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Air quality, emissions, and source contributions analysis for the Greater Bengaluru region of India

Sarath K. Guttikunda[a,b,c,*], K.A. Nishadh[a], Sudhir Gota[a], Pratima Singh[c], Arijit Chanda[c], Puja Jawahar[a], Jai Asundi[c]

[a] *Urban Emissions, New Delhi, India*
[b] *Division of Atmospheric Sciences, Desert Research Institute, Reno, USA*
[c] *Center for Study of Science, Technology & Policy, Bengaluru, India*

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ABSTRACT

Bengaluru - capital of the state of Karnataka is the original "Silicon Valley" of India. In this paper, we present a comprehensive snapshot of the state of air quality in Bengaluru, along with an emissions inventory for the pollutants necessary for chemical transport modeling at 0.01° grid resolution (approximately 1-km), for an urban airshed covering 60 × 60 grids (4300 km^2). For 2015, emission estimates for the city are 31,300 tons of $PM_{2.5}$, 67,100 tons of PM_{10}, 5300 tons of SO_2, 56,900 tons of NO_x, 335,550 tons of CO, and 83,500 tons of NMVOCs. Overall, transport is the key emission source for Bengaluru - vehicle exhaust and on-road dust resuspension account for a combined 56% and 70% of total $PM_{2.5}$ and PM_{10} emissions; followed by industries (17.8% including the brick kilns), open waste burning (11.0%), and domestic cooking, heating, and lighting (6.5%), in case of $PM_{2.5}$. We conducted particulate pollution source apportionment of local and non-local sources, using WRF meteorological model and CAMx chemical transport modeling system. A comparison of range of 24-hr average modeled $PM_{2.5}$ concentrations (36.5 ± 9.0 μg/m^3) and monitored $PM_{2.5}$ concentrations (32.3 ± 24.2 μg/m^3) by month, shows that the model catches the quantitative ranges and qualitative trends. The modeled source contributions highlight the vehicle exhaust (28%) and dust (including on-road resuspended dust and construction activities) (23%), and open waste burning (14%), as the key air pollution sources. Unless there is an aggressive strategy to improve urban planning and public transport options, pollutant emissions under the business as usual scenario are expected to increase at least 50% in 2030 and doubling the urban area with $PM_{2.5}$ annual averages above the national ambient standard of 40 μg/m^3.

1. Introduction

Bengaluru - capital of the state of Karnataka is the original "Silicon Valley" of India. Since the 1980s, its population has grown exponentially, and the boundaries of the city re-drawn multiple times to accommodate the influx of workers, information technology (IT) campuses, educational institutions, and for people who have made Bengaluru their home (Sudhira et al., 2007; BDA, 2007; SoE, 2015; BDA, 2017). No longer is it a quiet retirement town, rather it is one of India's youngest bustling metropolises.

For the Greater Bengaluru region, the number of studies reporting source emissions are limited, with most reporting analysis for the transport sector (Verma et al., 2015, 2017; Rahul and Verma, 2018). Vreeland et al. (2016) collected $PM_{2.5}$ samples at 24 open waste burning sites in the city, to analyze their chemical characteristics, carbon content, and toxicity. Liu et al. (2018) estimated the impact of seasonal open biomass burning activities on city's air quality using back-trajectories from HYSPLIT dispersion model and fire counts from MODIS satellite feeds for years 2007–13. Gulia et al. (2015) presented pollution analysis for an industrial estate using CALPUFF and AERMOD dispersion models for year 2009. To date (2018), the only comprehensive assessment of air quality in the city was conducted by the Central Pollution Control Board (CPCB, New Delhi, India) (CPCB, 2010), highlighting source contributions from on-road vehicle exhaust, on-road dust resuspension, construction activities, diesel generator sets (DGsets), coal and biomass burning in the domestic sector, industries including brick kilns, and open waste burning. Base year for this analysis was 2006–07, when the filter-based samples were collected and

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* Corresponding author. Urban Emissions, New Delhi, India.
E-mail address: sguttikunda@gmail.com (S.K. Guttikunda).

