Air Qual Atmos Health
DOI 10.1007/s11869-014-0303-6

Particulate and gaseous emissions in two coastal cities—Chennai and Vishakhapatnam, India

Sarath K. Guttikunda · Rahul Goel · Dinesh Mohan · Geetam Tiwari · Ravi Gadepalli

Received: 5 July 2014 / Accepted: 20 October 2014

Abstract The presence of land sea breezes is advantageous to Chennai and Vishakhapatnam. With most industrial and power plant emissions dispersed to the sea, their overall impact on the urban air quality is lessened. However, the same is not true for the diffused emissions, such as the vehicle exhaust, domestic cooking, open waste burning, and road dust, which are steadily increasing. The annual averages for 2012 in Chennai are 121.5±45.5, 12.1±3.5, and 20.8±7.0 and in Vishakhapatnam are 70.4±29.7, 18.9±14.4, and 15.6±6.3, for PM_{10}, SO_2, and NO_2 respectively. All the concentrations are reported in micrograms per cubic millimeter. In this paper, we present sector-specific emissions inventory for particulate and gaseous pollutants, which is spatially disaggregated at 0.01° resolution, suitable for atmospheric dispersion modeling. For the urban airshed, the ambient particulate concentrations were modeled using the ATMoS dispersion model, which when overlaid on gridded population, resulted in estimated 4,850 and 1,250 premature deaths and 390,000 and 110,000 asthma attacks in year 2012, for the Greater Chennai and the Greater Vishakhapatnam regions, respectively. The total emissions are also projected to 2030. Under the current growth rates and policy assumptions, the pollution levels are likely to further increase, if the expected changes in the industrial energy efficiency, environmental regulations in the power plants, and fuel standards for the vehicles are not introduced as planned.

Keywords Emissions inventory · Dispersion modeling · Health impacts · SIM-air · Air quality management

Highlights
1. An inventory of particulate and gaseous emissions for two coastal cities in India
2. Resources for activity data utilized for emissions inventory
3. Results of ATMoS dispersion modeling for ambient particulate pollution
4. Health impacts of particulate pollution

Electronic supplementary material The online version of this article (doi:10.1007/s11869-014-0303-6) contains supplementary material, which is available to authorized users.

S. K. Guttikunda · R. Goel · D. Mohan · G. Tiwari · R. Gadepalli
Transportation Research and Injury Prevention Program, Indian Institute of Technology, New Delhi 110016, India

S. K. Guttikunda (✉)
Division of Atmospheric Sciences, Desert Research Institute, Reno, NV 89512, USA
e-mail: sguttikunda@gmail.com

Introduction

Epidemiological studies from India show high rates of respiratory and cardiovascular diseases in populations exposed to particulate matter (PM), nitrogen oxides (NO_x), and ozone pollution (Chhabra et al. 2001; Pande et al. 2002; Gupta et al. 2007; Siddique et al. 2010; Balakrishnan et al. 2013), and there is a growing body of international evidence on the health impacts of outdoor air pollution (IHME 2013). In 2014, the World Health Organization (WHO) listed 37 Indian cities in the top 100 world cities with the worst air quality (WHO 2014). In 2011, a similar assessment listed 27 cities.

The array of air quality studies in India (Supplementary Material) point to significant need for information on spatial and temporal resolution of emission inventories and pollution dispersion characteristics in the cities. It is also important to build the necessary capacity of the state pollution control boards (SPCBs) to undertake focused analysis as well as scrutiny of pollution control programs to improve air quality.

In this paper, we present, for two coastal cities in India (Chennai and Vishakhapatnam), an overview of air quality monitoring data, emissions from all the known sectors, pollution dispersion characteristics, and an assessment of health impacts and discuss scenarios for building an urban air quality management program.

Published online: 01 November 2014

Data and methods

Study domain

We defined the study domains such that they were large enough to cover the main district area, the neighboring satellite cities, and locations with sources that could influence the air quality in the designated urban areas. The geographical location of the cities is presented in Fig. 1, along with the main roads, highways, points of interest, brick kiln clusters, industrial estates, power plants, and the main urban district boundary. The Greater Chennai domain covers an area of 44×44 km and the Greater Vishakhapatnam region covers an area of 40×40 km, with both the domains subdivided into grids at 0.01° (approximately 1 km) resolution. The two domains consist of three ports, handling up to one fourth of the total traffic at all the major ports of India (IPA 2013).

Chennai

Chennai (capital of the state of Tamil Nadu) is one of the four metropolitan cities of India, along with Delhi, Mumbai, and Kolkata. With its proximity to the Bay of Bengal and thus access to markets in East Asia, Chennai is also an important and busy port city. Apart from trade and shipping, the automobile industry, chemical and petrochemical industry, software services, medical care, and manufacturing form the foundation of the economic base for Chennai. Manufacturers like Ford, Hyundai, Mitsubishi, Ashok Leyland, Massey Ferguson, Eicher, and other engineering and manufacturing units have taken advantage of the proximity to the port, as well as skilled labor in the region, to establish manufacturing centers in Chennai, thus accounting for 30 % of India's auto industry.

The Ennore Port, the first major corporate port, handles coal (most of the supply is for the two thermal power plants with dedicated feeder lines running from the ports), iron ore, oil, and commercial commodities for the automobile and mineral industries. The annual capacity of 30 million tons of cargo in 2012–2013 is expected to triple by 2020, which is linked by road and rail transport, to most parts of South India.

There are 8.7 million inhabitants in the Greater Chennai region, covering a city area of 1,200 km^2. The percentage of households owning a car is 13 %, the percentage of households owning a motor cycle is 47 %, and the percentage of households using a nongas or nonelectric cook stoves is 17 % (Census-India 2012). With US$219 billion in 2012, Chennai metropolitan area is the fourth largest city by GDP in India.

Vishakhapatnam

Visakhapatnam is a coastal city, also on the eastern coast of India. It is the second largest urban agglomeration in the state of Andhra Pradesh, after Hyderabad. The port handles petroleum, oil, iron ore, coal, and other commercial goods, and the port is the second largest in India in terms of the cargo traffic. Close proximity to the port has also lead to industrial settlement in the city, consisting of steel, petroleum refining, and fertilizer industries. While the modeling domain size is the same as Chennai, a large part of the Vishakhapatnam domain is covered by hills and forests, and the built-up area is only 30 % of the modeling domain (Fig. 1). Besides the port, other factors contributing to the city's economic growth are its location between Chennai and Kolkata and a developed network of railways which changed this valley into an industrial hub.

There are 1.7 million inhabitants in the Greater Vishakhapatnam region, covering a city area of 530 km^2. The percentage of households owning a car is 8 %, the percentage of households owning a motor cycle is 36 %,

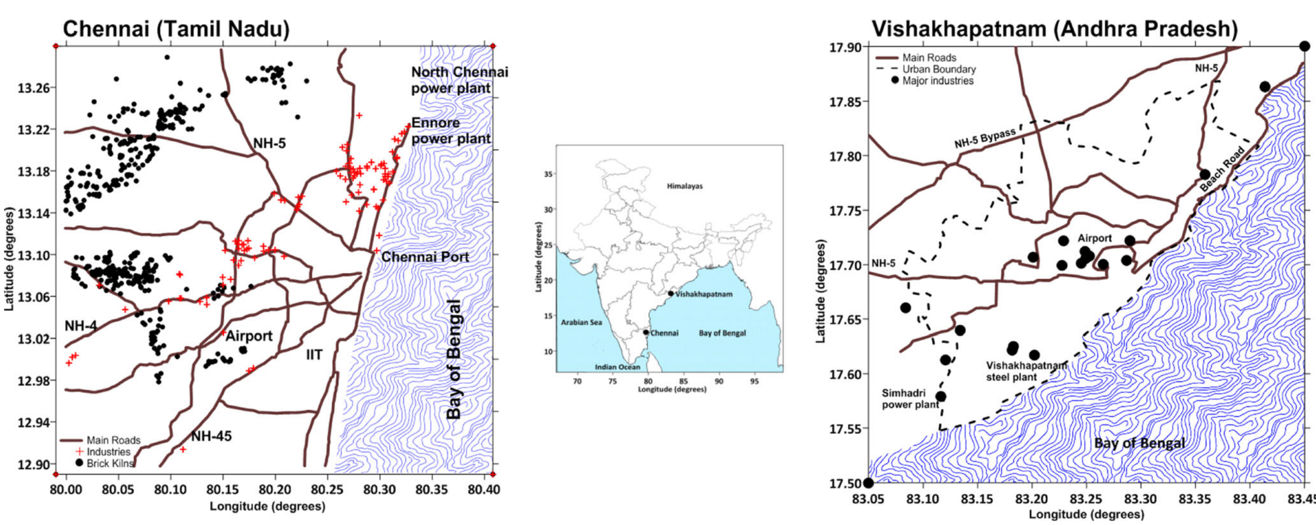

Fig. 1 Geography and the study domains of Chennai (Tamil Nadu) and Vishakhapatnam (Andhra Pradesh)

and the percentage of households using a nongas or nonelectric cook stoves is 21 % (Census-India 2012). With US$26 billion in 2012, Vishakhapatnam is the tenth largest city by GDP in India.

