Urban Climate 27 (2019) 124–141

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Air pollution knowledge assessments (APnA) for 20 Indian cities

Sarath K. Guttikunda[a,b,*], Nishadh K.A.[b], Puja Jawahar[b]

[a] *Division of Atmospheric Sciences, Desert Research Institute, Reno, USA*
[b] *Urban Emissions, New Delhi, India*

ARTICLE INFO

Keywords:
$PM_{2.5}$
Particulate pollution
India
Emissions inventory
Dispersion modeling
WRF-CAM_x
Source apportionment

ABSTRACT

Delhi, with a population of 22 million (1.6% of national total) is one of the most polluted capital cities in the world. Nearly 50% of the published literature in India focus on air pollution in Delhi. However, air pollution impacts are not limited only to the capital city. Yet, there is little information and attempt to quantify these impacts for Tier 1 and 2 cities, even though they account for > 30% of India's population. To remedy this vacuum of information, the Air Pollution knowledge Assessments (APnA) city program deliberately focuses on 20 Indian cities, other than Delhi. We established baseline multi-pollutant high-resolution emissions inventory, after collating information from multiple resources detailed in this paper, which was used to estimate spatial concentrations of key pollutants across city's urban airshed using WRF-CAMx chemical transport modeling system. The inventory includes anthropogenic sources, such as transport (road, rail, ship, and aviation), large scale power generation (from coal, diesel, and gas power plants), small scale power generation (from diesel generator sets for household use, commercial use, and agricultural water pumping), small and medium scale industries, dust (road resuspension and construction), domestic (cooking, heating, and lighting), open waste burning, and open fires and non-anthropogenic sources, such as sea salt, dust storms, biogenic, and lightning. The emissions inventory is currently in use for 3-day advance air quality forecasting for public release on an on-going basis. Using meteorological parameters and big data like gridded speed maps from google, the emissions inventory is dynamically updated. The results from this research will be valuable to local and national policy makers - especially the information on source contributions to air pollution.

1. Introduction

That air pollution is a serious environmental health issue in India is not under debate. The global burden of disease assessments estimated 0.74 million and 1.1 million premature deaths in 1990 and 2016 due to outdoor $PM_{2.5}$ and ozone pollution and 0.99 million and 0.78 million premature deaths in 1990 and 2016 due to household (indoor) $PM_{2.5}$ pollution (GBD, 2018). In the monitoring database released by the World Health Organization (WHO) in April 2018 covering 100 countries for the period of 2011 and 2016, India has 14 of the top 15 cities with the worst $PM_{2.5}$ pollution. Among megacities of the world, Delhi tops the list for PM_{10} pollution (WHO, 2018). What is unclear however is the extent of the problem in India. The maps in Fig. 1 compares surface $PM_{2.5}$ pollution levels for 1998, 2010, and 2016 extracted from Van Donkelaar et al. (2016). These data were produced using a combination of satellite observations, global chemical transport model using global emission inventories, and available ground-based measurements. Of the 640 districts in India (as per 2011 Census), 27% exceed the current annual standard of 40 μg/m^3 in 1998, 45% and 63%

* Corresponding author at: Division of Atmospheric Sciences, Desert Research Institute, Reno, USA.
E-mail address: sarath-guttikunda@uiowa.edu (S.K. Guttikunda).

https://doi.org/10.1016/j.uclim.2018.11.005
Received 3 August 2018; Received in revised form 9 November 2018; Accepted 19 November 2018

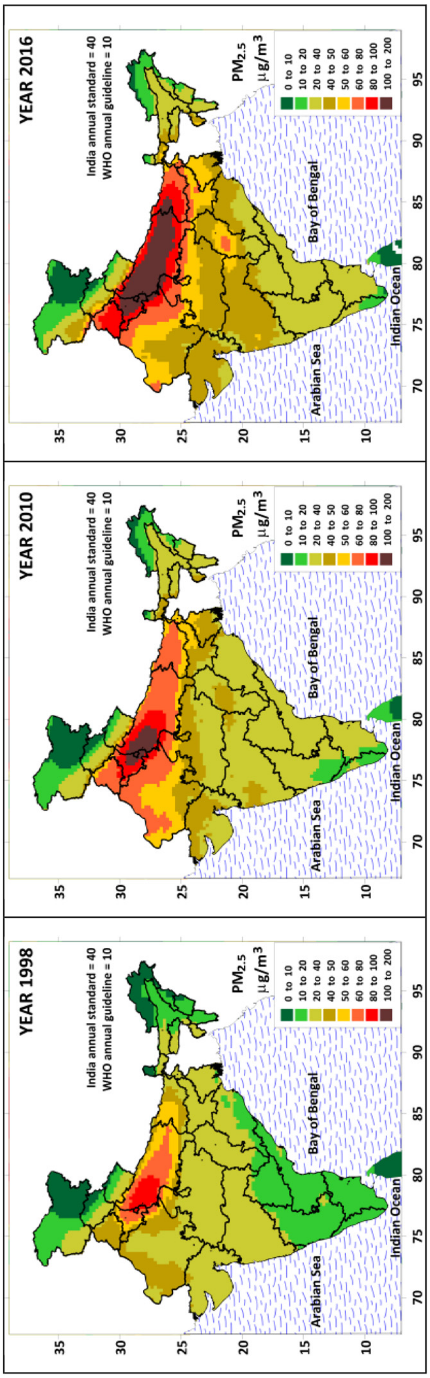

Fig. 1. Surface annual average $PM_{2.5}$ concentrations (in $\mu g/m^3$) for 1998, 2010, and 2016, based on satellite observations, global chemical transport model simulations using global emission inventories, and available ground-based measurements (Van Donkelaar et al., 2016).

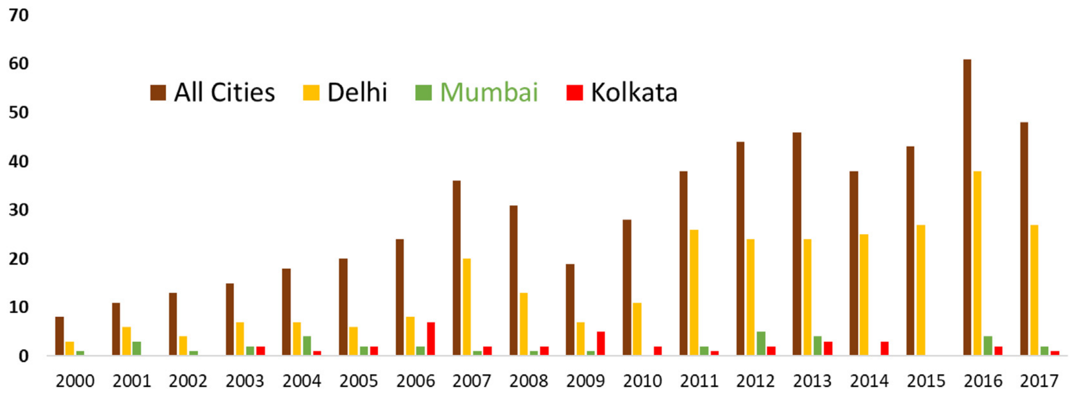

Fig. 2. Number of journal articles published between 2000 and 2017 (from SCOPUS search) with some reference to air pollution research in an Indian city.

exceed the same in 2010 and 2016. 99.5% of them exceed the WHO guideline of 10 μg/m^3 in 2016.

With urbanization, domestic migration is not only increasing population in the major metropolitan cities, but also in medium and small cities. These towns are adjusting their infrastructure needs, such as transport and waste management, to accommodate the growing population and economy. To take the air pollution policy debate further at the national scale, we need to move beyond anecdotal evidence, quantify and spatially map out pollution, and assess the impact of sources at the local scale (Guttikunda et al., 2014).

Big cities have some published studies that quantified source contributions, which led to some policy discussion (Pant and Harrison, 2012). The Central Pollution Control Board (CPCB, New Delhi, India) conducted a source apportionment study for six cities – Bengaluru, Chennai, Delhi, Kanpur, Mumbai, and Pune in 2006 (CPCB, 2011). It has been at least 12 years since CPCB has conducted any other source apportionment studies. There is very little information for other cities on ambient monitoring and source contributions. Of the number of scientific studies conducted to identify the sources of $PM_{2.5}$ and PM_{10} pollution via chemical analysis and receptor modeling since 2000, 70% repeatedly covered Delhi, Mumbai, Kolkata, Chennai, Hyderabad, and Agra (Guttikunda et al., 2014). We distilled relevant journal articles by conducting a full search on the SCOPUS database (title, abstract, and keywords) for all articles published between 2000 and 2017 for 50 Indian cities. This was done to get an idea of the state of research on topics related to air pollution - emission inventories, industrial studies, dispersion modeling, source apportionment, emission factors, and ambient monitoring. Accordingly, we collected 543 papers that mentioned at least one Indian city. Unsurprisingly, Delhi is the most studied city in India with 283 hits (> 50% of the total). Mumbai, the commercial capital of India and Kolkata, tied for a distant second with 35 hits each (Fig. 2). The trend in the number of publications is also an indication of the importance given to the air pollution problem in Delhi by the researchers, media, and national/international organizations.

Designing an effective air quality management plan for a city requires robust data on the sources of air pollution. The Air Pollution knowledge Assessments (APnA) city program is an attempt to fill the vacuum of information and by creating a baseline of air pollution related information for Indian cities, a necessary starting point for the policy makers, academic researchers, and citizens to chart out strategies for better air quality. We believe that establishing the baseline or quantifying the extent of the problem in cities other than the metropolitan cities is the starting point for change.

In this paper, we present our work on building these baselines for 20 Indian cities as (a) review of city characteristics such as ambient air quality, urban growth, census fields, geography, and meteorology (b) multi-pollutant emission inventory at 1-km resolution for the city airsheds and (c) WRF-CAMx chemical transport modeling to study trends and estimate source contributions to $PM_{2.5}$ and PM_{10} pollution.

2. City airsheds

For 20 Indian cities, we collated city geography and related characteristics as listed in Table 1. The list includes 2 megacities (Bengaluru and Chennai) with population above 10 million; 4 cities with population between 5 and 10 million (Chandigarh, Kanpur, Patna and Pune); 12 cities with population between 2 and 5 million; 2 cities (Dehradun and Ranchi) with population between 1 and 2 million. This list covers 13 states and 1 union territory (Chandigarh). These 20 cities host 90 million inhabitants (approximately 7.5% of national total) over an airshed of 44,000 sq.km (approximately 1.3% of national total). Table 2 catalogues a brief description of the selected cities.

The Supplementary resources include the Google KML files of individual city airsheds. For each city, on average 25% of airsheds area is designated as urban and extends beyond the political boundaries to include sources that may contribute to air pollution in the main city. 7 of 20 cities are on the Indo-Gangetic plain, the most polluted region in India (Fig. 1); 2 coastal cities with big commercial ports (Chennai and Kochi); 1 city in the hills (Dehradun); 14 North Indian cities and 6 South Indian cities.

For each airshed, we extracted built up area from Pesaresi et al. (2016) for 1975, 1990, 2000, and 2014 (Table 1). Fig. 3(a) offers a comparison of the built-up areas between 1990 and 2014 for 4 cities – Agra, Bengaluru, Chennai, and Patna. Remaining figures are

Table 1
List of cities included in the India APnA city program.

