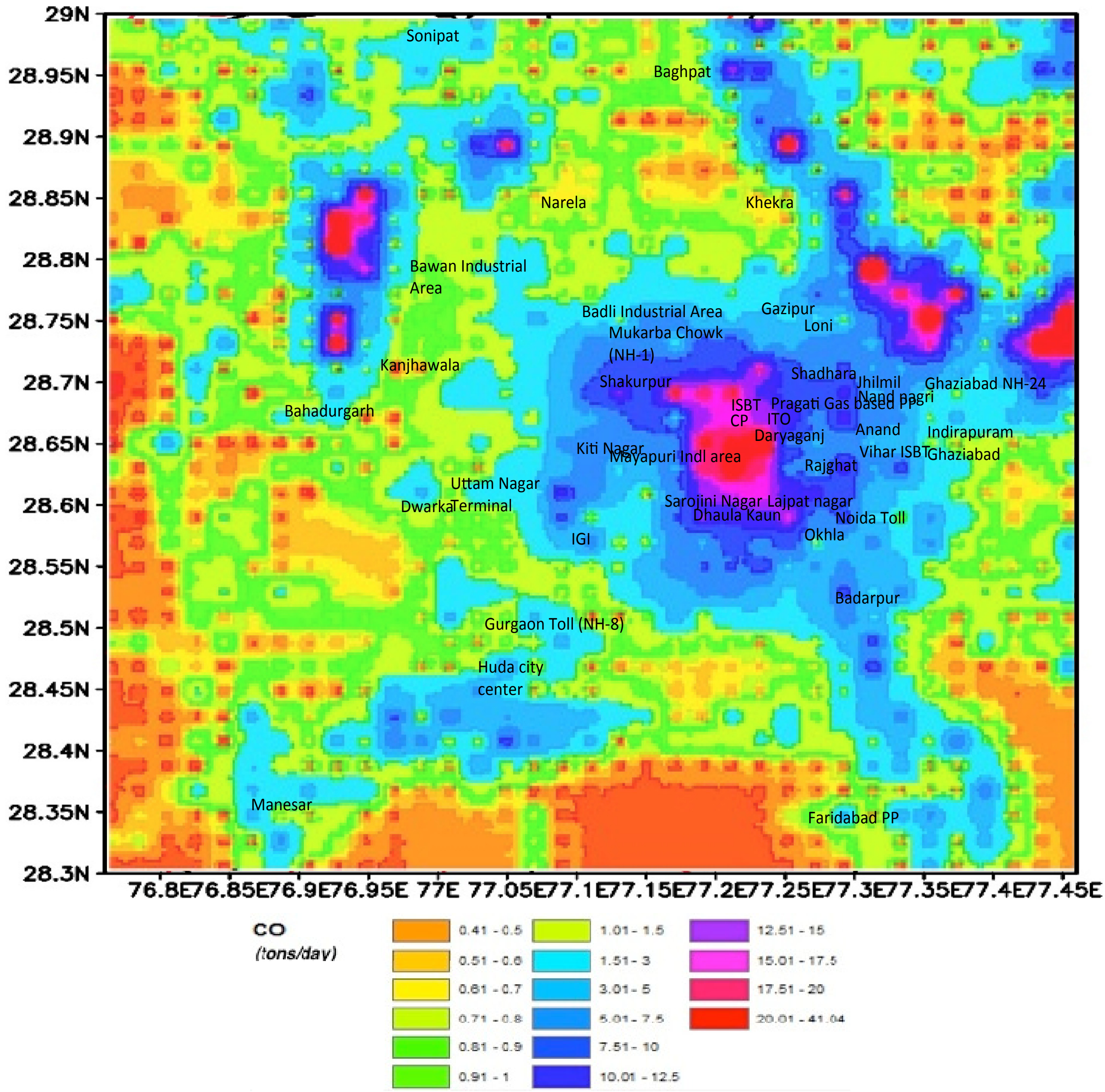

Fig. 6. Spatial distribution of CO over the study domain (tons/day).

Table 3. Range of Primary and Secondary Hotspot (tons/day).

Pollutant	CO	NO_x	SO_2	PM_{10}
Primary Hotspot Range (tons/day)	> 11	> 5.5	> 4	> 3
Secondary Hotspot Range (tons/day)	6–11	2.5–5.5	2–4	0.75–3

Uncertainty Assessment

Emission inventories are based on several assumptions and projections of missing data. Accurate estimation of emissions from all the sources in a region may not be possible due to spatial and temporal changing nature of all the sources (Sindhwani and Goyal, 2014). However, Uncertainty assessment of an emission inventory is necessary tool for defining control measures by the regulatory bodies in order to tackle the problem of degrading air quality (Gurjar *et al.*, 2004). This assessment may be conducted using a quantitative or a qualitative approach. Quantitative approaches are based on the use of numerical sampling techniques in a probabilistic modelling environment such as Monte Carlo Sampling and Latin Hypercube Sampling (Cullen and Frey, 1999; Zheng, 2002). Therefore, detailed information on the probability distribution function of EFs and activities are required to