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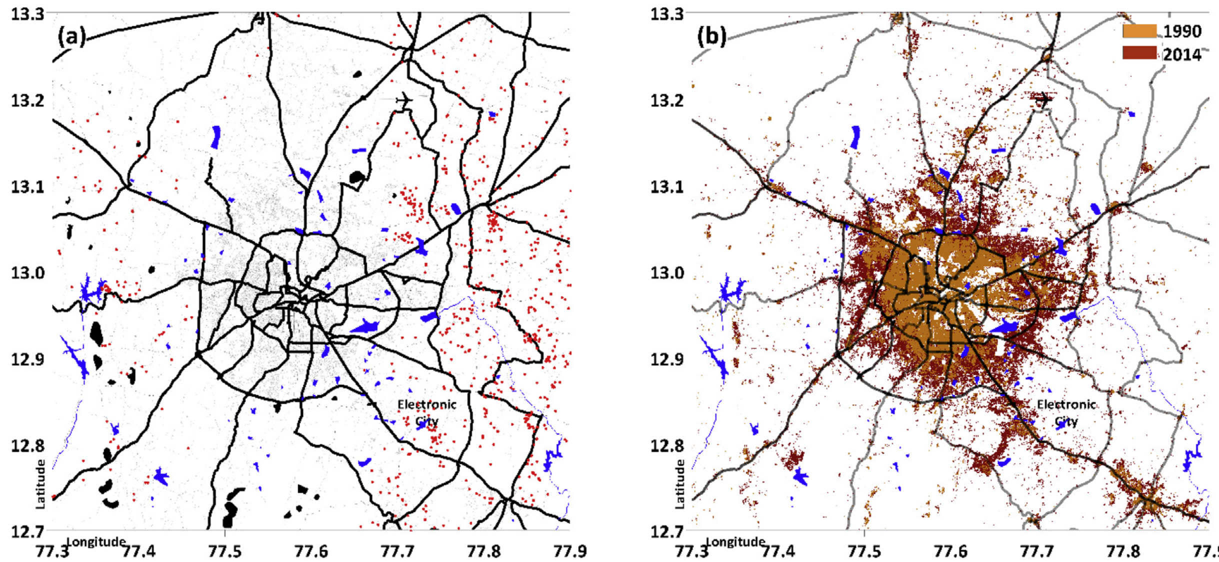

Fig. 1. (a) Selected urban airshed for the Greater Bengaluru region including main roads (thick lines), arterial roads (grey lines), water bodies (blue lines), airport (symbol), quarries (black patches), and brick kilns (red dots) (b) Urban built-up area in 1990 and 2014.

analyzed for receptor modeling and surveys were conducted to support emissions inventory and dispersion modeling using ISCST3 model, for an area covering 624 km^2. This study recorded on-road dust as the major contributor (50%) to PM_{10} pollution (Sharma et al., 2013).

As part of the Air Pollution Knowledge Assessment (APnA) city program for Indian cities, emissions inventory is established for 20 Tier I (with population more than 5 million) and Tier II cities (with population more than 2 million) (India-APnA, 2017). In this paper, we present a comprehensive assessment for the Greater Bengaluru region in three steps (a) review of the air quality data and studies (b) preparation of a multi-pollutant emission inventory at 1-km resolution using data available from multiple sources and (c) chemical transport modeling for the select urban airshed to estimate the source contributions to ambient $PM_{2.5}$ concentrations.

2. Data and methods

2.1. Modeling domain

The Greater Bengaluru region in Fig. 1 is part of the Deccan Plateau extending from 77.3°E to 77.9°E in longitude and from 12.7°N to 13.3°N in latitude. For emissions and pollution modeling purposes, we divided this domain into 60 × 60 grids at 0.01° resolution (approximately 1-km), covering a total area of 4300 km^2. The modeling domain includes the main urban center and the areas with sources which could influence the ambient air quality in the city.