	City name	State name	Domain pop	Urban pop	Airshed grids	Airshed area	Urban area	Built-up area (sq.km)	
			million	%	# x * # y	sq.km	%	1975	2014
1	Agra	Uttar Pradesh	4.1	91%	40 × 40	2230	26%	18	107
2	Amritsar	Punjab	2.3	85%	40 × 40	2327	27%	65	119
3	Bengaluru	Karnataka	11.9	93%	60 × 60	4574	27%	147	631
4	Bhopal	Madhya Pradesh	2.7	97%	40 × 40	2157	26%	47	141
5	Bhubaneswar	Odisha	3.7	88%	30 × 50	1982	27%	17	118
6	Chandigarh	Chandigarh	5.0	85%	60 × 60	5176	27%	300	420
7	Chennai	Tamil Nadu	10.7	93%	50 × 50	3177	27%	108	522
8	Coimbatore	Tamil Nadu	3.0	88%	50 × 50	3156	19%	42	224
9	Dehradun	Uttarakhand	1.2	88%	40 × 20	1149	19%	18	59
10	Indore	Madhya Pradesh	3.1	93%	40 × 40	2150	28%	28	247
11	Jaipur	Rajasthan	4.8	94%	40 × 40	2223	28%	48	294
12	Kanpur	Uttar Pradesh	5.2	90%	40 × 30	1661	26%	25	190
13	Kochi	Kerala	3.9	94%	40 × 40	2012	26%	135	374
14	Ludhiana	Punjab	2.8	87%	40 × 40	2310	28%	122	233
15	Nagpur	Maharashtra	3.7	96%	40 × 40	2125	27%	123	240
16	Patna	Bihar	5.3	85%	60 × 30	2473	19%	22	85
17	Pune	Maharashtra	6.9	97%	40 × 40	2091	28%	46	280
18	Raipur	Chhattisgarh	3.2	87%	60 × 30	2390	19%	110	314
19	Ranchi	Jharkhand	1.9	87%	40 × 40	2159	22%	19	71
20	Varanasi	Uttar Pradesh	4.2	71%	40 × 40	2193	16%	37	100

Example - Airshed grids 60 × 30 denotes 60 longitudinal and 30 latitudinal grids at 0.01° resolution; Airshed area is the area covered by these 60 × 30 grids; Note - Built-up area for 1975 and 2014 are extracted from the global human settlement (GHS) layer of landsat imagery (Pesaresi et al., 2016); Gridded population is from GRUMP (2015) and Landscan (2013); Urban pop % = fraction of population in the grids designated as urban in the select airshed; Urban area % = fraction of grids designated as urban in the select airshed.

included in the Supplementary. Built up area on average increased by 200% between 1975 and 2000 and by 40% between 2000 and 2014. Chandigarh, one of the original planned cities, showed the least increase in built-up area, while cities with the largest percentage change are Bhubaneswar, Indore, Jaipur, Kanpur, and Pune.

3. Air quality monitoring

The CPCB and the State Pollution Control Boards (SPCBs) maintain and operate the national ambient monitoring programme (NAMP). This is the only official ambient monitoring database available in India since 1990. The monitoring network is slowly expanding. In 2015, there were 206 manual monitoring stations in 46 cities. As of May 2018, there are 700 manual stations and 117 continuous stations (33 stations are operating in Delhi). In September 2017, there were 74 continuous stations in operation – a 50% increase over 6 months. The continuous ambient monitoring stations report pollution levels for all the criteria pollutants every 15 min. This data is available in real time on CPCB's website.

The manual stations measure $PM_{2.5}$, PM_{10}, SO_2, and NO_2 and the procedure includes manually changing and collecting samples. While $PM_{2.5}$ as a criteria pollutant was introduced in 2009, it was only added as a pollutant to be measured at the manual stations in 2016. The Supplementary includes all available manual monitoring network data for the years between 2011 and 2015. For the manual stations, details on time of sample collection and time of filter change are unknown. Standard protocol suggests that at least 100 samples per station are required. In 2016, number of collection days for all stations averaged 94.2 for PM_{10}, 93.9 for SO_2, 94.6 for NO_2, and 71.3 for $PM_{2.5}$.

The WHO (2018) report utilized the data from both manual and continuous networks. Table 3 lists a summary of the data used in the WHO report. Of the 14 Indian cities in the top 15 most polluted cities, except for Delhi, Lucknow, and Agra, the remaining 11 cities – Kanpur, Faridabad, Varanasi, Gaya, Patna, Muzaffarpur, Srinagar, Gurgaon, Jaipur, Patiala, and Jodhpur, have one monitoring station each. A sample of one is not enough to know the true spatial and temporal trend of air pollution in any city.

Including Delhi, all the cities are operating less than the required number of monitoring stations to truly represent the mix of sources and activities in the city. Unlike cities in Europe and the United States, where vehicle exhaust is the main source of pollution, the range of sources in Indian cities is wide - from large and small industries to vehicle exhaust to road dust to biomass burning every day for cooking and heating. Using the CPCB's thumb rule (CPCB, 2003), which considers the total population of an airshed and the mix of activities, we estimate a need for 4000 continuous monitoring stations in India – 2800 in the urban areas and 1200 in the rural areas, to represent a population of 1.3 billion. These details at the state and the district level are presented in the Supplementary. For example, Uttar Pradesh with a population of over 200 million requires 558 stations and Delhi with a population of over 20 million requires 77.

Table 4 is a summary of the available ambient monitoring data and the number of manual and continuous monitoring stations operational in 20 Indian cities from this study. Air monitoring capacity is low in all the cities. As of May 2018, 6 of 20 cities do not have any continuous monitoring stations; 11 cities have only one continuous monitoring station. Bengaluru added 5 new continuous

Table 2
General description of the cities included in the India APnA city program.

	City	Description
1	Agra	On the banks of river Yamuna, the city is known for the Taj Mahal – a UNESCO World Heritage site, which attracts at least 8 million tourists every year. Agra's economy is made up of a thriving small-scale industry sector connected to handicrafts, leather goods, and iron foundries, tourism, and agriculture. The delicate inlay and carving work in white marble of the Taj Mahal started getting affected by the rising air pollution levels. In 2000, the Supreme Court mandated a 50-km safe-zone known as the "Taj Trapezium Zone" (TTZ) – which will be free of polluting industry and fueled vehicles. This has had scant impact on the pollution levels in the city, as Agra ranked 4th most polluted in 2016.
2	Amritsar	City is home to the Golden Temple (the spiritual center for the Sikh community) and lies on the Grand Trunk road (GT Road) from Delhi to Lahore in Pakistan. The temple visitors frequently take inter-city buses contributing to the day to day commercial and transportation activities in the city. Within the city, majority of the short trips are covered by rickshaws, auto rickshaws, and taxis. Amritsar's economy is made up of tourism, carpets and fabrics, farm produce, handicrafts, service trades, and light engineering. Coupled with small and heavy vehicles plying along the GT Road, vehicle exhaust and road resuspended dust has become a major source of air pollution in the city, especially due to 50,000 unregistered autorickshaws and double that of the registered ones. A majority of these use petrol mixed with kerosene.
3	Bengaluru	Bengaluru (formerly Bangalore), the capital of Karnataka was a pioneer in that it was one of the first information technology (IT) hubs of India. What was once a laid-back retiree town, is now a bustling metropolis with 10+ million inhabitants. The population grew exponentially from 1980s with several companies, especially IT industry, establishing base in the city, creating higher demand for transport and construction. The unplanned growth in the city boosted the infrastructure activities that the municipality attempted to ease by constructing a flyover system and by imposing one-way traffic systems, which were unable to adequately address the on-road issues and associated increase in air pollution. As the demand for housing has grown, the city finds itself spreading beyond its erstwhile boundaries to accommodate it.
4	Bhopal	Bhopal, the capital of Madhya Pradesh, has been selected under National Smart Cities program's first round for integrated urban development. The old city of Bhopal is home for small and medium industries covering electrical goods, medicinal products, cotton, chemicals, jewelry, flour milling, cloth weaving, painting, matches manufacturing, wax manufacturing, and sporting equipment. It also houses the Bharath Heavy Electricals Limited (BHEL), which is one of the largest engineering companies in India that manufactures coal-fired power plant boilers (among many other heavy machinery). Mandideep, another industrial suburb to the south of the city, is the largest industrial area in Madhya Pradesh. Bhopal is also synonymous with the Union Carbide Bhopal Disaster in the early 1980s.
5	Bhubaneswar	Cuttack was replaced by Bhubaneswar as the capital of Odisha (formerly Orissa) in 1949 and is one of the first planned cities in India, along with Jamshedpur and Chandigarh. Together they are referred to as the twin cities of Odisha. The city lies on the banks of Mahanadi river and between the naturally rich plains of Daya river and Kuakhai Rivers. As a tier-2 city, it is emerging as a center for education and IT. With increasing population, construction activity, and transport demand and limited waste management options, air pollution is reaching critical levels, even in the summer months.
6	Chandigarh	Chandigarh is a union territory that serves as the capital for the states of Haryana (on the east) and Punjab (on the north, west and south). Chandigarh airshed includes Patiala and Ambala, all within a 30 km radius of each other. Chandigarh, was one of the first planned cities in India and is known for its urban design, by Swiss architect Lr Corbusier, and sometimes referred to as "Pensioner's Paradise". There are 15 medium to large industries and over 2500 smaller units manufacturing paper, basic metals and alloys, machinery, food products, sanitary ware, auto parts, machine tools, pharmaceuticals, and electrical appliances.
7	Chennai	As the capital city of Tamil Nadu, Chennai is one of four metropolitan cities of India with 10+ million inhabitants. With its proximity to the Bay of Bengal and thus access to markets in East Asia, it is also an important port city. Apart from trade and shipping, the automobile industry (30% of India's auto industry), chemical and petrochemical industry, software services, medical care, and manufacturing form the foundation of the economic base for Chennai. The Ennore Port, the first major corporate port with an annual capacity of 30 million tons of cargo in 2012–2013, 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.
8	Coimbatore	After Chennai, Coimbatore is the second largest city in Tamil Nadu, located on Noyyal river bank and surrounded by the Western Ghats, houses > 25,000 small, medium and large industries covering textile and cotton industry, manufacturing, poultry farming, education, IT, and health care.
9	Dehradun	Dehradun, is the capital of Uttarakhand, carved out of the state of Uttar Pradesh in 2000. The city capital lies in the Doon Valley, in the foothills of the Himalayas, between the river Ganges on the east and the river Yamuna on the west. The city was developed as a getaway from the hot summers of the plains and hosts several institutions such as the Indian Military Academy (IMA), ITBP Academy, Indira Gandhi National Forest Academy (IGNFA), Zoological Survey of India (ZSI), Forest Research Institute (FRI) among several others. Construction and transport are the fastest growing sectors in the region. The geographical and meteorological conditions do not allow for easy dispersal of emissions.
10	Indore	Indore is 200 km from Bhopal, is the largest city and the commercial center in the state of Madhya Pradesh and part of the 100 smart cities program in India. A network of national and state highways through the city (NH3 to Agra and Bombay; NH59 to Ahmedabad and Betul; SH27 to Burhanpur; and SH34 to Jhansi) made it an important transport and logistics hub in the country. Major industrial areas are in Pithampur and Sanwer special economic zones focusing on soybean processing, automobile, IT, and pharmaceuticals.
11	Jaipur	As the state capital of Rajasthan, Jaipur is located 260 km from New Delhi and forms a part of a popular tourist circuit with Agra (240 km). Jaipur also serves as a gateway to other tourist destinations in Rajasthan such as Jodhpur, Jaisalmer, Udaipur, and Mount Abu. City is an educational and administrative center and its economy is fueled by tourism, gemstone cutting for jewelry, luxury textiles, and IT. During winter months, flights towards New Delhi airport are often diverted to Jaipur airport under foggy conditions. Another telling statistic that illustrates the level of traffic congestion in Jaipur is that 60% of the city roads are used for parking – the highest in any city in India (CSE, 2017).
12	Kanpur	Kanpur is one of the largest industrial towns in North India, on the Indo-Gangetic plain, and the largest city in the state of Uttar Pradesh. Kanpur supports the largest textile and leather processing sectors in the region. Kanpur briefly attempted to put in place a public-private partnership system for solid waste management, which after failing led to one of the major causes of air, water, and waste management issues in the city. In 2011, CPCB's assessment of air pollution in six cities (Delhi, Mumbai, Kanpur, Pune, Chennai and Bangalore) reported that air pollution sources in Kanpur are industries (biggest cause) followed by open waste burning, vehicles, road dust, and domestic cooking (CPCB, 2011).
13	Kochi	

(*continued on next page*)

Table 2 (*continued*)