Urban air quality

The presence of land sea breezes is advantageous for both the cities, with most of the emissions, from the industrial clusters, petro-chemical refineries, and the power plants, getting dispersed to the sea and thus reducing their impact on the urban air quality. The same cannot be said for the diffused sources in the city, such as the vehicle exhaust, domestic cooking, open waste burning, and road dust. The monsoonal months are marked with heavy winds and precipitation. The meteorology over the two cities is derived from the National Center for Environmental Prediction (NCEP 2013). A summary of the wind speed and direction (at 6-h interval) as a wind-rose function and the monthly total precipitation are presented in the Supplementary Material.

A summary of the PM_{10}, SO_2, and NO_2 concentrations from the national ambient monitoring program (NAMP) stations is presented in Table 1 for Chennai (six stations) and Table 2 for Vishakhapatnam (six stations). All the stations are manually operated with samples collected two to three times per week. The annual averages for 2012 for all the stations in Chennai are 121.5±45.5, 12.1±3.5, and 20.8±7.0 and in Vishakhapatnam are 70.4±29.7, 18.9±14.4, and 15.6±6.3, for PM_{10}, SO_2, and NO_2 respectively. All the concentrations are reported in micrograms per cubic millimeter.

The SO_2 concentrations are often under compliance due to the introduction of low-sulfur fuel for all vehicles and higher efficiency norms for the industries. The sulfur content in the fuels is of Bharat-IV standard in Chennai and Bharat-III standard in Vishakhapatnam—equivalent of Euro-IV and Euro-III standards, respectively. Also, most of the industries, except for heavy-duty industries like power and steel, are operating on electricity and gas, which further reduced the sulfur emissions and ambient SO_2 concentrations. While the sulfur content is considered low in the Indian coals (Guttikunda and Jawahar 2014), between 2011 and 2012, the ambient SO_2 concentrations increased at least 30 %, due to increasing industrial activity and overall consumption of coal in both the cities. Both the cities are listed in the top 100 world cities with the worst PM_{10} pollution levels (WHO 2014). While the annual average NO_2 concentrations are under the national ambient standard (40 μg/m^3), the daytime peaks ranged between 60 and 120 μg/m^3 over the 12 months in 2012.

For Chennai, Mohanraj et al. (2011) reported $PM_{2.5}$ concentrations for industrial, commercial, and residential sites of Chennai during 2009–2010. The mean concentrations of $PM_{2.5}$ for four different seasons varied from 53 to 114 μg/m^3 for residential area, 70 to 95 μg/m^3 for industrial site, and 70 to 170 μg/m^3 in a commercial area. The national annual ambient standard for $PM_{2.5}$ is 40 μg/m^3. For Vishakhapatnam, two continuous monitoring stations are operational since February 2014, which includes $PM_{2.5}$. These results are not yet available from the Andhra Pradesh Pollution Control Board (APPCB).

Multi-pollutant emissions inventory

The gaseous and particulate emissions inventory was developed for the base year 2012 and also projected to 2030, based on

Table 1 Monitored monthly average concentrations (μg/m^3) in Chennai

	2011			2012		
	PM_{10}	SO_2	NO_2	PM_{10}	SO_2	NO_2
January	85.0±43.6	8.0±1.2	19.0±7.2	96.4±28.6	9.4±1.2	14.6±2.7
February	109.2±49.2	11.4±1.3	22.2±4.9	129.6±39.9	9.6±1.7	16.2±4.7
March	118.4±55.1	9.8±1.5	21.4±5.2	168.8±87.4	12±2.8	19.8±5.4
April	113.0±42.4	9.2±1.5	18.4±4.7	120.0±51.2	18.2±7.1	20.4±9.7
May	119.8±38.4	10.2±1.9	22.8±6.9	154.0±46.9	13.4±1.5	26.2±8.6
June	95.6±39.9	8.8±1.1	20.0±4.5	122.7±35.2	11±1.4	24.7±8.5
July	113.8±55.2	9.4±1.2	20.8±5.5	102.2±29.8	11.7±2.1	20.5±5.4
August	153.0±77.7	8.4±1.2	16.0±4.1	98.3±32.1	12.5±1.7	17.7±2.2
September	144.0±60.1	9.6±1.5	20.0±3.7	112.5±30.9	12.5±1.9	18.7±3.5
October	140.4±41.1	8.6±1.7	13.4±2.7	110.7±30.2	13±1.8	21.2±5.7
November	136.6±60.2	9.6±1.2	20.4±7.0	130.2±42.4	12±2.6	26.0±6.9
December	136.6±35.0	12.6±3.1	16.4±2.9	97.3±16.9	9.8±1.5	26.2±9.1
Annual average	122.1±50.2	9.6±1.9	19.2±5.3	121.5±45.5	12.1±3.5	20.8±7.0
Annual standard	60.0	50.0	40.0	60.0	50.0	40.0

Table 2 Monitored monthly average concentrations (μg/m^3) in Vishakhapatnam

	2011			2012		
	PM_{10}	SO_2	NO_2	PM_{10}	SO_2	NO_2
January	86.6±17.8	11.9±5.4	19.6±5.8	81.2±32.9	22.9±14.5	20.7±4.6
February	116.2±46.2	13.7±5.5	22.7±6.6	89.7±40.3	20.6±15.2	19.8±5.1
March	110.1±39.9	14.3±7.5	21.9±7.0	75.8±25.7	16.5±9.8	15.8±3.7
April	79.0±15.7	15.6±7.4	23.4±6.3	72.9±24.7	15.9±8.6	14.1±2.9
May	92.2±37.5	14.8±6.5	22.2±5.7	71.8±27.1	12.9±9.4	12.5±4.3
June	71.4±24.4	15.9±7.1	24.2±6.4	77.4±28.4	12.9±8.6	12.7±3.1
July	71.8±23.3	15.3±6.1	22.3±4.9	62.7±28.7	27.2±24.1	20.3±9.9
August	66.0±28.3	13.1±5.5	18.7±4.1	61.7±25.8	27.3±19.7	18.5±8.4
September	62.8±25.1	15.5±6.7	21.3±4.6	50.2±19.0	19.4±11.2	11.4±4.1
October	84.2±26.5	16.6±7.7	21.9±9.1	60.5±30.6	13.4±9.8	10.7±1.4
November	92.5±36.9	11.7±5.6	17.5±3.6			
December	89.9±34.4	17.0±11.9	19.8±5.7			
Annual average	85.2±33.6	14.6±6.7	21.3±6.0	70.4±29.7	18.9±14.4	15.6±6.3
Annual standard	60.0	50.0	40.0	60.0	50.0	40.0

assumed growth rates for various sectors and expected changes in the regulations.

Transport

We utilized the Activity–Share–Intensity–Factor (ASIF) methodology to calculate the vehicle exhaust emissions (Schipper et al. 2000), which takes into account, the vehicle type, fuel type, and age group, to calculate the total emissions. Previous studies have documented this method to estimate on-road emissions in the Indian cities (Gurjar et al. 2004; Mohan et al. 2007; CPCB 2010; Sahu et al. 2011; Guttikunda and Calori 2013; Guttikunda and Mohan 2014).

The total number of registered vehicles in Chennai is 3.8 million and in Visakhapatnam is 0.7 million (as of March 31st, 2012), with the vehicle categories listed in Table 3 (MoRTH 2013). Between 2002 and 2012, these registrations have at least tripled in Chennai and at least doubled in Vishakhapatnam (Fig. 2). According to the State Transport Authority of Tamil Nadu, the total number of new registrations increased from 516,000 in 2001–2002 to 1.82 million in 2012–2013, with a majority of this share in the cities of Chennai and Coimbatore. Presence of ports also resulted in higher proportion of goods vehicle registrations −4.8 and 3.6 % respectively, which is at least double the registrations in Delhi (1.8 %). The two-wheelers are the most popular mode of transport with at least 70 % registrations.

The average vehicle-kilometers traveled and average speed by mode are estimated from passenger travel surveys and field surveys by the Transport Research and Injury Prevention Program (TRIPP) at the Indian Institute of Technology (New Delhi, India) (Goel et al. 2014). Annual average vehicle-kilometers traveled is estimated as 11,000 and 9,500 for passenger cars in Chennai and Vishakhapatnam, 20,000 for multi-utility vehicles, some of which also substitute for taxis, 36,000 for taxis and three-wheelers (approximately 100 km per day), 50,000 for public transport buses (operating at approximately 15 km/h speeds and 8 h a day), and 30,000 for the heavy-duty and light-duty vehicles.