Fig. 1a presents the main road network of approximately 4500 km and Fig. 1b presents the built-up area mapped for 1990 and 2014 (Pesaresi et al., 2016). The built-up area nearly tripled from 330 km^2 to 850 km^2. With its increase in population and a change in the sectors driving its economy, the city is constantly playing catch-up with infrastructure services such as transport and public utilities. Air pollution is a consequence of these rapid changes and poor urban planning - congestion, open waste burning, and dusty construction sites. A city master plan for 2031 released by the local planning body, Bangalore Development Authority (BDA), suggested an expansion of 80 km^2 of built up area, to ease congestion and related environmental pollution, by restricting commercialization and development within the outer ring road (BDA, 2017). While the plan proposes to use the existing landscape productively and sustainably, any expansion of the urban area is inevitably linked to an increase in travel demand, on-road congestion, and consequently deterioration of urban air quality under the business as usual scenarios.

Rapid urbanization has changed the land-cover and the land-use pattern of the city, mostly in the eastern parts containing major IT parks like Whitefield and Electronic city. The total population of the region was an estimated 6.5 million in 2001 and 10.0 million in 2015. With increase in population and the expansion of the city, the demand for travel connectivity has risen. Personalized mode of transportation is preferred over the public mode. With growing number of personal vehicles, the urban planning approach remained road infrastructure centric. The city development plans for 2015 (released in 2007) and 2031 (released in 2017), both evaluated and considered road widening as a significant challenge to reduce traffic congestion and prioritized connectivity of the underdeveloped areas in the outskirts (BDA, 2007; BDA, 2017). Between 2003 and 2017, Bengaluru added more than 10,000 km of road.

2.2. Ambient monitoring data

Air monitoring data in India is available from national ambient monitoring programme (NAMP) under the Ministry of Environment and Forests (Pant et al., 2018). For the longest time, all the monitoring stations were operated manually - 2 samples were collected every week for PM_{10}, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) and the concentrations are recorded in the laboratory for regulatory purposes. From NAMP, only day average concentration data are available for the sampling days. In Bengaluru, these stations are operated by Central Pollution Control Board (CPCB) and Karnataka State Pollution Control Board (KSPCB). A summary of 2004–2015 monitoring data is included as graphs in the Supplementary. A summary of 2011–2015 monitoring data is presented in Table 1.

Impact of the adoption of Bharat IV diesel in Karnataka in 2015 is

Table 1
Annual average ambient concentrations (in μg/m^3) from manual monitoring stations in Bengaluru, 2011–2015.

Year	SO_2	NO_2	PM_{10}
2011	36.8 ± 30.3	69.7 ± 51.4	221.4 ± 187.5
2012	36.0 ± 21.3	73.5 ± 41.0	275.6 ± 180.8
2013	37.2 ± 24.4	77.0 ± 47.3	314.3 ± 213.4
2014	33.8 ± 19.1	74.7 ± 43.4	333.6 ± 216.3
2015	14.7 ± 8.5	54.0 ± 33.6	349.8 ± 205.8

Table 2
Annual average ambient concentrations (in μg/m^3) for 2016–17 from manual monitoring stations in Bengaluru (Category - C = commercial, T = traffic, I = industrial, H = hospital, R = residential).