	City	Description
		Kochi in the state of Kerala is an important port town and houses the Southern Naval Command of the armed forces, the largest international container trans-shipment terminal in India (the Cochin shipyard), and the offshore mooring of the Bharath Petroleum Corporation Limited (BPCL). It is also an important chemical industrial and manufacturing hub and an emerging IT center in Kerala.
14	Ludhiana	Ludhiana is an agricultural and industrial town in Punjab housing several small scale industrial units producing auto parts, appliances, machine parts, and apparel. The city has been on the most polluted list, drawn by WHO for multiple years. The distributed industries, generator use, agriculture burning, adulterated fuel for three-wheelers and adverse meteorological conditions (in the winter months), and open field burning (post-harvest season before the winter months) are responsible for its bad air quality.
15	Nagpur	Nagpur holds the distinction of being the geographical center of the Indian peninsula. Nagpur lies on the Deccan plateau and is the 3rd largest city and a major commercial and political center of the state of Maharashtra. Agriculture (in particular oranges and ayurvedic medicine processing) forms a large share of its economy, along with IT, manufacturing, transport systems, and mining. Due to its proximity to the coal belt in Central India, power generation from coal is large (47% of state's power is generated around Nagpur). The government is investing in Nagpur's infrastructure development to make it a freight movement hub.
16	Patna	As the state capital of Bihar, Patna with 72 wards is the largest in the state, located on the banks of rich Indo-Gangetic plain, and is among the states with the highest population density. The city economics is supported by agricultural activities (> 30% is rice), small scale manufacturing industries (including brick kilns, pulses, shoes, scooters, masur, chasra, electrical goods, and cotton yarn), and power generation (3000 MW power plant 100 km west of the city).
17	Pune	Once referred to as a city for students and retirees, Pune has now established manufacturing, glass, sugar, and metal forging industries, and more recently IT and auto industry. The Hinjewadi IT Park (located west of the Pimpri Chinchwad satellite city) is a project started by Maharashtra Industrial Development Corporation and Magarpatta city under a special economic zone scheme to the east has over 20,000 inhabitants, mostly working on IT. Construction of townships and developments mean that raw material from stone quarries, river sand and bricks are in constant demand. Fugitive dust emissions from the quarrying process, use of diesel for power generation in the commercial and industrial sectors, vehicle exhaust of heavy duty trucks moving in and out of the quarries, brick kiln clusters, and manufacturing industries is on the rise.
18	Raipur	In Chhattisgarh, Raipur-Durg-Bhilai (RDB) tri-city area hosts the new administrative capital of the state, interconnected by an expressway forming the industrial corridor, and located on the banks of the Mahanadi River. RDB is the largest steel manufacturing hub in India and is home to several foundries, metal-alloy plants, steel casting and rolling, sponge iron plants, cement production, and a large chemical (formalin) manufacturing plant. Bhilai Steel plant is the largest integrated steel plant in India. Most of the electricity generation at the power and the steel plants is coal-based. While Durg-Bhilai are largely industrial, Raipur has emerged as the commercial hub. Naya Raipur (New Raipur) is a satellite city located 17 km away from Raipur covering 8000 ha is expected to house 450,000 inhabitants.
19	Ranchi	Ranchi is the state capital of Jharkhand (the state was formed in 2000) and is part of the smart cities program in India. Much of the city's economy is driven by processing industry based on resources from the forests of Jharkhand. These include timber, matches, rayon, medicinal plants and seeds. It is a relatively small city, but from the time the state was formed in 2000, the number of vehicles in the city has increased 20 times. With an increase in population – this erstwhile hill station is now dealing with haphazard construction and insufficient systems for solid waste management leading to open burning.
20	Varanasi	Formerly Banaras, Varanasi lies on the banks of the Ganges river in Uttar Pradesh and is center for pilgrimage and tourism in India (~3 million domestic and 200,000 visitors annually). This puts a significant burden on city's solid waste management infrastructure, with much of the waste either burnt or dumped in landfills or in the river). City is famous for several handcrafted goods such as muslin and silk fabrics, perfumes, ivory works, and sculpture, diesel locomotive works, and Bharat Heavy Electricals Ltd.

monitoring stations in 2018, bringing their total to 10, which is 25% of the recommended capacity to represent approximately 11.9 million inhabitants.

All cities exceed the annual PM_{10} standard of 60 μg/m^3. Major sources of PM_{10} include combustion of coal, kerosene, petrol, diesel, biomass, cow dung, and waste as well as dust. Coimbatore reported just above the standard. 6 cities - Agra, Bengaluru, Jaipur, Kanpur, Ludhiana, and Raipur, recorded 4–6 times the annual standard. These are among the fastest growing Indian cities, traditionally known to be dusty due to a lot of construction activities and dust on the roads which is resuspended when vehicles pass.

All cities comply with the annual SO_2 standard of 50 μg/m^3. Major sources of SO_2 include combustion of coal and diesel. Bengaluru, Chennai, and Pune (most populated of the 20) recorded the highest SO_2 concentrations, indicating higher consumption of diesel in personal vehicles, freight vehicles, and diesel generator sets.

9 of 20 cities exceed the annual NO_2 standard of 40 μg/m^3. Major sources of NO_2 include combustion of petrol, diesel, and gas (i.e., transport related emissions) and large industries. Bengaluru, Chennai, Jaipur, Nagpur, Kanpur, and Pune record the highest concentrations.

Satellite observations coupled with global model simulations provide a useful baseline to monitor progress and validation (van Donkelaar et al., 2016). Table 3 lists data extracted for years 1998 and 2016. Refer to the Supplementary for data for all years in between and all 640 districts. These methodologies are an integral part of the global burden of disease estimates for outdoor and indoor air pollution (Brauer et al., 2016; GBD, 2018; Shaddick et al., 2018) and the premature death due to outdoor $PM_{2.5}$ estimates published by WHO (WHO, 2016). The model estimates underrepresent the pollution levels due to a mix of unknowns, such as model grid resolution, uncertainties in the emission inventories, lack of enough ground-based measurements to corelate with the satellite observations. Of the 20, only 5 cities show concentrations under the national ambient standard of 40 μg/m^3 – Chennai and Kochi are coastal cities and Bhubaneswar close to the coast, with the advantage of land-sea breeze that disperses most of the emissions from the industries, vehicles, and ports; Bengaluru and Coimbatore, also in South India have the advantage of strong winds to disperse most of the emissions. North India is landlocked, has a greater population density and a higher concentration of settlements. As a result, along with meteorological factors, there is an increase of 50–100% in their ambient $PM_{2.5}$ pollution levels between 1998 and 2016.

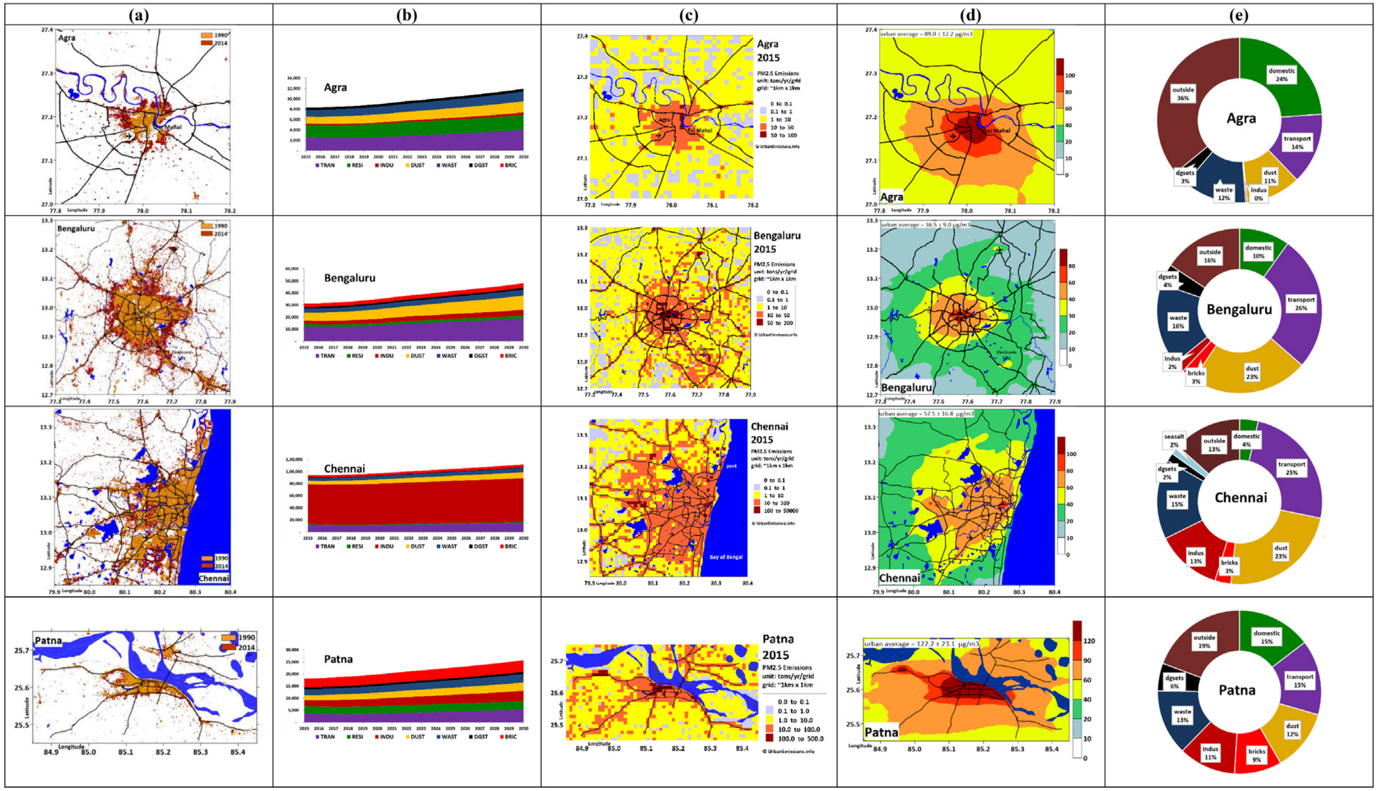

Fig. 3. Results for 4 out of 20 cities (a) Urban built-up area between 1990 and 2014 (b) Annual $PM_{2.5}$ emissions (in tons/year) between 2015 and 2030 under the business as usual scenario (RESI = cooking, heating, and lighting; TRAN = road, rail, shipping, for 20 Indian cities in 2015 brick kilns and including thermal power plants; WAST = open waste burning; DGST = diesel generator sets; BRIC = brick kilns in the selected airshed) (c) Gridded annual $PM_{2.5}$ emissions (in tons/year/grid) in 2015 (d) Modeled annual average $PM_{2.5}$ concentrations (in μg/m^3) in 2015 and (e) Modeled annual source contributions to $PM_{2.5}$ in 2015 (outside is the contribution of boundary conditions, representing the influence of regional sources). All the figures for 20 Indian cities are included in the Supplementary.

Table 3
Breakdown of the $PM_{2.5}$ concentrations data presented in WHO (2018).

Number of cities with measured $PM_{2.5}$	33
Number of cities with measured + converted $PM_{2.5}$	135
Average $PM_{2.5}$ for cities with measured concentrations	84.2 ± 46.2 μg/m^3
Average $PM_{2.5}$ for cities with converted concentrations	53.5 ± 30.4 μg/m^3
National annual ambient standard for $PM_{2.5}$	40 μg/m^3
World Health Organization annual guideline for $PM_{2.5}$	10 μg/m^3
Number of cities with 1 station only for $PM_{2.5}$ measurements	23
Number of cities with 1,2,3 stations for converted $PM_{2.5}$	30,28,33
Number of cities with 4+ stations for converted $PM_{2.5}$	7
Year of data reported for $PM_{2.5}$ measurements (number of cities)	2016(33)
Year of data reported for converted $PM_{2.5}$ (number of cities)	2011 (1), 2012 (97), 2013 (1), 2014 (1), 2015 (2)

Table 4
Number of operational stations (as of May 2018), number of minimum stations required, annual average $PM_{2.5}$, PM_{10}, SO_2, and NO_2 concentrations (in μg/m^3), and modeled surface $PM_{2.5}$ concentrations from Fig. 1, in the 20 cities under the APnA city program.