Table 3 Number of registered vehicles in Chennai and Vishakhapatnam as of May 31st, 2012

	Chennai	Vishakhapatnam
Multi-axle vehicles	98,000	14,600
Light motor vehicles (goods)	82,500	10,400
Buses	38,200	2,000
Taxis	82,500	9,000
Light motor vehicles passenger	104,400	36,800
Two-wheelers	2,630,800	516,600
Cars	653,300	73,000
Jeeps	12,500	3,500
Omni buses	8,800	2,500
Tractors	2,600	3,000
Trailers	11,800	10,500
Other vehicles	42,400	2,000
Total	3,767,800	683,900
% Goods vehicles	4.8	3.6
% Two wheelers	69.8	75.6
% Cars and jeeps	19.9	12.5
% Buses	1.2	0.6

Source: Ministry of road transport and highways, India (MoRTH 2013)

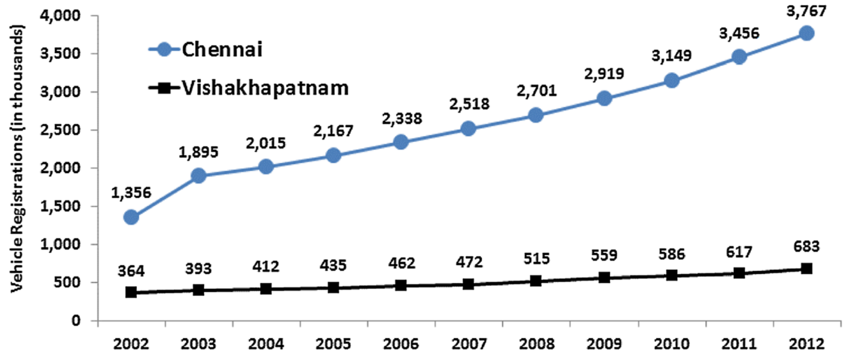

Fig. 2 Number of registered vehicles in Chennai and Vishakhapatnam during 2002–2012

The age mix of on-road vehicles is calculated using data from the "pollution under check" (PUC) program, under which all passenger and paratransit vehicles are required to undergo emission tests and receive an inspection and maintenance certificate, every 6 months. For the passenger cars and motorcycles, a large portion (50 %) of the fleet is less than 5 years. This was vital in estimating the fleet average emission factors for all the vehicle categories. We did not utilize the emission rate results from PUC tests, as they are based on 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 CPCB (2010) and adjusted for the urban travel behavior and current driving cycles, which indicate at least 20 % of the driving time for the private vehicles as idling (Goel et al. 2014). A summary of the fleet average emission factors for the base year 2012 is presented in the Supplementary Material for all the modes and for three fuels—petrol, diesel, and gas. The sulfur content in diesel and petrol is of Bharat-IV standard in Chennai and Bharat-III standard in Vishakhapatnam.

Due to the commercial shipping industry, a large number of trucks ply in the cities. Since the roads connecting the ports pass through populated parts of the city, movement of trucks leads to increased ambient pollution levels. Chennai has a radial network of national highways (NHs)—NH45, NH4, NH5, and NH205 connecting the port to the regional network. In Chennai, movement of trucks is restricted from 7 a.m. to 9 p.m. in most parts of the city, and between 8 and 11 a.m. and between 4 and 8 p.m., the restrictions are also implemented on major highway sections, to avoid congestion during the rush hours.

There are no restrictions for freight movement in Vishakhapatnam, along the national highway (NH5) that passes through the city. The highway also acts as an urban road connecting the industrial estate in the south to the residential and commercial areas in the north. Along the remaining urban roads, trucks are not allowed between 8 a.m. to 12 noon and 4 to 8 p.m. A large part of the city, particularly the slums, lies along the highway and is therefore exposed to the pollution from the highway traffic throughout the day.

The aircraft landing and takeoff (LTO) emissions are also included in the transport sector. The Chennai airport is a busy international airport with more than 350 LTO's per day, and Vishakhapatnam airport is smaller and caters predominantly to the domestic traffic with 50 LTO's per day. Both the airports are located within the city limits (Fig. 1). The airport emissions include some idling of the passenger vehicles, shuttling of passengers to and from the aircrafts by buses, and use of tractors for shuttling luggage to and from the aircrafts.

Road dust

We utilized the empirical functions from USEPA AP-42 to estimate the road dust resuspension rates (USEPA 2006; Kupiainen 2007). The total gridded road dust emissions are estimated based on the vehicle density fractions assigned for each vehicle type to two road categories (main and arterial). The overall assessment of the road dust emissions and their contribution to the ambient PM pollution was conducted through the dispersion model, coupled with the meteorological data. Compared to the drier and in-land cities like Delhi and Hyderabad, the humidity levels are higher in Chennai and Vishakhapatnam. Along with the sporadic rains, the overall resuspension rates are kept to a minimum.

Electricity generation and utilization

Chennai and Vishakhapatnam have thermal power plants located in the study domain. Chennai is supported by North Chennai (630 MW) and Ennore (450 MW) thermal power plants, together consuming 4.9 million tons of coal annually. Vishakhapatnam is supported by the Simhadri (2,000 MW) thermal power plant and Vizag Steel (1,040 MW) plant, together consuming 11.4 million tons of coal annually. Some cogeneration at the refineries in the vicinity of the thermal power plants also supplies power to the grid. The coal-fired thermal power plants follow limited environmental regulations for controlling the emissions. While most of the PM emissions are controlled via electrostatic precipitators, the gaseous emissions are dispersed at the stacks, with no desulfurization units in operation (Guttikunda and Jawahar 2014). The sulfur content in the coal utilized at the power plants is less than 0.5 %. However, mandating desulfurization units for coal-fired thermal power plants will have an immediate benefit for PM pollution control and further reduce the growing SO_2 levels in the vicinity.

Most of the electricity needs are met by the thermal power plants. Still, a substantial proportion of mobile phone towers, hotels, hospitals, malls, markets, large institutions, apartment complexes, and cinemas supplement their electricity needs with in situ diesel generator sets. For example, a five-star hotel or a big hospital is estimated to consume 10,000 l of diesel per month, a mobile phone tower experience 2–4 h power cuts per day is expected to consume between 3,000 and 5,000 l of diesel per month, and an apartment complex is expected to consume between 1,000 and 10,000 l of diesel per month, depending on the size of the complex. Emission factors for diesel generators are obtained from GAINS (2013).

Industries

Tamil Nadu has actively facilitated provision of land coupled with necessary infrastructure required to set up major industrial units through the State Industries Promotion Corporation of Tamil Nadu (SIPCOT). This has been one of the key factors in attracting manufacturing companies in the fields of engineering, electronics, chemicals, food processing, automotive, etc. While most of the industries rely on the grid electricity for their energy needs, there are frequent power outages, which force them to use in situ diesel generators.

Vishakhapatnam is home to one of the busiest ports of the country which handles around 50–55 million tons of cargo, annually. The port, over the years, has supported the development of several heavy industries like the steel plant, dockyard of the eastern naval command of India, and a shipbuilding yard. In addition, the city is constructing another deep sea port, which, once built, will have the highest cargo handling capacity in the country. The city is promoted as an industrial hub by the state government by setting up three special economic zones, spread across 23 km^2 to support information technology services, alloy manufacturing, steel manufacturing, pharmaceuticals, textiles, cement, refineries, and food processing industries. The Visakhapatnam urban development authority is also developing petroleum, chemical, and petrochemical investment regions between Visakhapatnam and Kakinada, a nearest port city. The region spreads across two districts, over an area of 640 km^2, and is expected to accelerate the industrial growth of the city further.

The industrial emissions inventory is based on fuel (coal, gas, and liquid) consumption information obtained from the Ministry of Statistics (New Delhi, India) which collates information on the industrial location, their fuel consumption based on fuel receipts, their work force, and finances.

Brick kilns and construction

Besides the traditional manufacturing industries, there are kiln clusters around the metropolitan city, supporting the growing demand for traditional red and fired clay bricks for construction. The location of the brick kiln clusters in Chennai is marked in Fig. 1, predominantly to the west of the city. At the kiln clusters around Chennai, the rectangle-shaped clay bricks are sun-dried and readied for firing in the fixed chimney bull trench kilns (FCBTK) with a 50-m chimney to disperse emissions. In the case of Vishakhapatnam, the bricks are sun-dried and fired in "clamps"—a pile of bricks with intermittent layers of sealing mud and fuel (most of these are located farther to the west, outside the modeling domain). In clamps, a significant amount of energy is lost during the cooling with no possibility of recycling. At the FCBTK's, all the material is fired at once and cooled to draw the bricks. The emerging technologies and emission factors for kilns in India are documented in Weyant et al. (2014). The inventory also includes fugitive dust estimates for construction sites (USEPA 2006).

Domestic sector

The domestic sector emissions are based on fuel consumption estimates for cooking. Using census statistics, household total energy consumed in the form of solid (coal and wood), liquid (kerosene), and gaseous (LPG) fuels was estimated at the grid level (IFMR 2013). In the city, the dominant fuel is LPG. In slum areas, construction sites, some restaurants, and areas outside the municipal boundary, the use of coal, biomass, and agricultural waste is common. The gridded population at 30-s spatial resolution from GRUMP (2010) was interpolated to the model grid, with the high density areas utilizing mostly LPG and the low density areas utilizing a mix of fuels. The percentage of households using a nongas or nonelectric cook stoves is 17 % in Chennai and 21 % in Vishakhapatnam (Census-India 2012).

Open waste burning

Garbage burning in the residential areas emits substantial amount of pollutants and toxins, and this is a source with the most uncertainty in the inventories. Because of the smoke, air pollution, and odor complaints, the city municipality banned this activity, but it continues unabated at makeshift landfills. The Municipality of Chennai operates two landfill facilities—Kodungaiyur and Perungudi—with a combined waste collection capacity of 2,000 t per day, and the Municipality of Vishakhapatnam operates one landfill with a waste collection capacity of 500 t per day (Annepu 2012). It is assumed that at least once a week, nearly 50 % of the uncollected waste is put to fire at 1,000 and 500 makeshift sites in Chennai and Vishakhapatnam, respectively.