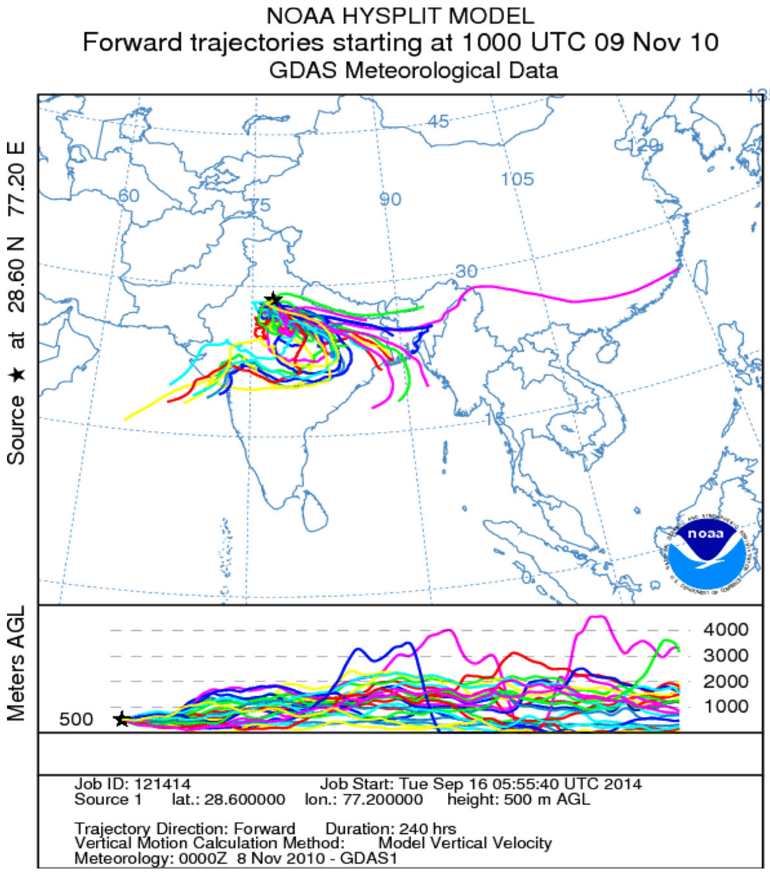

Fig. 7. 10-day forward trajectory from Delhi During November, 2010.

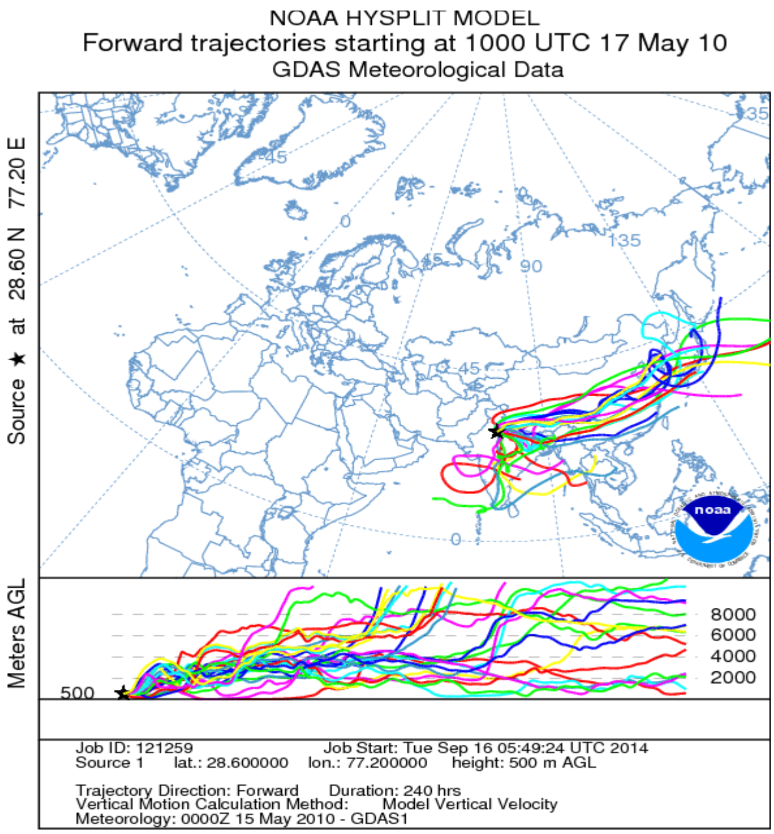

Fig. 8. 10-day Forward trajectory from Delhi during May, 2010.

apply such approaches properly. In contrast to this, qualitative approaches are based on an evaluation of the accuracy and the reliability of activity data, estimation methods and uncertainty in emission factors without a quantification of the uncertainties (Waked *et al.*, 2012). In this study, qualitative approach has been used to assess the uncertainty in emission estimates and scenario analysis has been conducted for vehicular sector.