		Monitoring stations			2011–2015 manual			2015–2017 continuous	$PM_{2.5}$ from Fig. 1	
	City name	Man.	Cont.	Reco.	PM_{10}	NO_2	SO_2	$PM_{2.5}$	1998	2016
1	Agra	6	1	23	362.2 ± 193.1	43.9 ± 22.1	9.3 ± 5.4	98.6 ± 86.1	77.1	116.9
2	Amritsar	3	1	18	195.6 ± 44.9	38.9 ± 7.6	13.8 ± 2.6	65.9 ± 64.8	41.5	79.1
3	Bengaluru	16	10	41	302.5 ± 208.0	69.2 ± 44.0	30.9 ± 23.5	32.3 ± 24.2	19.7	28.9
4	Bhopal	5	1	18	196.3 ± 117.3	23.2 ± 16.9	2.9 ± 2.5	47.8 ± 35.1	31.7	56.5
5	Bhubaneswar	5	0	22	128.0 ± 102.7	26.9 ± 17.2	3.0 ± 1.5		17.1	37.9
6	Chandigarh	5	1	27	226.9 ± 103.6	44.3 ± 32.4	4.0 ± 1.9	59.4 ± 62.7	44.8	78.7
7	Chennai	11	3	38	199.8 ± 101.5	65.5 ± 37.1	39.7 ± 31.8	47.7 ± 73.7	17.6	32.6
8	Coimbatore	3	0	19	62.5 ± 39.7	26.9 ± 15.3	4.0 ± 1.7		14.1	26.0
9	Dehradun	3	0	13	170.3 ± 53.8	26.3 ± 8.0	23.9 ± 7.3		53.5	87.4
10	Indore	3	1	20	139.2 ± 69.8	18.9 ± 3.9	11.3 ± 3.7	40.4 ± 23.1	27.7	46.1
11	Jaipur	6	3	26	313.9 ± 141.3	79.8 ± 25.3	14.5 ± 7.5	70.4 ± 76.8	43.1	68.3
12	Kanpur	8	1	27	421.1 ± 188.5	70.7 ± 32.0	14.0 ± 11.7	111.4 ± 79.7	69.7	106.6
13	Kochi	7	0	23	221.6 ± 167.0	38.4 ± 30.5	10.7 ± 10.6		13.9	26.1
14	Ludhiana	4	1	20	335.0 ± 149.6	48.0 ± 14.4	18.7 ± 6.0	74.4 ± 46.1	44.9	83.9
15	Nagpur	7	1	22	192.1 ± 112.5	64.7 ± 36.0	20.7 ± 18.8	53.9 ± 26.7	28.4	47.3
16	Patna	2	1	26	162.5 ± 91.7	33.0 ± 24.3	4.6 ± 5.0	121.3 ± 89.5	52.1	90.8
17	Pune	4	1	30	162.2 ± 104.3	82.5 ± 45.0	40.3 ± 20.9	43.1 ± 25.7	30.9	47.5
18	Raipur	2	0	19	275.2 ± 81.0	35.3 ± 13.3	12.9 ± 5.0		29.6	54.6
19	Ranchi	1	0	16	190.1 ± 52.3	35.1 ± 5.4	18.3 ± 2.0		32.5	55.6
20	Varanasi	2	1	23	139.3 ± 15.9	26.2 ± 6.7	18.4 ± 2.5	106.2 ± 83.4	51.7	94.0

Note: Man. = manually operated stations where filter papers are collected 2 times per week on average; Cont. = continuous ambient monitoring stations reporting data every 15 min; Reco. = recommended number of continuous monitoring stations for the city.

4. Urban emission inventories

4.1. Methods and data

We built an emissions inventory for each of the 20 cities for year 2015 for the following pollutants – particulate matter (PM) in four classes (a) PM_{10} (b) $PM_{2.5}$ (c) black carbon (BC) and (d) organic carbon (OC), SO_2, nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), and carbon dioxide (CO_2). We also projected the emission loads to year 2030 under a business as usual scenario after accounting for policy interventions already under implementation (e.g. accelerated introduction of liquified petroleum gas (LPG) for cooking). The emissions inventory developed under the APnA programme is the first of its kind for most of them. The main challenge is that useful and formatted data necessary to build an emissions inventory is hard to come by. We thus accessed data from a wide array of sources for each sector.

We built the emissions inventory at a resolution of 0.01° (approximately 1-km). This includes anthropogenic sources, such as transport (road, rail, ship, and aviation), large scale power generation (from coal, diesel, and gas power plants), small scale power generation (from diesel generator sets for household use, commercial use, and agricultural water pumping), small and medium scale industries, dust (road resuspension and construction), domestic (cooking, heating, and lighting), open waste burning, and open fires and non-anthropogenic sources, such as (where relevant) sea salt, dust storms, biogenic, and lightning. Using geospatial platforms, the inventory is formatted such that it can be used for urban and regional chemical transport modeling.

We use the SIM-air (Simple Interactive Models for better air quality) family of tools to estimate total emissions. This is a function of fuel burnt which is then converted to emission loads using relevant emission factors. We used the same methodology for similar projects for 10 Indian cities – Pune, Chennai, Ahmedabad, Indore, Surat, Rajkot, Hyderabad, Chennai, Vishakhapatnam, and Delhi

(Guttikunda and Jawahar, 2012; Guttikunda and Calori, 2013; Guttikunda and Kopakka, 2014; Guttikunda et al., 2014); national transport sector (Guttikunda and Mohan, 2014); national power plant sector (Guttikunda and Jawahar, 2014); and Delhi transport sector (Goel and Guttikunda, 2015). We used multiple sources to collate a library of emission factors for transport, industrial, and domestic sectors (CPCB, 2011; Pandey et al., 2014; Sadavarte and Venkataraman, 2014; IIASA, 2015; Goel and Guttikunda, 2015; Sakar et al., 2016). For this purpose, we documented and digitized information available from the annual reports, maps, and databases such as census and ambient measurements. A copy of the India specific emission factors for all the sectors from IIASA (2015), by fuel and by activity, is available online (registration required).

Data to build the emissions inventory includes;

- Static Data - CPCB, state PCBs, Census Bureau, Niti Aayog, National Sample Survey Office (NSSO), Ministry of Road Transport and Highways (MoRTH), Society of Indian Automobiles Manufacturers (SIAM), Directorate general of Civil Aviation (DGCA), Ministry of Petroleum and Natural Gas (MoPNG), Ministry of Statistics and Program Implementation, Annual Survey of Industries (ASI), Central Electrical Authority (CEA), National Power Program (NPP), Cement Manufacturers Association (CMA), and Municipalities.
- Dynamic inputs - NASA satellite feeds on open fires, dust events, and lightning, 3D meteorological feeds processed through Weather Research and Forecasting (WRF) model, traffic speed maps (a paid service from google), weekday and weekend profiles for transport sector (pre-decided based on speed profiles), power demand and consumption rates from the load dispatch centers, and annual/seasonal reports from various sectors listed above.
- Monitoring data: monitoring data from official and unofficial networks to evaluate model performance.
- Google: We used a paid API service from Google to map various establishments in the city – hotels, hospitals, restaurants, bus stops, train stops, traffic lights, fuel stations, cinema halls, residential complexes, institutions, banks, bars, cafes, worship places, funeral homes, markets, and parks. We then used the data as layers to spatially allocate estimated total emissions to 1-km x 1-km grids.

A detailed list of these resources is available @ India-APnA (2017). Table 5 summarizes resources and methodologies applied by sector. We did not conduct any primary surveys in any of the cities. Table 6 lists the key statistics used to create the emissions inventory.

4.2. Urban emissions inventory

Table 7 is a summary of the emissions inventory for the 20 urban airsheds in India. Projections to 2030 under the business as usual scenario are influenced by the city's social, economic, landuse, urban, and industrial layout and hence the projected (increasing and decreasing) rates that we assume in this study are an estimate only. We based the vehicle growth rate on the sales projection numbers from SIAM; industrial growth on the gross domestic product of the state; domestic sector, construction activities, brick demand, diesel usage in the generator sets, and open waste burning on population growth rates from Census-India (2012). We used these estimates to evaluate the trend in the total emissions and their likely impact on ambient $PM_{2.5}$ concentrations through 2030. Fig. 3(b) shows the total $PM_{2.5}$ emissions between 2015 and 2030 under the business as usual scenario for Agra, Bengaluru, Chennai, and Patna. Figures for all the 20 cities are presented in the Supplementary and more details are available for each pollutant at India-APnA (2017). The totals summarized in Table 7 and Fig. 3(b), do not include natural source emissions like seasalt and dust storms.

The main emission sources for all cities include vehicle exhaust, on-road resuspended dust, construction dust, industrial exhaust, and domestic cooking and heating. While the methodology and the main data resources applied for each of the cities are the same, the final inputs for a city's emissions inventory are customized for each city. For example, of the 20 cities; Chennai and Nagpur airsheds host a power generation unit; Raipur's airshed hosts India's largest integrated steel manufacturing unit with co-generation; small and medium scale industries are major emission sources in Tier 2 cities like Amritsar, Bhopal, Chandigarh, Coimbatore, Kanpur, Ludhiana, and Pune; Chennai and Kochi host India's large commercial ports. Similarly, the meteorology is different for cities in the North and cities in the South - thus affecting space and water heating patterns. The spread of brick kilns in and around each city is different - accordingly we have mapped the location of these for individual cities and spatially allocated emissions. Data from google maps is valuable in calculating average vehicle speeds for each city (e.g. vehicle speeds in a megacity like Chennai are different from smaller cities).

Industries, dust (due to movement of the vehicles on the roads), and vehicle exhaust are the major sources of PM_{10} and $PM_{2.5}$, other sources include residential fuel combustion, garbage burning, construction activities, and generator usage at commercial and residential locations. Industries contribute the largest share of emissions for SO_2, NO_x and VOCs. For CO, the share of emissions is spread equally between vehicle exhaust, domestic cooking and heating, and industries. The level of uncertainty for the emissions inventory is about 20–30% (Guttikunda and Jawahar, 2012).

We used multiple layers of spatial proxies to grid the estimated emissions and create a gridded inventory (Fig. 4). The details of the methodology are described in Guttikunda and Jawahar (2012). We have created the emissions inventory on a GIS platform of 0.01° spatial resolution. This resolution lends itself well to atmospheric chemical transport modeling. Certain sectors such as domestic heating change daily as per meteorological conditions or forest fires that are dynamically updated every day. Fig. 3(c) shows maps of 4 cities with gridded total $PM_{2.5}$ emissions for 2015. $PM_{2.5}$ gridded emission maps for all the 20 cities are presented in the Supplementary. Emission hotspots in each city - highways, high population density areas, brick kiln clusters, airport, and large point sources - clearly show up.

Table 5
Summary of methodologies and resources utilized for building the emissions inventory for Indian cities under the APnA city program (India-APnA, 2017).