Atmospheric dispersion modeling

The Atmospheric Transport Modeling System (ATMoS) dispersion model was utilized to estimate the ambient PM concentrations (Calori and Carmichael 1999), previously utilized for urban and regional applications in Asia (Arndt et al. 1998; Guttikunda et al. 2001; Holloway et al. 2002; Guttikunda and Jawahar 2012; Guttikunda and Goel 2013; Guttikunda and Kopakka 2014). This is a Lagrangian puff transport model, where the area and point sources are treated as puffs from their respective release points and allowed to expand horizontally and vertically, following the meteorological conditions in time and space. The horizontal resolution of the model for both the cities is maintained at 0.01° (approximately 1 km), which is similar to the emissions inventory. The puffs are transported and evaluated every hour, and the results are averaged every month. The vertical resolution of the model is in three layers—surface (varying between 300 m at night to 500 m during the day), mixing layer height (calculated from the meteorological conditions), and one top layer capping at 4 km. The puffs are subjected to dry and wet deposition schemes. 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, which is added to the total $PM_{2.5}$ and PM_{10} concentrations. The mechanisms are explained in Guttikunda et al. (2001) for sulfates and Holloway et al (2002) for nitrates. The meteorological fields for three vertical levels, mixing heights, and precipitation fields are preprocessed (with archives since 1990) utilizing the National Center for Environmental Prediction (NCEP 2013), available at 6-h interval.

Health impacts

The health impacts of ambient PM concentrations in terms of mortality and morbidity are calculated based on concentration-response functions established from epidemiological studies and explained in previous applications (GAINS 2013; IHME 2013; Guttikunda and Goel 2013; Guttikunda and Kopakka 2014). The total health risk for mortality is quantified using the relative risk functions quantified as

$$\delta E = \sum_{i=1}^{\#grids} \left(1 - \frac{1}{\exp(\beta * \delta C_i)}\right) * \delta POP_i * IR \qquad (1)$$

The total health risk for morbidity is quantified as

$$\delta E = \sum_{i=1}^{\#grids} \beta * \delta C_i * \delta POP_i \qquad (2)$$

where

- δE number of estimated health effects (various end points for mortality and morbidity)
- IR incidence rate of the mortality and morbidity endpoints. A total death incidence rate for India is set at 7.1 per 1,000 inhabitants
- δPOP the population exposed to the incremental concentration δC in grid i, defined as the vulnerable population in each grid
- β the concentration-response function, which is defined as the change in number cases per unit change in concentrations per capita. For all-cause mortality in this study, the function is defined as 3.9 % change in the mortality rate per 4 μg/m^3 of change in the $PM_{2.5}$ concentrations (Hart et al. 2011). We also estimate morbidity in terms of asthma cases, chronic bronchitis, hospital admissions, and work days lost. The uncertainty in the concentration-response functions is explained in Atkinson et al. (2011), Hart et al. (2011), and Jahn et al. (2011).
- δC the change in concentrations from the ambient standards in *grid i*.

Results and discussion

Emission budgets, projections, and contributions

For the base year 2012, the total emissions along with sector contributions are summarized in Table 4 for Chennai and Table 5 for Vishakhapatnam, and the projected emissions for PM_{10}, SO_2, NO_x, and CO_2 through 2030 are presented in Fig. 3 for Chennai and Fig. 4 for Vishakhapatnam.

For the projections to 2030, (a) the vehicle growth rate is assumed from the national road transport emissions study (Guttikunda and Mohan 2014), based on the sales projection numbers from the Society of Indian Automobile Manufacturing (New Delhi, India), (b) the industrial growth is projected according to the gross domestic product of the state, and (c) the domestic sector, construction activities, brick demand, diesel usage in the generator sets, and open waste burning are linked to the population growth rates according to the 2011 census (Census-India 2012).

In the projections through 2030, the only sector showing a downward or tapering trend is the vehicle exhaust. This is primarily due to the expected improvement in the fleet average emission factors over the years. As the newer fleet with better emission standards is introduced and the older fleet retiring, there is an inherent improvement in the fleet average emission factor, which is resulting in tapering of the vehicle exhaust emissions, irrespective of higher vehicle sales and increasing congestion times on the roads. Under the current energy efficiency norms for the industries, environmental regulations for the power plants and road map for the vehicles, the overall emissions in the city are expected to increase through 2030.

Table 4 Estimated particulate and gaseous pollutant emissions inventory for the Greater Chennai region for the base year 2012

Category	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC	CO_2
Transport	21,600 (42 %)	25,400 (34 %)	1,200 (3 %)	124,400 (61 %)	265,600 (44 %)	118,600 (75 %)	11.6 (49 %)
Domestic	3,100 (6 %)	3,400 (4 %)	1,150 (3 %)	1,450 (0.%)	161,000 (27 %)	5,900 (3 %)	0.8 (3 %)
Open waste burning	1,950 (3 %)	2,800 (3 %)	150 (1 %)	750 (0.%)	11,100 (1 %)	950 (1 %)	0.1 (1 %)
Construction	650 (1 %)	3,100 (4 %)	50 (1 %)	800 (0.%)	1,050 (1 %)	50 (1 %)	0.1 (1 %)
Manufacturing industries	11,100 (21 %)	15,700 (21 %)	9,600 (27 %)	20,600 (10 %)	54,300 (9 %)	16,400 (10 %)	2.6 (11 %)
Power plants	6,700 (13 %)	9,000 (12 %)	21,000 (59 %)	29,300 (14 %)	11,000 (1 %)	1,100 (1 %)	6.7 (28 %)
Generator sets	950 (1 %)	1,050 (1 %)	250 (1 %)	19,300 (9 %)	20,200 (3 %)	7,500 (4 %)	1.1 (4 %)
Road dust	1,100 (2 %)	7,300 (9 %)					
Brick kilns	4,000 (7 %)	5,500 (7 %)	2,050 (5 %)	4,100 (2 %)	68,700 (11 %)	7,300 (4 %)	0.5 (2 %)
Total	51,200	73,300	35,500	200,700	593,000	157,800	23.5

All the emissions are in tons/year, except for CO_2 in million tons/year. Transport emissions include road, aviation, and port activities

Particulate emissions

In the greater Chennai region, PM_{10} emissions originated from diffused (area) sources such as vehicle exhaust (34 %), road dust (9 %), generator sets (1 %), domestic (4 %), and open waste burning (3 %), and the point sources such as power plants (12 %), industries (21 %), and brick kilns (7 %). In the greater Visakhapatnam region, PM_{10} emissions originated from diffused (area) sources such as vehicle exhaust (23 %), road dust (14 %), generator sets (1 %), domestic (2 %), and open waste burning (2 %), and the point sources such as power plants (36 %) and industries (14 %).

The estimated annual $PM_{2.5}$ emissions in 2012 in Chennai and Vishakhapatnam are 51,200 and 39,000 t. For comparison, 63,000 t of $PM_{2.5}$ emissions were estimated for Delhi in 2010 (Guttikunda and Calori 2013), and the total population of the Greater Chennai region is half and the Greater Vishakhapatnam region is one tenth of the Greater Delhi region.

Unlike the city of Delhi, where the transport sector is considered one of the primary emission sources, in Chennai and Vishakhapatnam, the power plants and the manufacturing industries dominate the PM emissions. The share of the road dust is among the least in $PM_{2.5}$ due to its coarser nature, and in general, the road dust resuspension is lower due to high humidity in the coastal air. The share of diesel generator sets is also lower due to the presence of large dedicated power plants within the city limits.

Gaseous emissions

The SO_2 emissions from the power plants (59 and 88 %) and industries (27 and 9 %) in Chennai and Vishakhapatnam, respectively, are the highest, due to their dependency on coal, and no desulfurization units in operation at the power plants (Guttikunda and Jawahar 2014). In Chennai, brick kilns contribute to 5 % of the total SO_2 emissions, followed by small contributions from the other sectors. The fuel used at the brick kilns varies from agricultural waste to fossil fuels like coal and bunker fuel oil from the shipyard.