Emission estimates from power plants, showed least uncertainty compared to other sources due to the use of bottom-up approach and availability of activity level data such as plant load factor for each power plant. A little uncertainty arises due to the choice of emission factors. The residential sector has been identified as a major cause of uncertainty in Asia (Streets *et al.*, 2003), due to the lack of reliable statistics and measurements of local emission factors. Emissions calculated from domestic sector are based on fuel statistics available from government reports but much more emissions are expected from this sector due to use of kerosene, and dung cake, which is a major source of cooking by the street vendors and slums. Moreover no time series data is available for coal and firewood fuels used in the residential sector. In addition to this, uncertainty is further increased due to spatial distribution of domestic emissions via top-down approach based on population density in each region.

Diesel generators, which have emerged as an important source of PM_{10} emissions in this study, the uncertainty in their activity data is related to uncertainty in the fraction of fuel used and distribution of diesel generators over study domain. An estimate presented here is based on the data available in the literature. Uncertainty in the vehicular emissions arises due to lack of local vehicle emission measurements and fleet characteristics, also from the discrepancy in vehicle classifications between annual statistical reports. The vehicle kilometer travelled (VKT) numbers are estimated through surveys, since they are not available through official reports. This leads to a systematic bias in estimating emissions from mobile sources (Sindhwani and Goyal, 2014). However, the total VKT used in this study seems to be consistent with the CPCB (2001) with a difference of about 9%.

Further, three scenarios have been considered to assess emissions from various vehicle categories in the future year 2020.

Scenario 1: Continuation of present emission standard as well as growth rate of vehicle till 2020.

Scenario 2: Introduction of new Bharat Stage IV emission standards (say–in 2015) leading to change in emissions in 2020.

Scenario 3: Improvement in emission factors accompanied with the reduction of growth rate of on the assumption grounds of improvement in public transport. A case of 30% reduction has been taken up.

This assessment further results in decrease in emissions of CO, NO_x, SO_2 and PM_{10} by about 63%, 58%, 52% and 23% in 2020 on application of scenario 3 w.r.t Scenario 1. However, Scenario 2 doesn't show an appreciable decrement in emissions as increasing number of vehicles would negate the effect of improved emission standards.

Biomass burning emissions considered in the present study involve a lot of uncertainty due to unavailability of sub-region wise information regarding these emissions as well as top-down approach used in the segregations of these emissions.

CONCLUSIONS

An attempt has been made to develop a gridded emission inventory of criteria pollutants 2 km × 2 km spatial resolution over an area of 4900 km^2, centered around metropolitan city Delhi and covering its adjoining areas. The main findings of the study are as follows:

- Vehicular emissions have been identified as the major contributor corresponding to NO_x and CO emissions with the estimated proportion of 47% and 46% respectively.
- NO_x emissions from industries and power plants together contribute nearly 20% towards total emissions. These emissions are further estimated to rise due to increase use of natural gas as fuel in power plants. Moreover, Delhi Government plans to shift coal-based power plants to gas based, may further result in rise in NO_x emissions in coming years. Also, approximately 1% of NO_x emissions are contributed by aircrafts, which may rise at a very fast pace in near future in order to meet urban demand.
- Power Plants, industries and brick kilns together are still the highest contributors towards SO_2 emissions contributing nearly 80% of the total emissions, followed by the transport sector (14%). SO_2 emissions from transport sector are further expected to rise in future years due to rapid rise in diesel-operated passenger cars in the NCR. Moreover, contribution of SO_2 from power plants is expected to reduce in future years, as Government plans to shift from coal to natural gas as fuel in power plants.
- Industries, power plants and brick kilns located in the study domain contribute 33% of PM_{10} emissions. Increase in infrastructural building activities in Delhi and its surrounding areas have resulted in contribution of 9% of PM_{10} emissions from construction sector. Road dust and vehicular sources contribute nearly 39% to PM_{10} emissions, which is very alarming.
- Assessment of the impact of long-range transport of the pollutants has been included during two extreme seasons over the study domain using HYSPLIT Model.
- Finally, the present study concludes that, with this emission inventory one can address to the air pollution problems in a better way. Further improvements in the emission inventory could be made by collection of more detailed information about biomass burning areas, small scale industries working in the residential areas of Delhi and its surrounding areas like wood-cutting, welding. Moreover, this inventory could form the basis of relative contribution of PM_{10} emitted by vehicular sources and power plants (including industries) on the mortality and morbidity of the region. The present emission inventory can also be validated after simulating the concentration from chemical transport model (CTM) in the near future.

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