Sector	Methodology and data resources
Meteorology	Weather Research and Forecasting (WRF) model with global inputs from NCEP (2016) was used to build all the necessary 3-dimensional meteorological fields, such as wind speeds, wind directions, temperature, relative humidity, pressure, precipitation, mixing layer heights, and surface threshold velocities (and others), at 0.01° spatial resolution and 1-h temporal resolution for the year 2015. A summary of the meteorological fields for the 20 cities as graphs and data files (in excel csv format) is available in the Supplementary.
Population	Census-India (2012) database at the district level and gridded population from GRUMP (2015) (available at 30-s spatial resolution) was used to create 0.01° resolution population databases for the cities. At the national scale, the population database was also projected to 2030, using state level birth rates and death rates (by age group). The built-up area information in Fig. 3 was used to designate the grids and the gridded population as urban and rural.
On-road transport	ASIF principles (Schipper et al., 2000) - total travel activity (A), modal shares (S) in vehicle-km traveled per day, modal energy intensity (I) representing energy use per kilometer and an emission factor (F) defined as the mass emitted per vehicle-km traveled - were used to calculate the on-road vehicle exhaust emissions. The total vehicle exhaust emissions are available by vehicle type, vehicle age, and fuel type and calculated following the methodology discussed in Guttikunda and Mohan (2014) for Indian states and districts. A database of average emissions factors for current and projected fleets is available as Supplementary material in Goel and Guttikunda (2014). Annual reports of MoRTH publish the number of registered motor vehicles under various categories by state and by city, for all major vehicle types – heavy duty vehicles (HDVs), light duty vehicles (LDVs), buses (in city and long distance), 4-wheelers (cars, jeeps, sports utility vehicles, taxis), 3-wheelers (passenger and freight), and 2-wheelers (scooters, mopeds, and motorcycles). Monthly reports by SIAM publish national vehicle sales for major categories.
On-road dust	Methodologies detailed in USEPA (2006) and Kupiainen (2007) were utilized to build a base on-road dust resuspension inventory. In addition to this, the precipitation fields after the WRF meteorological model processing were utilized to adjust for soil moisture in the grids. If the grids had precipitation of > 1 mm/h, then the on-road dust resuspension is zeroed and maintained at minimum levels for the next 2 h. The grid-level speed maps from google maps (pre-defined) was also used to adjust on-road resuspension, when the average (cumulative) speed in the grid is under 5 km/h – an indication of congestion and speed under the threshold to support resuspension. These corrections were introduced to reduce any overestimation.
Aviation	Flight landing and takeoff (LTO) statistics are obtained from DGCA and http://flightstats.com with information available by airport. Assuming average occupancy per flight of approximately 180, we estimated the idling emissions of cars dropping off and picking up passengers and emissions from general airport operations (luggage handling, fueling, shuttling of passengers, cargo movement, and other support activities) supported by cars, SUVs, buses, fuel trucks, taxing vehicles, and tractors, often using diesel as fuel. The average LTO emission rates are obtained from IIASA (2015) and on-road fleet average emission rates from Goel and Guttikunda (2014).
Shipping	To emissions from domestic and cargo handling at the ports and along the shipping routes intersecting the selected airsheds (for the coastal cities) are obtained from the Task Force on Hemispheric Transport of Air Pollution (TF HTAP - http://htap.org). No primary inventory was developed for this sector.
Domestic cooking	The HH10 database of Census-India (2012) for all 640 districts includes nine fuel categories (crop residue, wood, coal, cow dung, kerosene, coal and charcoal, LPG, biogas, electric, and a small share of others), urban-rural fuel usage profiles, and inside-outside cooking preferences. The electric share of households is taken as zero emissions. The survey records only the primary fuel for cooking. In the calculations, the share of the fuel preferences at the district level is used as a proxy. Average energy consumed by household for cooking is calculated based on NSSO survey database, which lists amount of food varieties cooked at the state level (Pandey et al., 2014) which is assumed constant for all the districts within a state. Gridded population (discussed above), landuse information to urban-rural classification within the grid and district, and emission factors from IIASA (2015) were overlaid for gridded emissions from household solid, liquid, and gaseous fuel consumption for cooking. Cooking emissions are constant for all days in a year.
Domestic lighting	The HH7 database of Census-India (2012) for all 640 districts includes four fuel categories (kerosene, solar, electricity, and a small share of others) and urban-rural fuel usage profiles. The solar and electric share of households is taken as zero emissions. The survey records only the primary fuel for lighting. Similar to the cooking methodology, gridded population (discussed above), landuse information to urban-rural classification within the grid and district, and emission factors from IIASA (2015) were overlaid for gridded emissions from household liquid fuel consumption for lighting. Lighting emissions are constant for all days in a year.
Domestic space and water heating	In addition to cooking food and lighting, water and space heating emissions for the domestic sector were estimated after linking the surface temperature profiles at the grid level and the population by age groups. This was used to improve the emissions in two ways (a) no more approximation of the heating needs by north or south or summer or winter. A running average temperature was tracked to trigger the need for space heating needs (b) it is our assumption that hot water requirement for age groups under 15 and over 55 years is all year round, and rest of the age with varying usage. The water heating and space heating emissions vary daily.
Open waste burning	Global trash burning database is available at 0.1° x 0.1° using a methodology involving waste generation rates, waste mix, collection efficiencies, open waste burning rates, and emission factors (Wiedinmyer et al., 2014; IIASA, 2015). Total waste generation in India is approximately 150,000 tons per day at the rate of 0.5 kg per day per person, of which we estimate approximately 25% is burnt in the urban areas and more in the rural areas with no waste management system in place (Annepu, 2012). Because of smoke, air pollution, and odor complaints, the local authorities have banned open waste burning, but it continues unabated at makeshift landfills. Linked to the built-up area map for the airshed (Fig. 3) and notes from the municipal reports on local waste management activities, emissions were estimated assuming that the urban areas have higher waste collection efficiency. The modeled grid level precipitation data, a threshold of 1 mm/h is used to zero the open waste burning emissions.

(*continued on next page*)

Table 5 (*continued*)

Sector	Methodology and data resources
Power plants	The database of power plants includes geographical location, number of boiler units, coal characteristics, coal consumption rates, and installed control equipment. These details were documented from their respective environmental impact assessment reports and data published by the state electricity boards (public entities) and private operators (Guttikunda and Jawahar, 2014; NPP, 2018). Under NAMP, all the large point sources such as the coal-fired thermal power plants, are required to conduct continuous emissions monitoring from all the operational stacks, for all the criteria pollutants. However, these emission rates are not public and only reports based on intermittent audits are presented as averages (MoEFCC, 2010; CEA, 2013; MoEFCC, 2015; CEA, 2017; MoEFCC, 2018). A summary of the emission factors and an analysis of current and planned power plants is presented in Lu et al. (2013), Guttikunda and Jawahar (2014), Sadavarte and Venkataraman (2014), and IIASA (2015).
Diesel generator sets	The spatial allocation of the in-situ emissions from burning of diesel in small and large generator sets was refined using the hotspot information available as geospatial layers, including the locations of hotels, hospitals, malls, markets, funeral homes, religious worship centers, industrial areas, apartment complexes, commercial centers, and telecom towers. These layers were extracted from open sources such as Open Street Maps and paid sources such as google API. The shortages in the power supply at the state and the grid level were sourced from CEA reports, NPP statistics, and load dispatch center reports. Emission factors by generator set size are summarized in Sahu et al. (2015).
Heavy industries	Other than the thermal power plants, details of heavy industries covering fertilizers, cement, refineries, iron and steel, and mineral ore processing were collated using information from respective sector annual reports, http://www.indiastats.com, and emission factors from Sadavarte and Venkataraman (2014) and IIASA (2015). The plant details include location information and production rates.
Light industries	The heavy industries is further substantiated with the industrial fuel consumption data (as solid, liquid, and gaseous fuels) from the Ministry of Statistics, conducted as part of the annual survey of industries (ASI, 2015; MSME, 2017). Broad categories covered under this survey are food processing, textile works, leather works, wood processing, paper and ink, coke products, pharmaceuticals, rubber and plastics works, glass works, manufacturing & repairs, power generation, and waste & water treatment. The fuel consumption data by various industrial categories is based on the fuel purchase receipts at the district level and the emission factors database is from Sadavarte and Venkataraman (2014) and IIASA (2015).
Construction	Besides the traditional manufacturing industries, construction is among the fastest growing sectors in India. The demand for traditional red and fired clay bricks is high, along with cement, and the location of these clusters in and around the urban airsheds were tagged using the open google earth imagery. Most of them are located along the river, with easy access to top soil and water for raw material. Traditionally, the rectangle shaped clay bricks are sun dried and readied for firing in “clamps” - a pile of bricks with intermittent layers of sealing mud and fuel. Technology for firing has changed for mass production with the fixed chimney brick kilns having a capacity to produce 10,000 to 20,000 bricks per day (World-Bank, 2010; Mathiel et al., 2012; Guttikunda et al., 2013; Rajarathnam et al., 2014). This fuel would vary from agricultural waste to biofuels like cow dung and wood to fossil fuels like coal and heavy fuel oil. Emission factors for various technologies were summarized from Weyant et al. (2014), IIASA (2015), Akinshipe and Kornelius (2018). The inventory also includes fugitive dust estimates for construction sites based on empirical functions proposed in USEPA (2006) and operational guidelines from CPCB (2017).
Open fires	The location of open fires (from VIIRS and MODIS satellite feeds @ https://worldview.earthdata.nasa.gov), along with pixelated information of landuse fractions (agricultural, forest, urban, water, and arid) were used to estimate the total emissions. The Fire INventory from NCAR (FINN) model estimates total emissions using these satellite feeds, provide emissions information suitable for chemical transport modeling at a horizontal resolution of 1 sq.km. The global archives dating back to 2002, along with a database of landuse based emission factors, and data processing procedures to prepare model ready emission inventory are available @ http://bai.acom.ucar.edu/Data/fire (Akagi et al., 2011; Wiedinmyer et al., 2011).
Dust storms	The GOCART dust module from WRF simulates the dust outbreaks and also propagates these emissions in the CAMx dispersion model as a separate source.
Seasalt	A CAMx pre-processor calculates seasalt emissions, where applicable, using the 3-dimensional meteorological input for WRF.

5. Modeled particulate sector contributions

5.1. Chemical transport model

We used the Comprehensive Air Quality Model with Extensions (CAMx), to estimate particulate concentrations for each urban airshed. CAMx is an open-source Eulerian photochemical dispersion model that supports (a) 3-dimensional advection linked to 3-dimensional meteorological data at the grid level, including plume rise calculations for point sources (b) scavenging schematics in the form of dry and wet deposition (c) multiple chemical mechanisms to characterize photochemistry (d) gas to aerosol conversions (from SO_2 to sulfates, NO_x to nitrates, and VOCs to secondary organic aerosols) (e) links to online emission calculations for certain sources like seasalt and (f) modular processing of area and point sources to estimate contributions by pre-defined region and source. We use the WRF meteorological model to derive meteorological data (3D wind, temperature, pressure, relative humidity, and precipitation fields) (data files are presented in the Supplementary). The vertical resolution of the model was stretched over 28 layers under 12 km, to improve our simulations of ground level concentrations. The lowest layer is designated at 30 m and there are 12 layers within 1 km.

To account for activities outside the designated urban airshed, we use boundary conditions from a model run covering the Indian Subcontinent (details on national emissions inventory and modeling framework are available online @ http://www.indiaairquality.info). We used the MOZART global model to get boundary conditions for the Indian Subcontinent. CAMx modeling system (http://

Table 6
Key household, geography, and transport statistics for 20 Indian cities.

	City name	A	B	C	D	E	F	G	H	I	J	K	L
1	Agra	36.2	6.7	37.4	79.7	91.1	33.2	high	–	800	–	–	0.90
2	Amritsar	46.9	11.7	58.3	96.0	85.8	26.8	high	120	300	–	–	0.93
3	Bengaluru	44.3	17.5	75.5	98.0	93.3	40.2	low	700	6000	–	–	5.56
4	Bhopal	43.7	12.4	57.8	92.9	74.2	36.2	medium	–	400	–	–	1.10
5	Bhubaneswar	33.8	6.8	32.8	71.5	63.8	37.0	medium	160	300	yes	–	1.30
6	Chandigarh	46.7	25.7	71.6	98.4	94.2	40.7	high	160	600	yes	–	0.80
7	Chennai	46.6	13.2	82.4	99.1	94.1	41.0	very low	430	2400	yes	yes	4.93
8	Coimbatore	47.1	9.2	71.5	94.8	81.8	36.2	low	120	6000	yes	–	1.90
9	Dehradun	47.1	14.9	72.4	96.3	90.4	26.5	high	10	750	–	–	0.50
10	Indore	46.6	10.5	67.8	96.5	78.2	30.2	medium	110	900	yes	–	1.71
11	Jaipur	45.7	12.5	49.8	86.4	90.2	26.6	high	200	1600	yes	–	2.25
12	Kanpur	30.3	6.2	51.5	63.0	69.7	35.2	high	125	1200	yes	–	1.46
13	Kochi	40.7	17.1	63.2	97.4	93.7	6.1	very low	260	400	yes	yes	0.60
14	Ludhiana	50.4	16.8	68.3	98.3	93.4	29.4	high	190	3000	yes	–	1.77
15	Nagpur	42.8	7.2	60.2	92.1	69.4	30.0	medium	130	900	yes	–	1.30
16	Patna	18.4	5.2	33.8	57.1	70.0	30.1	high	310	450	–	–	1.00
17	Pune	48.8	13.2	67.9	92.7	87.8	46.5	medium	150	3000	yes	–	2.34
18	Raipur	20.6	3.6	19.4	84.6	47.5	38.7	medium	120	800	yes	–	1.80
19	Ranchi	25.3	6.1	29.6	63.0	47.7	19.2	high	110	100	–	–	0.60
20	Varanasi	29.1	4.5	37.4	62.0	77.0	28.5	high	450	200	–	–	0.77

Note: A to F statistics are extracted from Census-India (2012). A = % households with at least one motorcycle; B = % households with at least on 4-wheeler (cars and vans); C = % households with primary cooking supported by gas and electricity; D = % households with primary lighting supported by electricity; E = % households with permanent houses; F = % households with < 2 rooms; G = need for winter heating; H = number of mapped brick kilns in the city's selected airshed from open google earth imagery; I = number of small scale industries listed under ASI (2015); J = existence of heavy industries (including power plants) in the city's selected airshed; K = coastal or not; L = total number of registered vehicles in 2015 in millions (MoRTH, 2016).

Table 7
Estimated annual emissions totals for the 20 Indian cities in 2015.