For NO_x and CO emissions, diesel and biomass combustion account for major shares in the respective sectors and dominated by the vehicle exhaust emissions. In the transport sector, freight movement via heavy-duty and light-duty trucks

Table 5 Estimated particulate and gaseous pollutant emissions inventory for the Greater Vishakhapatnam region for the base year 2012

Category	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC	CO_2
Transport	11,600 (29 %)	13,600 (23 %)	600 (1 %)	67,400 (43 %)	94,700 (41 %)	38,900 (62 %)	3.1 (15 %)
Domestic	3,200 (8 %)	3,700 (6 %)	800 (1 %)	700 (1 %)	79,400 (34 %)	8,400 (13 %)	0.5 (2 %)
Open waste burning	850 (2 %)	1,200 (2 %)	100 (1 %)	350 (1 %)	4,900 (2 %)	450 (1 %)	0.1 (1 %)
Construction	400 (1 %)	1,750 (2 %)	50 (1 %)	500 (1 %)	600 (1 %)	50 (1 %)	0.1 (1 %)
Manufacturing industries	5,800 (14 %)	8,300 (14 %)	5,100 (9 %)	9,100 (5 %)	14,900 (6 %)	8,800 (14 %)	0.9 (4 %)
Power plants	15,500 (39 %)	21,000 (36 %)	49,000 (88 %)	68,400 (44 %)	25,700 (11 %)	2,500 (4 %)	15.6 (76 %)
Generator sets	350 (1 %)	400 (1 %)	100 (1 %)	7,300 (4 %)	7,600 (3 %)	2,850 (4 %)	0.5 (1 %)
Road dust	1,250 (3 %)	8,100 (14 %)					
Total	39,000	58,100	55,800	153,800	227,800	62,000	20.8

All the emissions are in tons/year, except for CO_2 in million tons/year. Transport emissions include road, aviation, and port activities

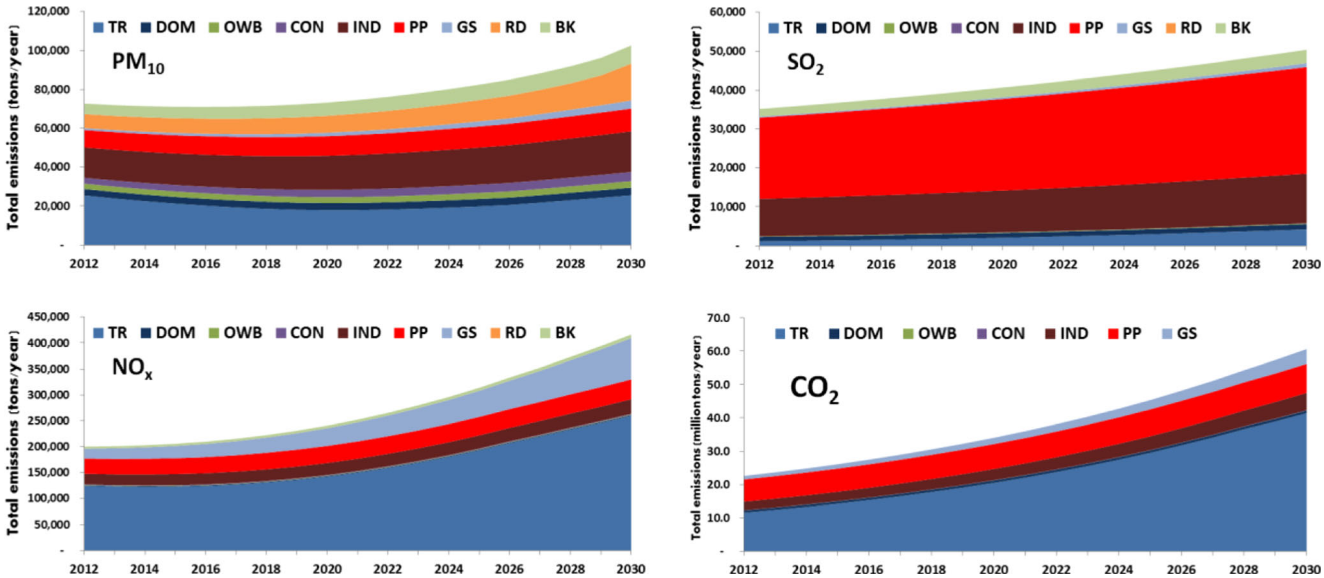

Fig. 3 Estimated emissions inventory for Chennai between 2012 and 2030 (*TR* vehicle exhaust; *DOM* domestic cooking and heating; *OWB* open waste burning; *IND* industries; *PP* power plants; *GS* generator sets; *RD* road dust; *BK* brick kilns)

(all running on diesel) is the largest contributor. Most of the freight movement is to and from the ports to the industrial estates and to the regional industrial hubs in South India. For NO_x emissions, vehicle exhaust accounts for 60 and 43 % in Chennai and Vishakhapatnam.

Gridded emissions inventory

The emissions inventory is maintained on a GIS platform and spatially disaggregated to a finer resolution of 0.01° (equivalent of 1 km) for further use in atmospheric dispersion modeling. We used spatial proxies to allocate the emissions from each sector to the grid, similar to the methodology utilized for Delhi and Hyderabad (Guttikunda and Calori 2013; Guttikunda and Kopakka 2014). In the case of the transport sector, we used grid-based population density, road density (defined as number of kilometers per grid), and commercial activity like industries, brick kilns, hotels, hospitals, apartment complexes, and markets to distribute emissions on feeder, arterial, and main roads. Separate weights were allocated for heavy-duty trucks plying on the highways, to and from the ports. Emissions from industries were allocated to the respective estates, and brick kiln emissions were directly assigned to their respective clusters. The domestic sector and garbage burning emissions are distributed based on the population density (GRUMP 2010; Census-India 2012).

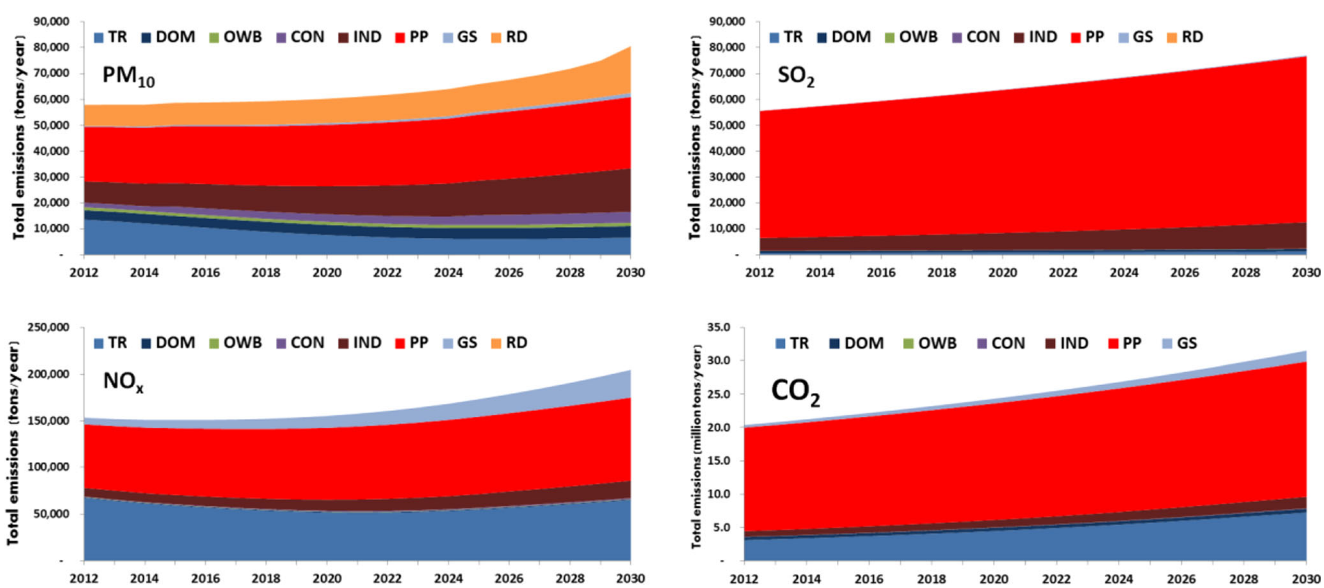

Fig. 4 Estimated emissions inventory for Vishakhapatnam between 2012 and 2030 (*TR* vehicle exhaust; *DOM* domestic cooking and heating; *OWB* open waste burning; *IND* industries; *PP* power plants; *GS* generator sets; *RD* road dust; *BK* brick kilns)