		Annual emissions (CO_2 in million tons/year and rest in tons/year)								
	City name	$PM_{2.5}$	PM_{10}	BC	OC	NO_x	CO	NMVOC	SO_2	CO_2
1	Agra	8350	15,600	2100	2950	10,250	79,250	16,400	950	1.55
2	Amritsar	8600	13,450	2000	2600	12,050	72,100	16,500	2400	2.4
3	Bengaluru	31,300	67,100	9350	8450	56,900	335,550	83,500	5300	10.42
4	Bhopal	5900	13,650	1300	1550	8950	54,300	15,100	900	1.65
5	Bhubaneswar	11,250	22,400	2700	3600	22,250	129,050	27,350	1350	2.28
6	Chandigarh	18,300	33,600	3450	4850	56,300	160,350	35,850	3200	3.91
7	Chennai	94,050	132,350	14,500	11,250	207,400	345,550	92,900	26,600	9.76
8	Coimbatore	14,100	23,900	3500	3050	25,150	113,100	28,200	2650	3.13
9	Dehradun	4650	7500	1300	1700	7200	39,450	8600	750	1.04
10	Indore	11,850	27,600	3250	3150	15,200	83,700	22,250	1400	2.72
11	Jaipur	17,200	34,800	4700	5250	20,400	137,600	31,550	2650	3.79
12	Kanpur	34,550	43,900	5150	5550	24,750	166,000	34,100	2450	2.39
13	Kochi	9150	16,400	2250	2100	63,900	69,550	14,850	20,900	2.4
14	Ludhiana	14,500	24,200	4550	3850	31,200	128,550	25,900	3750	3.53
15	Nagpur	67,100	86,300	6900	7900	128,100	176,850	52,900	9600	6.89
16	Patna	18,050	29,500	4800	6150	18,350	171,450	27,650	3850	2.86
17	Pune	17,700	36,900	5600	4150	37,000	166,050	41,900	3950	5.81
18	Raipur	41,500	59,650	9150	9050	60,700	163,300	118,150	7600	3.13
19	Ranchi	13,150	24,300	3350	4550	13,150	128,500	25,300	1950	2.31
20	Varanasi	12,100	17,450	3050	4850	14,050	134,400	21,850	2300	1.79

www.camx.com) has a pre-processor module to link MOZART model results. The WRF-CAMx modeling system, boundary conditions, and the national emissions inventory for ozone precursor pollutants was evaluated against ground based and satellite observations in Sarkar et al., 2016.

The total PM concentrations includes primary aerosols (metals, BC, and OC) and secondary contributions (from chemical conversion of gaseous SO_2 to sulfate aerosols and gaseous NO_x to nitrate aerosols). In CAMx, the primary PM is modeled in two bins to account for differential deposition and advection characteristics – coarse fraction (CPRM) comprises of PM_{10} to $PM_{2.5}$ mass and fine fraction (FPRM) comprises of everything less than $PM_{2.5}$ mass. All the secondary aerosols are considered as part of $PM_{2.5}$ mass. We set up the dispersion model calculations to also estimate sector contributions to ambient $PM_{2.5}$ concentrations in the urban airshed of each city.

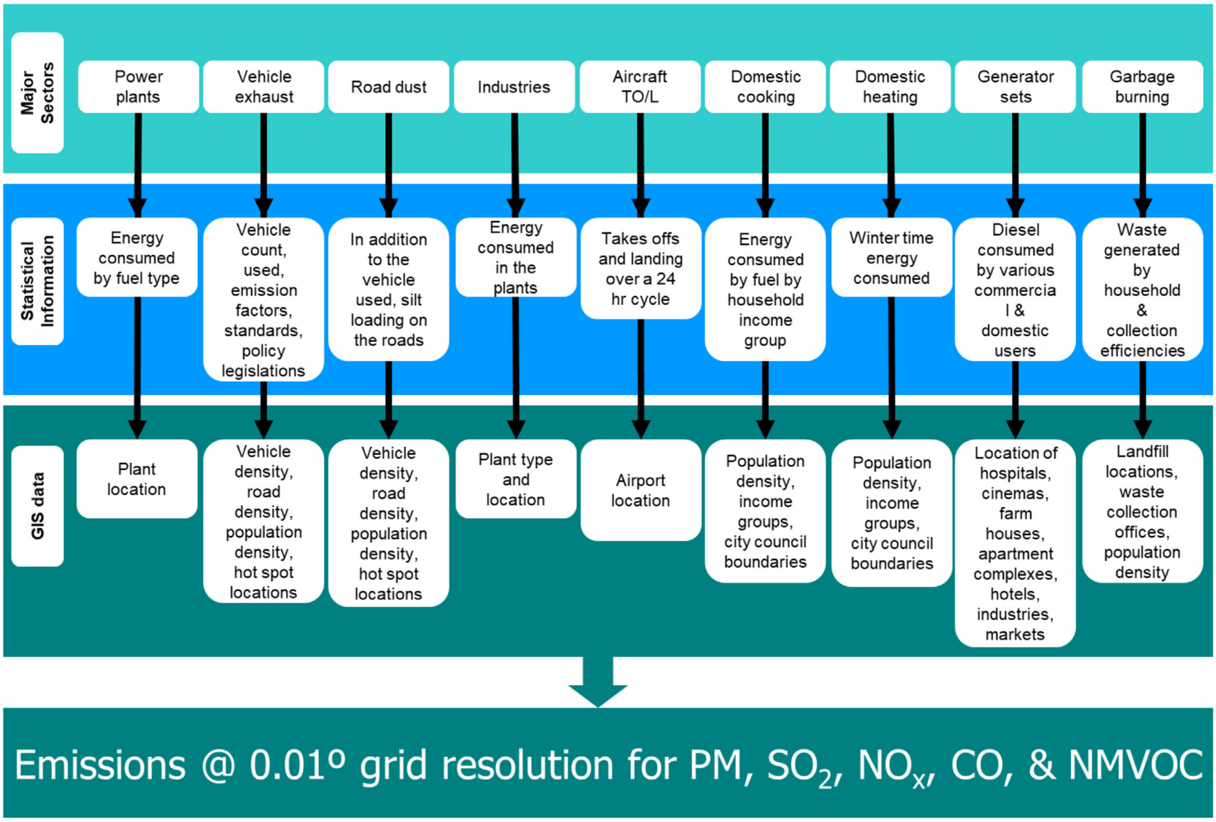

Fig. 4. Multiple geospatial layers and data sources accessed to spatially distribute the annual emissions to 0.01° grids over the urban airshed selected for 20 Indian cities.

Table 8
Comparison of (A) WRF-CAMx modeled $PM_{2.5}$ annual average (for the urban parts of the airshed) (B) Measured annual average concentrations and standard deviation of all the available continuous monitoring data (in brackets – number of continuous monitoring stations operational in the city). (C) satellite-derived $PM_{2.5}$ annual average concentration from van Donkelaar et al. (2016) (all values in μg/m^3).

	City name	Modeled	A - Measured (continuous stations only)	B – 2016 satellite-derived from Fig. 1
1	Agra	89.0 ± 27.1	98.6 ± 86.1 (1)	116.9
2	Amritsar	83.4 ± 25.4	65.9 ± 64.8 (1)	79.1
3	Bengaluru	36.5 ± 19.7	32.3 ± 24.2 (3)	28.9
4	Bhopal	49.9 ± 16.0	47.8 ± 35.1 (1)	56.5
5	Bhubaneswar	47.7 ± 26.5		37.9
6	Chandigarh	58.1 ± 18.4	59.4 ± 62.7 (1)	78.7
7	Chennai	57.5 ± 31.3	47.7 ± 73.7 (3)	32.6
8	Coimbatore	19.4 ± 9.5		26.0
9	Dehradun	51.2 ± 17.6		87.4
10	Indore	66.3 ± 31.1	40.4 ± 23.1 (1)	46.1
11	Jaipur	99.6 ± 29.5	70.4 ± 76.8 (3)	68.3
12	Kanpur	114.1 ± 44.4	111.4 ± 79.7 (1)	106.6
13	Kochi	29.1 ± 15.7		26.1
14	Ludhiana	90.2 ± 33.7	74.4 ± 46.1 (1)	83.9
15	Nagpur	84.9 ± 40.8	53.9 ± 26.7 (1)	47.3
16	Patna	122.2 ± 68.2	121.3 ± 89.5 (1)	90.8
17	Pune	56.3 ± 28.4	43.1 ± 25.7 (1)	47.5
18	Raipur	82.3 ± 43.1		54.6
19	Ranchi	73.0 ± 36.7		55.6
20	Varanasi	78.4 ± 26.9	106.2 ± 83.4 (1)	94.0

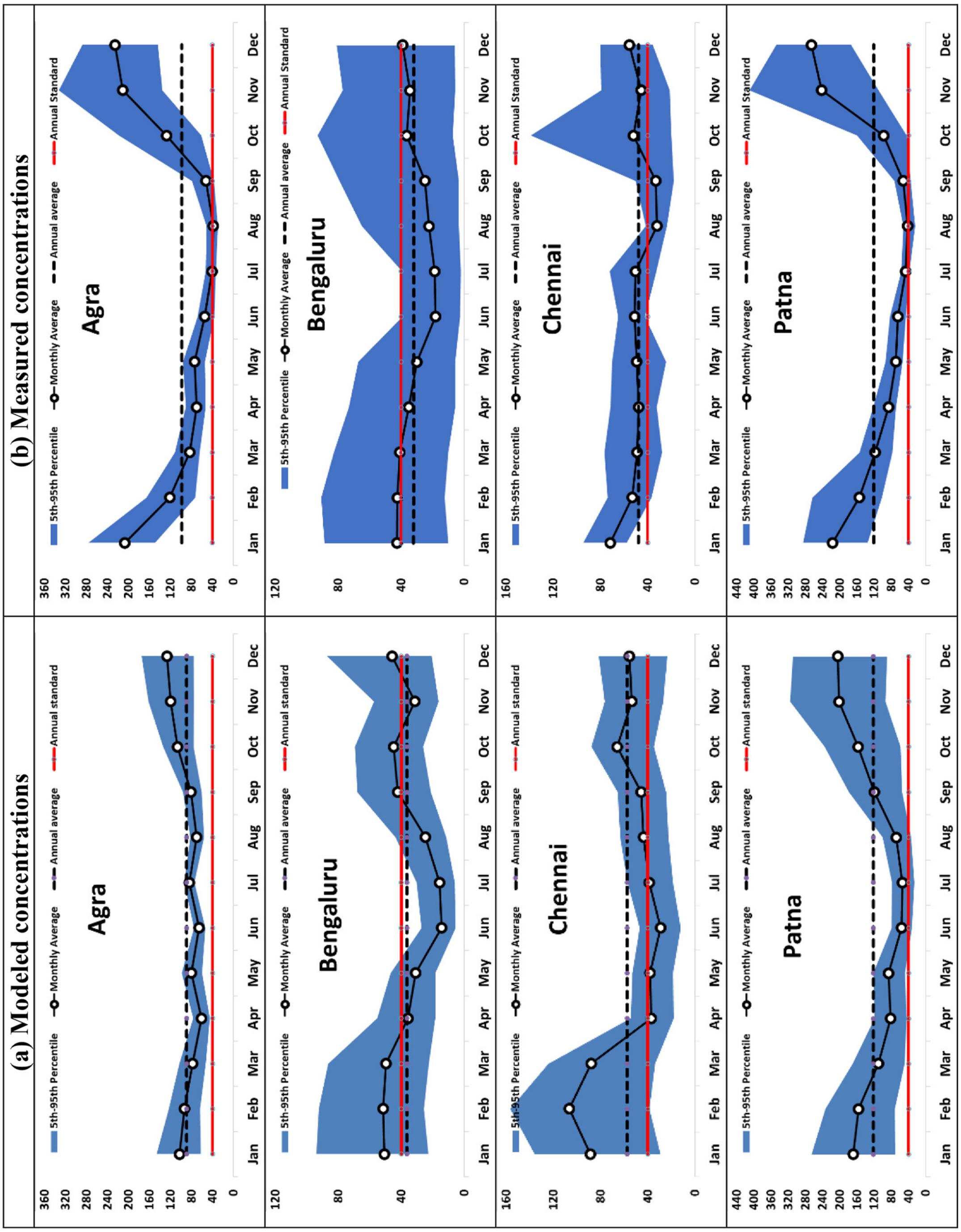

Fig. 5. Comparison of (a) WRF-CAMx modeled $PM_{2.5}$ monthly average concentrations (in $\mu g/m^3$) over the urban grids and (b) available measured $PM_{2.5}$ concentrations (in $\mu g/m^3$) from continuous monitoring stations in the city.

5.2. Modeled particulate concentrations

Table 8 summarizes the modeled annual average $PM_{2.5}$ concentrations. We also present PM concentration maps in Fig. 3(d) for Agra, Bengaluru, Chennai, and Patna. Concentration maps for all the 20 cities are presented in the Supplementary. Except for Coimbatore and Bengaluru (both from Southern India), all the urban airsheds exceed the national annual standard of 40 $\mu g/m^3$ for $PM_{2.5}$.

In case of $PM_{2.5}$, only 14 cities have at least one station operational. This data is summarized as measured in Table 8, along with the number of monitoring stations operational in each city. A direct comparison of the modeled and measured concentration is not available, due to limited number of (often one) operational monitors. Even in case of Bengaluru, while there are 10 operational continuous monitoring stations, 5 stations came online only in 2018 with no data in the public domain and of the remaining 5, only 3 report $PM_{2.5}$ concentrations. The average and standard deviation value for the modeled concentrations in the table represents data for all the urban grids and 12 months. Fig. 5(a) shows the dispersion model results by month to highlight the seasonality of air quality over the course of a year for 4 cities and rest are presented in the Supplementary. The daily average variation by month for all the data from the continuous monitoring stations (1 for Agra and Patna and 3 for Bengaluru and Chennai) is presented in Fig. 5(b). The monthly average maps are not presented in this paper and the data is available upon request. The modeled graphs present the variation (5th and 95th percentile) in the $PM_{2.5}$ monthly average concentrations among the urban grids, along with the annual average concentration.

We capture the quantitative ranges and the seasonality in the model results and note that the sample size is not enough to make any scientific conclusions. There is also lack of information on the representativeness of the location of the continuous stations. Often the first continuous monitoring station is located near the pollution control board for safety and maintenance reasons. As more stations come online in each of these cities, we will revisit the modeling results to further explore the trends and to assess the overall assumptions in our calculations. At this stage, we are expecting the emissions and dispersion modeling results to start a much-needed conversation in the policy circles to examine the hot spots in the city and to push for an increase in the monitoring stations to spatially and temporally represent the pollution levels in the city.

For all the cities, variation in the 24-hr concentration values is large, with the general trend pointing to higher levels of pollution during the winter months and lower levels during the summer and monsoon months, which coincides with the trend in the meteorological fields – lower mixing heights, lower wind speeds, and lower precipitation rates during the winter months and vice versa during the summer months. This seasonality is strongly associated with the mixing heights (summary tables are presented in the Supplementary). The variation is very high for the cities on the Indo-Gangetic plain when compared to the 4 Southern cities (Bengaluru, Chennai, Coimbatore, and Kochi), which experience a uniform mixing height. For example, on average, Bengaluru's winter time heights are at least 2 times higher than those reported for Northern cities, which means on average there is at least double the volume of air to disperse emissions and consequently result in better air quality. While meteorology is crucial in determining the levels of air pollution in any city, it cannot not be part of the control strategy to reduce pollution.

5.3. Source contributions

For all cities, industries, vehicle exhaust, domestic cooking and heating, open waste burning, diesel generator sets, road dust, and construction dust are the primary sources of ambient $PM_{2.5}$ pollution, apart from the regional contributions. This list is not an unknown. With the changing emission patterns, it has become a prerequisite to ascertain the source contributions pertinent to a city's geographical and economic conditions, to prioritize a series of control options for both regulatory and health purposes (Sagar et al., 2016). We summarize the modeled percent contributions of these sources to 20 Indian cities in Table 9 and Fig. 3(e).

We estimate these contributions using a bottom-up technique following the sequence of building an emissions inventory, using WRF to process meteorological data, and using CAMx for dispersion modeling. Ideally, this process should be accompanied by a top-down technique where filter samples are collected at representative locations in the city for representative seasons, followed by chemical analysis for metals, ions, and carbon species and statistical receptor modeling with the help of pre-defined library of source profiles. CPCB (2011) using the samples and surveys collected in 2006 was the last study published for Delhi, Bengaluru, Chennai, Pune, Kanpur, and Mumbai. In the past 10 years, these 6 cities and many from across India have at least doubled their vehicle fleet and increased their demand for construction material, electricity, and other industrial products, and consequently air pollution (Fig. 1). While top-down methods ascertain the chemical signature of a fuel in a given sample of air, they fail to pin point the source itself, such as diesel consumed in a truck versus a generator set, or if the source of pollution is local or regional. This gap is best addressed in the bottom-up technique, accompanied with the boundary conditions to account for outside contributions and the emission inventory providing the details at the source level (by fuel type, by vehicle type, by region or grid, and by season).

GBD-MAPS (2018) is the recent study to model source contributions at the national level, highlighting the same sources. Domestic cooking and heating was reported as the largest contributor (24%), which is double the percentages observed in the cities. This primarily points to the fact that larger proportions of population are using biomass and coal as their primary fuel for cooking and heating in the rural areas. In the global model simulations at coarser resolutions, the national shares tend to also get diluted like in case of transport with 2% (with most of these emissions concentrated over a very small percentage of grids in the modeling domain) as compared to an average 18.0% in the study. While the national scale simulations raise the awareness of the problem at the central level, the urban scale simulations highlight the shares of the local sources and the importance of regional coordination for effective management of the problem.

The regional contributions are an important source of pollution (from a low of 13–15% in case of Chennai and Bengaluru to

Table 9
Annual average source contributions to WRF-CAMx modeled $PM_{2.5}$ concentrations for 20 Indian cities in 2015 (A = domestic cooking, heating, and lighting; B = transport including road, rail, shipping, and aviation; C = dust including on-road resuspension and construction; D = brick kilns; E = all industries excluding brick kilns and including thermal power plants; F = open waste burning; G = diesel generator sets; H = natural source for coastal cities only; Outside = contribution of boundary conditions to the urban airshed, representing the influence of regional sources).

		Modeled contributions								
	City name	A	B	C	D	E	F	G	H	Outside
1	Agra	23.8%	13.9%	10.7%	0.0%	0.2%	12.4%	2.7%		35.9%
2	Amritsar	10.6%	10.5%	7.1%	2.1%	7.3%	6.1%	3.1%		52.7%
3	Bengaluru	9.8%	26.5%	23.0%	2.5%	2.1%	16.1%	4.0%		15.6%
4	Bhopal	10.2%	14.1%	17.1%	0.0%	2.8%	8.7%	4.9%		41.8%
5	Bhubaneswar	15.9%	17.0%	20.8%	4.0%	0.6%	5.7%	3.6%		32.0%
6	Chandigarh	11.4%	10.6%	12.6%	1.3%	1.3%	8.9%	2.6%		50.8%
7	Chennai	3.6%	24.5%	23.5%	3.1%	12.8%	15.5%	1.6%	1.8%	13.3%
8	Coimbatore	6.4%	18.3%	13.7%	1.0%	11.1%	14.1%	2.4%		32.5%
9	Dehradun	14.3%	14.2%	4.4%	0.4%	1.3%	19.6%	3.8%		41.7%
10	Indore	8.1%	26.9%	22.7%	2.0%	2.4%	7.8%	2.0%		27.8%
11	Jaipur	13.4%	24.1%	17.5%	1.7%	2.4%	8.4%	2.2%		29.9%
12	Kanpur	33.8%	13.7%	8.9%	1.2%	6.5%	8.8%	4.1%		22.5%
13	Kochi	9.5%	20.2%	16.3%	3.8%	4.1%	3.8%	4.5%	16.5%	20.9%
14	Ludhiana	7.8%	16.3%	12.3%	2.8%	7.9%	9.2%	2.6%		40.7%
15	Nagpur	6.8%	17.2%	10.9%	3.2%	26.7%	11.6%	1.8%		21.4%
16	Patna	14.6%	14.8%	12.1%	9.3%	11.2%	12.9%	5.4%		19.2%
17	Pune	5.8%	24.0%	23.4%	2.6%	9.8%	6.4%	2.8%		24.7%
18	Raipur	11.8%	17.2%	11.5%	1.4%	22.8%	6.2%	2.8%		25.8%
19	Ranchi	18.0%	21.1%	14.1%	3.2%	1.1%	12.2%	1.3%		28.5%
20	Varanasi	20.9%	13.5%	8.2%	6.1%	0.2%	16.2%	3.3%		31.2%
	20 city average	12.9 ± 7.1%	18.0 ± 5.1%	14.6 ± 5.8%	2.6 ± 2.2%	6.8 ± 7.4%	10.6 ± 4.2%	3.1 ± 1.1%		30.5 ± 10.9%

50–52% in Amritsar and Chandigarh). This shows that air pollution in India is not limited to cities alone and *peri* urban and rural areas also generate and contribute to pollution. This is especially true for cities on the Indo-Gangetic plain, given the density of population in the region and concentration of settlements, which makes it harder to distinguish between rural and urban areas based on modeled $PM_{2.5}$ concentrations alone (as seen in Fig. 1). Large external contributions in Amritsar, Chandigarh, and Ludhiana from the state of Punjab, highlight their proximity to sources like power plants not located in the airsheds, seasonal dust storms from the neighboring state of Rajasthan, sources of emissions from across the Indian border, and open field burning emissions after the harvest season, which can only be addressed in a regional framework of air quality management. The cities with outside contributions between 30 and 40% are mostly Tier 2 category. This percentage will likely reduce to about 15% as the city grows and emissions from within the city increase over time.

We also projected results to 2030 under a business as usual scenario by modeling emissions, dispersion, and source apportionment. For brevity we have only included emission projection graphs in Fig. 3(b). The gridded emission maps, and modeled concentration maps, and source contributions for 2030 are available at India-APnA (2017).

We list a few emission management options for the main pollution sources, the benefits of which can only be evaluated if and when they are implemented. At the national scale, these options were evaluated as what-if scenarios in GBD-MAPS (2018) and Venkataraman et al. (2018) for the period of 2015–2050, and the benefits are clear – no emissions at the sources will result in better air quality in the future.

- Two of the 20 cities lie on the coast – Kochi and Chennai. These two cities host large commercial ports, with significant contributions to $PM_{2.5}$ and SO_2 pollution from freight movement (ships and on roads heavy duty trucks). This sector can benefit from a freight management program. For example, movement of freight on rail, restrictions on vehicle types entering the port area, restrictions on the fuel quality used by ships anchored at the ports.
- All the cities need to aggressively promote public and para transportation systems, to reduce the use of millions of passenger vehicles and their respective emissions. By 2030, the vehicle exhaust emissions are expected to remain constant or tend lower, if and only if, Bharat 6 (equivalent of Euro-6) fuel standards are introduced nationally in 2020, as recommended by the Auto Fuel Policy. A sustainable transport policy must also promote non-motorized transport (walking and cycling) infrastructure, to not only reduce the contribution of vehicle exhaust emissions but also to reduce on-road dust re-suspension.
- By 2030, the share of emissions from residential cooking and lighting is expected to decrease with an increasing share of LPG and electrification available for primary cooking under the Prathan Mantri Ujjwala Yojana scheme (MoPNG, 2018).
- All the 20 cities lack a comprehensive waste management system. The practice of open waste burning is hard to regulate and monitor. This sector contributes significantly to air pollution unless the municipalities address this internally, starting from reducing waste generation, collecting waste efficiently, and managing the collected waste.
- Upgrading the brick kiln technology from the current fixed chimney and clamp-style baking to (for example) zig-zag for the approximately 4000 brick kilns mapped in these 20 urban airsheds will improve their overall energy efficiency and reduce

emission loads (World-Bank, 2010; Maithel et al., 2012).

- Coal-fired power plants and large industries with captive power plants need to enforce stricter emission standards for all the criteria pollutants to reduce their share of influence on urban air quality. The densely populated Indo-Gangetic plain has cities and rural areas near these large point sources that strongly influences each other's ambient air quality (Guttikunda and Jawahar, 2014).
- A regional air quality management, spanning multiple states, districts, and stakeholders is necessary to reduce the pollution loads for all the cities. In April 2018, draft of the National Clean Air Programme (NCAP) is a step in the right direction designed to build institutional and technical capacity of CPCB and SPCBs "to meet the prescribed annual average ambient air quality standards at all locations in the country in a stipulated timeframe" (CPCB, 2018).