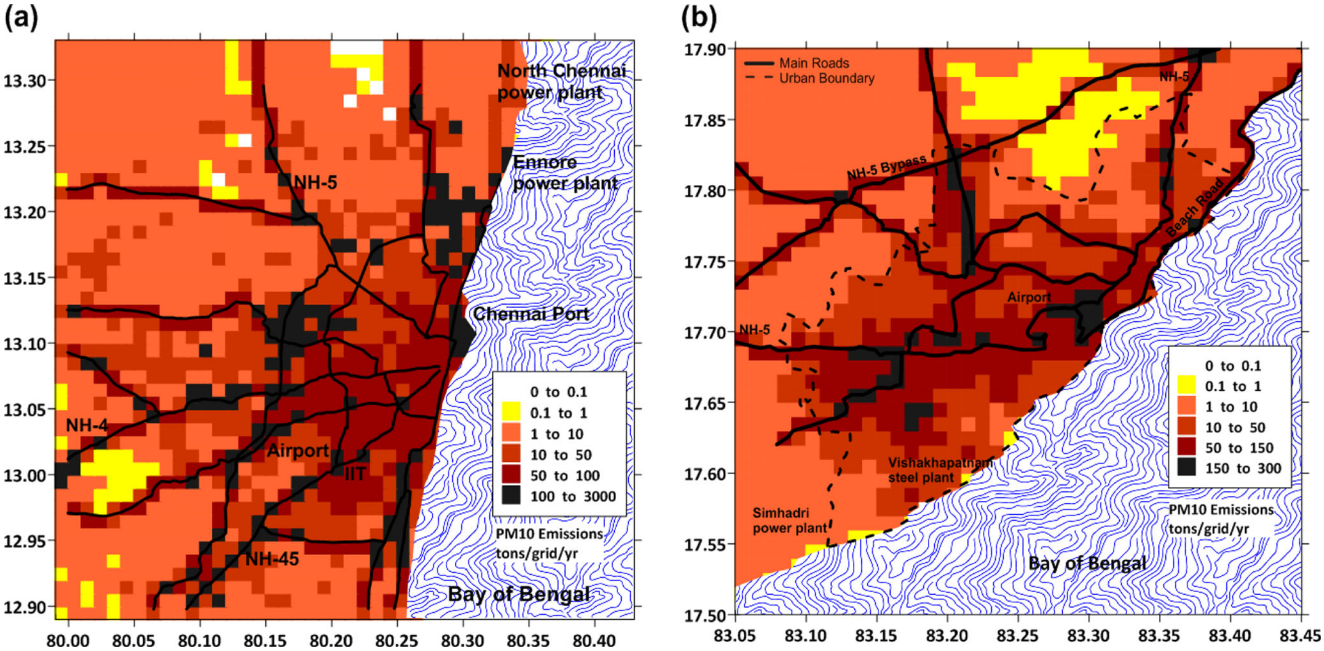

Fig. 5 Gridded PM_{10} emissions (total minus the large power plants) in **a** Chennai and **b** Vishakhapatnam for year 2012

Two panels of gridded PM_{10} emissions (in tons/year/grid) are presented in Fig. 5 for Chennai and Vishakhapatnam. In the case of vehicle exhaust, the highest density of emissions is observed along the major roads, highlighted by the traffic to and from the ports and the industrial estates. The gridded fields are also available for $PM_{2.5}$, SO_2, NO_x, CO, and VOC, in the format ready for use in urban and regional chemical transport models.

Modeled particulate pollution

The modeled annual average PM_{10} concentrations for Chennai and Vishakhapatnam for year 2012 are presented in Fig. 6. We limited the dispersion modeling to PM pollution, which includes both the primary PM contributions and the secondary contributions from SO_2 to sulfate aerosols and NO_x to nitrate aerosols. The primary PM emissions are modeled in two bins due to differential deposition and advection characteristics—coarse fraction comprises of PM_{10} to $PM_{2.5}$ mass and fine fraction comprises of everything less than $PM_{2.5}$ mass. All the secondary aerosols are considered as part of $PM_{2.5}$. For convenience and the availability of monitoring data, only PM_{10} concentrations are presented here. Annual and seasonal concentration maps are also available for $PM_{2.5}$ and SO_2.

The PM_{10} concentrations in the urban areas exceed the national annual standards. The concentrations in Fig. 6 are an

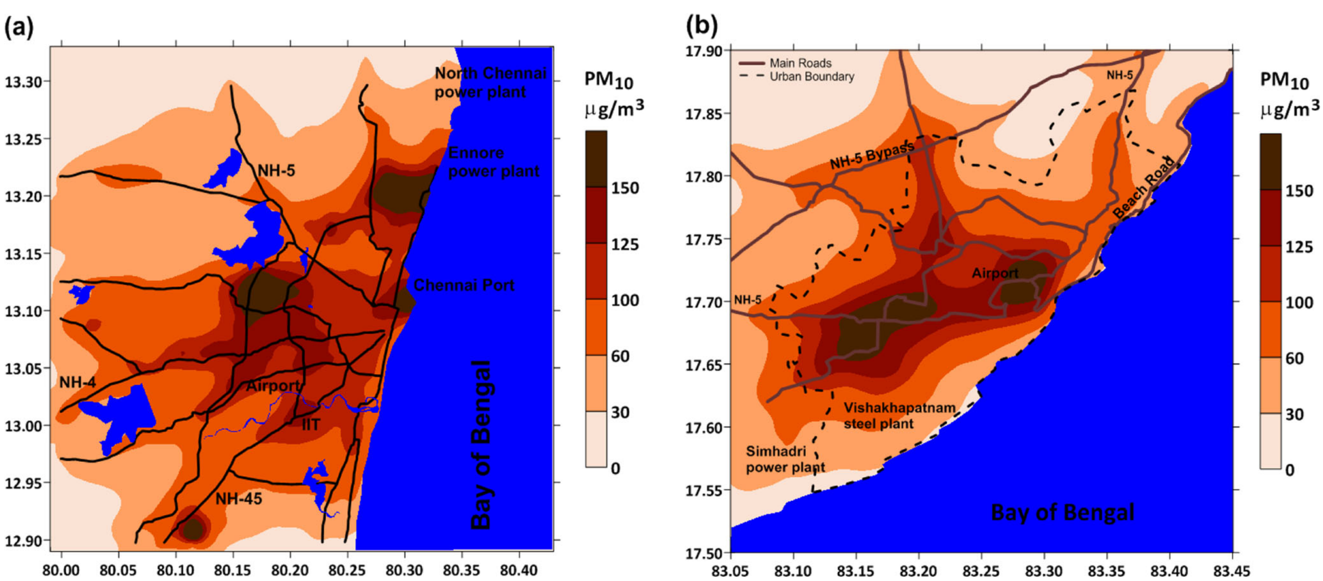

Fig. 6 Modeled annual average PM_{10} concentrations over **a** Chennai and **b** Vishakhapatnam for year 2012

average over 12 months (2012), which take into consideration the seasonal cycle of the emissions. For example, the brick kiln emissions are modeled only during the nonmonsoonal months, no emissions assigned during the heavy rainy period. Similarly, the road dust resuspension emissions are suppressed during the rains.

We compared the modeled concentrations against monitoring data from the NAMP stations in Chennai (Table 1) and Vishakhapatnam (Table 2). A comparison of monthly average PM_{10} concentrations is presented in Fig. 7. Over the urban areas of the modeling domains, the grid average modeled PM_{10} concentrations ranged 109.3±28.9 and 83.1±40.7 μg/m^3 and the monitoring data for 2012 ranged 121.5±45.5 and 70.4±29.7 μg/m^3 in Chennai and Vishakhapatnam, respectively. The seasonal pattern in the monitoring data is also captured in the modeled averages. The variation in the modeled data (Fig. 7) is spatial in nature, i.e., it represents the standard deviation in the monthly average concentrations over an area covering the urban parts of the city's. This was done to capture the representative average of concentrations in the city, given the variations in the spatial representation of the emissions and load of emissions. The station measurements are mostly representative of the surroundings of the monitoring location, which are located closer to the traffic junctions in the case of Chennai, thus tend to report higher numbers, and located away from the industrial estates in the case of Vishakhapatnam, thus underreporting their representative share in the ambient concentrations.

The dispersion modeling results capture the annual and seasonal variation in the PM_{10} concentrations. The qualitative comparison of the ranges of PM pollution also ascertains the emissions inventory estimation, spatial disaggregation to 1-km^2 grids, and dispersion model architecture, which captures primary and secondary PM contributions.

Of the total PM_{10} concentrations in Fig. 6, approximately 40 % in the urban areas are from secondary chemical reactions. A measurement campaign in the institutional area (near Anna University, Chennai) showed dominance of sulfate cations in PM_{10} and $PM_{2.5}$ samples (Srimuruganandam and Shiva Nagendra 2011), which, following the chemical mass balance modeling, resulted in estimated 43–52 % contribution from diesel exhaust, 6–16 % from gasoline exhaust, and the remaining originating from the road dust, cooking, and marine sea salt (Srimuruganandam and Shiva Nagendra 2012). These studies reported 77–98 μg/m^3 of PM_{10} and 56–74 μg/m^3 of $PM_{2.5}$ during the measurement campaigns.

We account for the uncertainties in measured and in modeled data to ensure that the emission estimates and the dispersion model are representative of the regional geography and meteorological conditions. Overall, the emissions inventory estimation and dispersion modeling has an uncertainty of ±20–30 %. Since the inventory is based on bottom-up activity data in the city and secondary information on emission factors, mostly from the studies conducted in India, Asia, and global databases, it is difficult to accurately measure the uncertainty in our estimates. In the transport sector, the largest margin is in vehicle-kilometers traveled and vehicle age distribution with an uncertainty of ±20 % for passenger, public, and freight transport vehicles. The silt loading, responsible for road dust resuspension, has an uncertainty of ±25 %, owing to continuing domestic construction and road maintenance works. In the brick manufacturing sector, the production rates, which we assumed constant per kiln, have an uncertainty of ±20 %. The data on fuel for cooking and heating in the domestic sector is based on national census surveys with an uncertainty of ±25 %. Though lower in total emissions, open waste burning along the roads and at the landfills has the largest uncertainty of ±50 %. The fuel consumption data for the in situ generator sets is obtained for random surveys to hotels, hospitals, large institutions, and apartment complexes, with an uncertainty of ±30 %. The fuel consumption data with the least uncertainty is from the power plants.