6. Policy implications of a knowledge base

In policy circles, the debate on air quality in India and how to best tackle it, is limited to metropolitan cities. Yet, India lives in its villages and smaller towns. We need to look at the state of air pollution in Tier 1 and 2 cities, quantify its extent and understand its sources. With a growth in population and ever-increasing concentration of settlements (especially in the Indo-Gangetic plain), the need for baselines and a start to tackle air pollution is urgent. In the short term, there is an immediate need to increase the ground level monitoring network, which can further support establishing air pollution trend lines for the cities and help monitor action plans.

Urban India is growing rapidly and infrastructure and management systems are yet to catchup with growing urban population, more waste generation (per capita and totals), greater share of motorized transport for individual and commercial purposes, an increase in industrial and manufacturing activity, and a growing demand for clean fuels for cooking and heating. With the lack of systems, cities resort to ad-hoc methods to deal with increased pressure on existing infrastructure. Hence cities need to start planning by anticipating the challenges they will face as they grow and be proactive about solutions to reduce air pollution.

For most of the cities in this study, this is the first time an emissions inventory has been built for the city, followed by a dispersion modeling exercise to assess the particulate pollution trend and identify source contributions. Local governments can use these numbers as a start to develop an air pollution control policy. Apart from numbers, identifying the spatial spread in pollution hotspots lends itself to immediate action. With information, cities can plan for the long-term action by simulating different scenarios that are customized to each city. Simply publishing these numbers will not reduce pollution. But in the absence of any other concrete information, results from this study can support the policy makers establish baselines and plot a roadmap to improve air quality in the long run.

While the analysis presented in this paper focused on the long-term air pollution knowledge assessment, we use the same information base for on-going short-term air quality forecasting (for 3-days) releasing data on an open platform (details @ http://www.indiaairquality.info).

Acknowledgements

We would like to thank the Shakti Sustainable Energy Foundation (SSEF, New Delhi, India) for supporting the India-APnA city program.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: https://doi.org/10.1016/j.uclim.2018.11.005. These data include the Google maps of the most important areas described in this article.

References

Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crounse, J.D., Wennberg, P.O., 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. Atmos. Chem. Phys. 11, 4039–4072.

Akinshipe, O., Kornelius, G., 2018. Quantification of atmospheric emissions and energy metrics from simulated clamp kiln technology in the clay brick industry. Environ. Pollut. 236, 580–590.

Annepu, R.K., 2012. Sustainable Solid Waste Management in India. Masters Thesis. Earth Engineering Center, Columbia University, New York, USA.

ASI, 2015. Annual Survey of Industries, New Delhi, India.

Brauer, M., Freedman, G., Frostad, J., van Donkelaar, A., Martin, R.V., Dentener, F., Dingenen, R.v., Estep, K., Amini, H., Apte, J.S., Balakrishnan, K., Barregard, L., Broday, D., Feigin, V., Ghosh, S., Hopke, P.K., Knibbs, L.D., Kokubo, Y., Liu, Y., Ma, S., Morawska, L., Sangrador, J.L.T., Shaddick, G., Anderson, H.R., Vos, T., Forouzanfar, M.H., Burnett, R.T., Cohen, A., 2016. Ambient air pollution exposure estimation for the global burden of disease 2013. Environ. Sci. Technol. 50, 79–88.

CEA, 2013. All India Electricity Statistics - General Review 2012, New Delhi, India.

CEA, 2017. All India Electricity Statistics - General Review 2016, New Delhi, India.

Census-India, 2012. Census of India 2011, 15th Edition. The Ministry of Home Affairs, Government of India, New Delhi, India.

CPCB, 2003. Guidelines for Ambient Air Quality Monitoring. Ministry of Environment, Forest, and Climate Change (MoEFCC). Government of India, New Delhi, India.

CPCB, 2011. Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities. Central Pollution Control Board. Government of India, New Delhi, India.

CPCB, 2017. Guidelines on Environmental Management of Construction & Demolition and Wastes. Ministry of Environment, Forest, and Climate Change (MoEFCC). Government of India, New Delhi, India.

CPCB, 2018. National Clean Air Programme (NCAP) - India. Ministry of Environment, Forest, and Climate Change (MoEFCC). Government of India, New Delhi, India.

GBD, 2018. The Global Burden of Disease 2010: Generating Evidence and Guiding Policy. Institute for Health Metrics and Evaluation, Seattle, USA.

GBD-MAPS, 2018. Burden of disease attributable to major air pollution sources in India. Health Effects Institute, Boston, USA.
Goel, R., Guttikunda, S.K., 2015. Evolution of on-road vehicle exhaust emissions in Delhi. Atmos. Environ. 105, 78–90.
GRUMP, 2015. Gridded Population of the World and Global Rural and Urban Mapping Project. Center for International Earth Science Information Network (CIESIN) of the Earth Institute, Columbia University, New York, U. S. A.
Guttikunda, S.K., 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, S.K., Jawahar, P., 2012. Application of SIM-air modeling tools to assess air quality in Indian cities. Atmos. Environ. 62, 551–561.
Guttikunda, S.K., Jawahar, P., 2014. Atmospheric emissions and pollution from the coal-fired thermal power plants in India. Atmos. Environ. 92, 449–460.
Guttikunda, S.K., Kopakka, R.V., 2014. Source emissions and health impacts of urban air pollution in Hyderabad, India. Air Quality Atmos. Health 7, 195–207.
Guttikunda, S.K., Mohan, D., 2014. Re-fueling road transport for better air quality in India. Energy Policy 68, 556–561.
Guttikunda, S.K., Begum, B.A., Wadud, Z., 2013. Particulate pollution from brick kiln clusters in the Greater Dhaka region, Bangladesh. Air Quality Atmos. Health 6, 357–365.
Guttikunda, S.K., Goel, R., Pant, P., 2014. Nature of air pollution, emission sources, and management in the Indian cities. Atmos. Environ. 95, 501–510.
IIASA, 2015. Greenhouse Gas and Air Pollution Interactions and Synergies - South Asia Program. International Institute of Applied Systems Analysis, Laxenburg, Austria.
India-APnA, 2017. Air Pollution Knowledge Assessments (APnA) City Program. Urban Emissions Info, New Delhi, India.
Kupiainen, K., 2007. Road dust from pavement wear and traction sanding. Monographs of the Boreal Environment Research, No. 26. Finnish Environmental Institute, Helsinki, Finland.
Landscan, 2013. Gridded Global Population Database. Developed by the Department of Energy's Oak Ridge National Laboratory. Distributed by East View Information Services, U.S.A.
Lu, Z., Streets, D.G., de Foy, B., Krotkov, N.A., 2013. Ozone monitoring Instrument observations of interannual increases in SO2 emissions from Indian coal-fired power plants during 2005-2012. Environ. Sci. Technol. 47, 13993–14000.
Maithel, S., Uma, R., Bond, T., Baum, E., Thao, V.T.K., 2012. Brick kilns performance assessment, emissions measurements, & a roadmap for cleaner brick production in India. In: Study Report Prepared by Green Knowledge Solutions, New Delhi, India.
MoEFCC, 2010. Environmental Impact Assessment Guidelines for Thermal Power Plants. Ministry of Environment and Forests, the Government of India, New Delhi, India.
MoEFCC, 2015. Environment Standards for Thermal Power Plants Along With the Corrigendum, S.O.3305(E), Ministry of Environment and Forests, The Government of India, New Delhi, India.
MoEFCC, 2018. Reports at Environmental Impact Assessment Division. Ministry of Environment and Forests, the Government of India, New Delhi, India.
MoPNG, 2018. Prathan Mantri Ujjwala Yojana (PMUY). Ministry of Petroleum and National Gas, Government of India, New Delhi, India.
MoRTH, 2016. Annual Report 2016. Ministry of Road Transport and Highways, Government of India, New Delhi, India.
MSME, 2017. District Industrial Profile. Miro, Small, and Medium Enterprises (MSME) - Development Institute. Ministry of MSME, Government of India, Bengaluru, India.
NCEP, 2016. National Centers for Environmental Prediction. In: National Oceanic and Atmospheric Administration. U. S. A, Maryland.
NPP, 2018. National power portal by central electrical authority. Ministry of Power. In: Government of India. India, New Delhi.
Pandey, A., Sadavarte, P., Rao, A.B., Venkataraman, C., 2014. Trends in multi-pollutant emissions from a technology-linked inventory for India: II. Residential, agricultural and informal industry sectors. Atmos. Environ. 99, 341–352.
Pant, P., Harrison, R.M., 2012. Critical review of receptor modelling for particulate matter: a case study of India. Atmos. Environ. 49, 1–12.
Pesaresi, M., Ehrlich, D., Florczyk, A.J., Freire, S., Julea, A., Kemper, T., Syrris, V., 2016. The global human settlement layer from landsat imagery, Geoscience and Remote Sensing Symposium (IGARSS). 2016 IEEE International. IEEE 7276–7279.
Rajarathnam, U., Athalye, V., Ragavan, S., Maithel, S., Lalchandani, D., Kumar, S., Baum, E., Weyant, C., Bond, T., 2014. Assessment of air pollutant emissions from brick kilns. Atmos. Environ. 98, 549–553.
Sadavarte, P., Venkataraman, C., 2014. Trends in multi-pollutant emissions from a technology-linked inventory for India: I. Industry and transport sectors. Atmos. Environ. 99, 353–364.
Sagar, A., Balakrishnan, K., Guttikunda, S., Roychowdhury, A., Smith, K.R., 2016. India leads the way: a health-centered strategy for air pollution. Environ. Health Perspect. 124, A116.
Sahu, S.K., Schultz, M.G., Beig, G., 2015. Critical pollutant emissions from the Indian telecom network. Atmos. Environ. 103, 34–42.
Sarkar, M., Venkataraman, C., Guttikunda, S., Sadavarte, P., 2016. Indian emissions of technology-linked NMVOCs with chemical speciation: an evaluation of the SAPRC99 mechanism with WRF-CAMx simulations. Atmos. Environ. 134, 70–83.
Schipper, L., Marie-Lilliu, C., Gorham, R., 2000. Flexing the Link between Transport and Greenhouse Gas Emissions: A Path for the World Bank. International Energy Agency, Paris, France.
Shaddick, G., Thomas, M., Amini, H., Broday, D.M., Cohen, A., Frostad, J., Green, A., Gumy, S., Liu, Y., Martin, R.V., Simpson, D., van Donkelaar, A., Brauer, M., 2018. Data integration for the assessment of population exposure to ambient air pollution for global burden of disease assessment. In: Environmental Science & Technology.
USEPA, 2006. Clearinghouse for Inventories & Emissions Factors - AP 42, fifth ed. United States Environmental Protection Agency, Washington DC, USA.
Van Donkelaar, A., Martin, R.V., Brauer, M., Hsu, N.C., Kahn, R.A., Levy, R.C., Lyapustin, A., Sayer, A.M., Winker, D.M., 2016. Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors. Environ. Sci. Technol. 50, 3762–3772.
Venkataraman, C., Brauer, M., Tibrewal, K., Sadavarte, P., Ma, Q., Cohen, A., Chaliyakunnel, S., Frostad, J., Klimont, Z., Martin, R.V., 2018. Source influence on emission pathways and ambient PM2.5 pollution over India (2015–2050). Atmos. Chem. Phys. 18, 8017–8039.
Weyant, C., Athalye, V., Ragavan, S., Rajarathnam, U., Lalchandani, D., Maithel, S., Baum, E., Bond, T.C., 2014. Emissions from South Asian Brick Production. Environ. Sci. Technol. 48, 6477–6483.
WHO, 2016. Global Health Observatory data - Mortality and burden of disease from ambient air pollution. http://www.who.int/gho/phe/outdoor_air_pollution/burden/en/ last accessed July 8th, 2018. World Health Organization, Geneva, Switzerland.
WHO, 2018. WHO Global Ambient Air Quality Database (Update 2018). World Health Organization, Geneva, Switzerland.
Wiedinmyer, C., Akagi, S.K., Yokelson, R.J., Emmons, L.K., Al-Saadi, J.A., Orlando, J.J., Soja, A.J., 2011. The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning. Geosci. Model Dev. 4, 625–641.
Wiedinmyer, C., Yokelson, R.J., Gullett, B.K., 2014. Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. Environ. Sci. Technol. 48, 9523–9530.
World-Bank, 2010. Vertical Shaft Brick Kiln - Design Manual. ESMAP Publication Series. The World Bank, Washington DC, USA.