Sectoral contributions

Besides the total PM concentrations, the ATMoS dispersion model was applied at the sectoral level, where emissions from

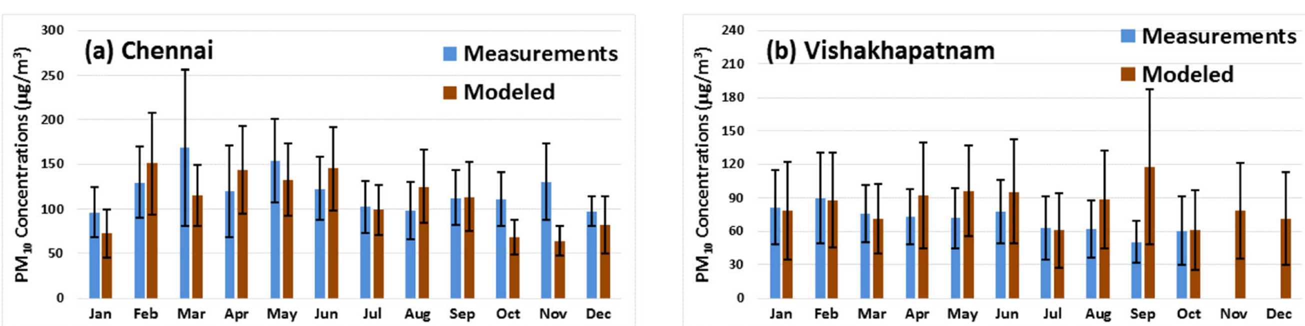

Fig. 7 Comparison of measured vs. modeled monthly average PM_{10} concentrations for **a** Chennai and **b** Vishakhapatnam. The variation in the measured data is the standard deviation for daily average measurements from all the stations in 2012, and the variation in the modeled data is the standard deviation in the monthly average concentrations for the urban grids (~350 each)

each sector are modeled independently and aggregated to obtain the percent contributions. For the urban area in each city, these contributions are extracted and presented in Fig. 8. Both the cities are industrial hubs with an average 21 and 15 % of the annual PM_{10} originating from the coal, diesel, and gas combustion at these boilers, followed by the coal combustion at the power plants contributing 3 and 7 % in Chennai and Vishakhapatnam, respectively. The power plants in Chennai are more coastally located than those in Vishakhapatnam, which is reflected in their share of contribution to the annual pollution. Also, being coastally located, their share to the annual PM pollution is limited due to the land-sea breeze, even though their total emissions are much larger than the vehicle exhaust and domestic cooking. The freight movement through the cities is among the highest in the country, and along with the industrial and the commercial activity in the cities, the contribution of the vehicle exhaust is the highest (37 and 36 %) in the urban parts.

The percentage contributions in Fig. 7 are for the designated urban municipality alone. Since most of the monitoring stations are located within the urban municipal boundary, the shares are extracted and presented for this region. These percentages vary significantly over the region. For example, to the west of urban Chennai, where the industrial hubs are located, the industrial emissions dominate the overall contributions, and similarly, farther west where the brick kilns are located (Fig. 1), their emissions dominate the local ambient concentrations, along with the vehicle exhaust, mostly shuttling the raw material to and from the kilns.

In the case of Vishakhapatnam, the urban region is split into two parts, the southern half is the industrial hub (dominated by steel plant, power plant, ship yard, and refinery), and it has a significant proportion of work force residing in close proximity. The northern half of the city contains the commercial and institutional hubs and a large residential zone. The rush hour traffic is prominently marked into the Southern hub in the morning and away from the Southern hub in the evening.

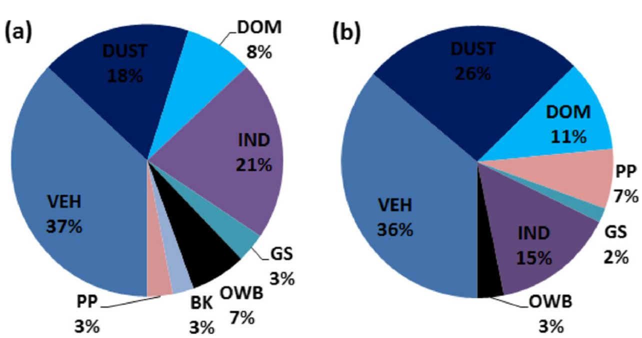

Fig. 8 Modeled source contributions to the annual average PM_{10} concentrations over **a** urban Chennai and **b** urban Vishakhapatnam for year 2012. *VEH* vehicle exhaust, *DOM* domestic cooking and heating, *OWB* open waste burning, *IND* industries, *PP* power plants, *GS* generator sets, *DUST* road and construction dust, *BK* brick kilns

The Ministry of Environment of Forests (New Delhi, India) and the Central Pollution Control Board (New Delhi, India) coordinated the particulate source apportionment study in six cities (CPCB 2010). For Chennai, the particulate sampling was conducted at seven sites—one background, two curbside, two residential, and two industrial. This study estimated the sector contributions to PM pollution in Chennai, which ranged from 35.1 to 48.3 % for vehicle exhaust, 6.3 to 27.0 % for road dust resuspension, 3.9 to 20.9 % for domestic sources, 13.8 to 15.6 % for diesel generator sets, 3.5 to 5.4 % for bakeries, and the remaining attributed to kerosene and coal. These results represent average estimates for filter samples from select monitoring sites in 2007, and the results are mostly representative of the 2–3-km radius of the monitoring location. Hence, collectively, these results can be interpreted as representative of the city, but knowledge about the spatial spread of emissions and concentrations is crucial to assessing sectoral contributions. The source apportionment study coordinated by the Asian Institute of Technology (Bangkok, Thailand) also highlighted vehicle exhaust and industry as the key sources in Chennai, for three seasons among the samples collected during 2001 and 2004 (Oanh et al. 2006).

Mortality and morbidity estimates

For the modeled $PM_{2.5}$ concentrations, we applied Eqs. (3) and (4) and estimated 4,850 and 1,250 premature deaths and 390,000 and 110,000 asthma attacks in year 2012, for the Greater Chennai and the Greater Vishakhapatnam regions, respectively. For comparison, Guttikunda and Goel (2013) estimated 7,350 to 16,200 premature deaths for Delhi in 2010. For cities similar in size, the estimated premature mortality in 2010 was 3,600 for Pune and 4,950 for Ahmedabad (Guttikunda and Jawahar 2012). For 2000, Gurjar et al. (2010) estimated 14,700 premature deaths for Dhaka, 14,100 for Cairo, 11,500 for Beijing, and 11,500 for Delhi.

Based on the current sectoral growth rates and emission projections presented in Fig. 3 for Chennai and Fig. 4 for Vishakhapatnam, the pollution levels are likely to remain the same (at the current high levels) or further increase if the expected changes in the industrial energy efficiency, environmental regulations in the power plants, and fuel standards for the vehicles are not introduced as planned. This will further increase the health impact estimates for the two cities.

Pollution management

Both the cities are industrialized and operate major ports. With less than half the population of Greater Delhi region, the Greater Chennai region has similar magnitude of total $PM_{2.5}$ emissions. However, there are large differences in the sectoral contributions. Chennai has more than twice the share of $PM_{2.5}$ from transport sector (39 %) compared to that in Delhi (17 %).

While the growth of private vehicles has occurred at a rapid rate, major contributors to road transport emissions were the freight vehicles, all running on diesel, to and from the ports. In such cases, emissions cannot be wholly attributed to city road transport usage alone, as most of the freight movement is regional or national in nature. This is also the case of Delhi where 75 % of all the freight goods that come to the city are redistributed to other parts of the country (mostly northern India).

Similarly, the total number of registered private vehicles (cars and 2Ws) in Chennai and Visakhapatnam is less than half and less than one tenth of those in Delhi, respectively. As a result, there is a large difference in sectoral distribution of pollutants which are associated with vehicular traffic—CO, VOC, and NO_x. In addition, unlike Delhi where some power plants are gas-based (and hence leading to more CO emissions), all the power plants in Chennai and Vishakhapatnam are coal-powered. Given the size of the cities, Visakhapatnam has a disproportionate share of electricity production plants. The greater Delhi region (80×80 km) has an installed capacity of 4,000 MW of power plants, while the greater Visakhapatnam region (40×40 km) has an installed capacity of 3,000 MW. While most power plants in and around Delhi cater to Delhi's demand, power plants in Visakhapatnam cater to regional demand through national grid.

Currently, most of the vehicles in Chennai and Visakhapatnam ply on petrol and diesel, and a few three-wheelers (3Ws) on LPG. With increasing vehicular emissions in Chennai, efforts were made to convert petrol-driven 3Ws to LPG for which Tamil Nadu Pollution Control Board provided a subsidy of INR 3,000 to owners. In addition, permits for new petrol and diesel 3Ws were banned, in order to promote LPG-based vehicles. However, due to lack of LPG filling stations in the city (less than 30 by 2012), most LPG 3Ws have shifted back to petrol or diesel. In a similar situation, in Delhi, during late 1990s, compressed natural gas (CNG) was made mandatory for taxis, 3Ws, and buses. However, due to insufficient supply of CNG in the city, a large number of public transport vehicles had to remain off the roads. This led to inconvenience to thousands of daily commuters, thus encouraging them to shift to private vehicles. Government-operated Municipal Transport Corporation of Chennai runs a fleet of 3,400 diesel-run buses in which the city plans to convert to CNG.

Vishakhapatnam sees its growth in industry, health, and tourism. Construction of the new port, petrochemical corridor, and a pharmaceutical city will lead to high industrial growth and some additional emissions. The 40-km bus rapid transport corridor is now functional and is expected to attract intense land use development alongside. The city also allocated land along this corridor for a health hub for the nearby districts. Land along the beach road has been earmarked for this purpose, and the development authority also has plans for a tourism hub, all of which are likely to increase the total emissions in the city. In addition to the BRT corridor, the city is developing designs for a metro network. The city will move from Bharat-III standard fuel to Bharat-IV in 2014–2015.

An integrated solid waste management program was started in Visakhapatnam in 2013, which includes garbage collection from residential areas and segregation into wet and dry garbage at the sorting facilities, where the former will be composted to manure. These measures are likely to reduce burden of land-fill sites and, thus, burning of solid waste in the residential areas. Given the large share of industries and power plants in both the cities and the limited number of point sources, the potential for improving the energy efficiency and reducing the total emissions and air pollution in the city is higher for these two sectors. For example, an immediate application of flue gas desulfurization at the power plants will result in reducing the SO_2 emissions by at least 50 % and 80 % in Chennai and Vishakhapatnam, respectively, and a subsequent reduction in the formation of secondary sulfate particulates.

Conclusions

The consolidated results from the emissions and the dispersion modeling provided a greater understanding of the spatial spread and the temporal trends in emissions and particulate pollution in the coastal cities of Chennai and Vishakhapatnam. Given the uncertainties, these results further emphasized the need for such integrated studies to support air quality management and to address policy-relevant questions like which sources to target.

In an effort to continuously improve the quality of the data, the emission inventory and activity datasets will be made available via the internet. The inconsistencies in the procedures, such as emission factors and spatial weights for gridding, will be corrected and supplemented with additional data as they become available in future research in Chennai and Vishakhapatnam. In this study, we presented the results for total PM pollution, a key criteria pollutant and often exceeding the national ambient standards. However, the emissions inventory includes ozone precursor pollutants (NO_x, VOCs, and black carbon) and their spatial and temporal disaggregation, suitable for photochemical transport modeling. We intend to extend the dispersion modeling analysis to total chemical transport modeling using models like CAMx to evaluate impacts of ozone on health and environment.

Acknowledgments We would like to acknowledge the partial support from the PURGE project (Public health impacts in urban environments of Greenhouse gas Emissions reductions strategies) funded by the European Commission by its 7th Framework Programme under the Grant Agreement No. 265325.

References

Annepu RK (2012) Sustainable solid waste management in India. Masters thesis, Earth Engineering Center, Columbia University, New York, USA

Arndt RL, Carmichael GR, Roorda JM (1998) Seasonal source: receptor relationships in Asia. Atmos Environ 32:1397–1406

Atkinson RW, Cohen A, Mehta S, Anderson HR (2011) Systematic review and meta-analysis of epidemiological time-series studies on outdoor air pollution and health in Asia. Air Qual Atmos Health 5: 383–391

Balakrishnan K, Ganguli B, Ghosh S, Sambandam S, Roy S, Chatterjee A (2013) A spatially disaggregated time-series analysis of the short-term effects of particulate matter exposure on mortality in Chennai, India. Air Qual Atmos Health 6:111–121

Calori G, Carmichael GR (1999) An urban trajectory model for sulfur in Asian megacities: model concepts and preliminary application. Atmos Environ 33:3109–3117

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

Chhabra SK, Chhabra P, Rajpal S, Gupta RK (2001) Ambient air pollution and chronic respiratory morbidity in Delhi. Arch Environ Health Int J 56:58–64

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

GAINS (2013) Greenhouse gas and air pollution interactions and synergies—South Asia program. International Institute of Applied Systems Analysis, Laxenburg

Goel R, Guttikunda SK, Mohan D, Tiwari G (2014) Benchmarking vehicle and passenger travel characteristics in Delhi for on-road emissions analysis, (submitted manuscript) transportation research and injury prevention programme. Indian Institute of Technology, New Delhi

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

Gupta SK, Gupta SC, Agarwal R, Sushma S, Agrawal SS, Saxena R (2007) A multicentric case-control study on the impact of air pollution on eyes in a metropolitan city of India. Indian J Occup Environ Med 11:37–40

Gurjar B, Van Aardenne J, Lelieveld J, Mohan M (2004) Emission estimates and trends (1990–2000) for megacity Delhi and implications. Atmos Environ 38:5663–5681

Gurjar BR, Jain A, Sharma A, Agarwal A, Gupta P, Nagpure AS, Lelieveld J (2010) Human health risks in megacities due to air pollution. Atmos Environ 44:4606–4613

Guttikunda SK, Calori G (2013) A GIS based emissions inventory at 1 km×1 km spatial resolution for air pollution analysis in Delhi, India. Atmos Environ 67:101–111

Guttikunda SK, Goel R (2013) Health impacts of particulate pollution in a megacity—Delhi, India. Environ Dev 6:8–20

Guttikunda SK, Jawahar P (2012) Application of SIM-air modeling tools to assess air quality in Indian cities. Atmos Environ 62:551–561

Guttikunda SK, Jawahar P (2014) Atmospheric emissions and pollution from the coal-fired thermal power plants in India. Atmos Environ 92:449–460

Guttikunda S, Kopakka R (2014) Source emissions and health impacts of urban air pollution in Hyderabad, India. Air Qual Atmos Health 7: 195–207

Guttikunda SK, Mohan D (2014) Re-fueling road transport for better air quality in India. Energy Policy 68:556–561

Guttikunda SK, Thongboonchoo N, Arndt RL, Calori G, Carmichael GR, Streets DG (2001) Sulfur deposition in Asia: seasonal behavior and contributions from various energy sectors. Water Air Soil Pollut 131:383–406

Hart JE, Garshick E, Dockery DW, Smith TJ, Ryan L, Laden F (2011) Long-term ambient multipollutant exposures and mortality. Am J Respir Crit Care Med 183:73–78

Holloway T, Levy Ii H, Carmichael G (2002) Transfer of reactive nitrogen in Asia: development and evaluation of a source–receptor model. Atmos Environ 36:4251–4264

IFMR (2013) Atlas of household energy consumption and expenditure in India, 2013th edn. The Institute for Financial Management and Research, Chennai

IHME (2013) The global burden of disease 2010: generating evidence and guiding policy. Institute for Health Metrics and Evaluation, Seattle

IPA (2013) Annual report. Indian Port Authority, the Government of India, New Delhi

Jahn HJ, Schneider A, Breitner S, Eißner R, Wendisch M, Krämer A (2011) Particulate matter pollution in the megacities of the Pearl River Delta, China—a systematic literature review and health risk assessment. Int J Hyg Environ Health 214:281–295

Kim Oanh N, Upadhyay N, Zhuang Y-H, Hao Z-P, Murthy D, Lestari P, Villarin J, Chengchua K, Co H, Dung N (2006) Particulate air pollution in six Asian cities: spatial and temporal distributions, and associated sources. Atmos Environ 40:3367–3380

Kupiainen K (2007) Road dust from pavement wear and traction sanding. Monographs of the boreal environment research, No. 26. Finnish Environmental Institute, Helsinki

Mohan M, Dagar L, Gurjar B (2007) Preparation and validation of gridded emission inventory of criteria air pollutants and identification of emission hotspots for megacity Delhi. Environ Monit Assess 130:323–339

Mohanraj R, Solaraj G, Dhanakumar S (2011) Fine particulate phase PAHs in ambient atmosphere of Chennai metropolitan city, India. Environ Sci Pollut Res 18:764–771

MoRTH (2013) Road transport yearbook 2011-12. Minister of Road Transport and Highways, the Government of India, New Delhi

NCEP (2013) National centers for environmental prediction. National Oceanic and Atmospheric Administration, Maryland

Pande JN, Bhatta N, Biswas D, Pandey RM, Ahluwalia G, Siddaramaiah NH, Khilnani GC (2002) Outdoor air pollution and emergency room visits at a hospital in Delhi. Indian J Chest Dis Allied Sci 44:9

Sahu SK, Beig G, Parkhi NS (2011) Emissions inventory of anthropogenic PM2.5 and PM10 in Delhi during commonwealth games 2010. Atmos Environ 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

Siddique S, Banerjee M, Ray M, Lahiri T (2010) Air pollution and its impact on lung function of children in Delhi, the capital city of India. Water Air Soil Pollut 212:89–100

Srimuruganandam B, Shiva Nagendra SM (2011) Characteristics of particulate matter and heterogeneous traffic in the urban area of India. Atmos Environ 45:3091–3102

Srimuruganandam B, Shiva Nagendra SM (2012) Source characterization of PM10 and PM2.5 mass using a chemical mass balance model at urban roadside. Sci Total Environ 433:8–19

USEPA et al (2006) Clearinghouse for inventories & emissions factors—AP 42, 5th edn. United States Environmental Protection Agency, Washington DC

Weyant C, Athalye V, Ragavan S, Rajarathnam U, Lalchandani D, Maithel S, Baum E, Bond TC (2014) Emissions from South Asian brick production. Environ Sci Technol 48:6477–6483

WHO (2014) Outdoor air pollution in the world cities. World Health Organization, Geneva