	Name of the Station	Category	SO_2	NO_2	PM_{10}	$PM_{2.5}$	NH_3	Lead	CO
1	Export pro park, Whitefield	C, T	2.0[a]	33.1	130.9	54.8	29.3	0.1	
2	KHB industrial area, Yelahanka	T, R	2.0	28.5	110.8	53.8	25.4	0.1	
3	Ecopark, Peenya industrial area	I	2.0	37.0	108.9	51.7	36.6	0.1	
4	Swan Silk, Peenya industrial area	I	2.3	37.9	98.9	50.2	35.0	0.1	
5	Yeshwanthpura police station	T	2.0	39.6	93.3	45.9	36.0	0.1	
6	AMCO Batteries, Mysore Road	I	2.0	38.0	106.8	51.0	36.1	0.2	
7	Central Silk Board, Hosur Road	T	2.3	39.4	131.9	58.0	37.8	0.1	
8	DTDC House, Victoria Road	R	2.0	33.7	127.0		23.9	0.1	
9	Banswadi police station	R	2.0	26.8	80.3	41.2	22.0	0.3	
10	CAAQM City railway station	T, R	6.5	45.8	101.9			0.0	900.0
11	CAAQM S. G. Halli	R	3.7	30.3	45.9			0.0	500.0
12	Kajisonnenahalli	R	2.0	24.3	83.2	40.3	22.0	0.1	
13	TERI Office, Domlur	T, C	2.0	32.0	120.1	55.4	39.3	0.2	
14	UVCE, K.R Circle	R, T	2.0	26.3	86.2	38.2	22.9	0.2	
15	Victoria Hospital	H, R	2.0	36.3	79.9	39.7	32.4	0.1	
16	Indira Gandhi children care	H, R	2.0	31.0	77.6	35.9	28.0	0.1	
	City average ± deviation		**2.4 ± 1.2**	**33.8 ± 5.8**	**99.0 ± 23.2**	**47.4 ± 7.5**	**26.7 ± 12.0**	**0.1 ± 0.1**	**700. ± 300.**
	National ambient standard		**50.0**	**40.0**	**60.0**	**40.0**	**100.0**	**0.5**	**2000.0**

[a] These are officially reported values. Concentrations of 2.0 μg/m^3 are likely instrumentation minimums.

evident in the SO_2 concentrations. Sulfur content of diesel was reduced from 350 ppm to 50 ppm. A 25% drop in the NO_2 concentrations can be linked to change in the transport fuel quality. A 50% increase in the PM_{10} concentrations can be linked to growing number of vehicles on the road, dust resuspension linked to the movement of vehicles, and construction activities.

In 2016, KSPCB increased the number of manual stations to 16 and included $PM_{2.5}$. A summary of annual average concentrations at these locations is presented in Table 2. While the data from these exists as 24-hr average concentrations for days on which samples were collected, day-wise information is not available for further analysis and there is a 1-year lag in the availability of this data in the public domain. We are presenting the available annual averages as a reference point. These stations are also categorized into commercial, traffic, industrial, hospital, and residential, depending on the prominent sources of pollution or point of interest (like a hospital) in the immediate vicinity of the station. On an annual basis, PM_{10} and $PM_{2.5}$ exceed the national ambient standards and NO_2 is closer to the standard. SO_2 concentrations are lower than the standard, but questionable since the low values of 2 μg/m^3 are likely instrument minimums. While lead (Pb) is banned for use in the petrochemical products (since the nationwide adoption of unleaded gasoline in 2000), traces of it are still measured. PM_{10} averages in 2016–17 are significantly less than those reported in 2011–15. We speculate that the reason is likely due to an increase in number of monitors and better sampling techniques, along with the introduction of stringent regulations for the construction sector to control dust pollution (CPCB, 2017).

In addition to the manual monitoring network, CPCB and KSPCB started to operate continuous monitoring stations, to report air quality information in real time. Prior to 2018, only 5 stations were operational in the city. In 2018, 5 new stations were introduced by KSPCB. We summarized the ambient concentrations data between March 2015 and February 2018 from all the available stations in Fig. 2. The data pool is small with limited meta information on the instruments and their calibration process. Only conclusion drawn from this figure is that the pollution levels have remained constant between 2015 and 2018. All data average for PM_{10} concentration is nearly double the $PM_{2.5}$ concentration, suggesting a large dust source in the city – mostly road dust resuspension and construction activities.

Of the monitoring data-based studies conducted in Bengaluru, most utilized the open access NAMP data (Nagendra et al., 2007; Sabapathy, 2008; Dholakia et al., 2014; Chinnaswamy et al., 2015, 2016; Thakur, 2017). Some studies collected monitoring data over small periods of time, with various objectives. Both et al. (2011) reported 50–74 μg/m^3 of $PM_{2.5}$ over 168 days in 2008–09 in low- and middle-income neighborhoods in the city. Vailshery et al. (2013) reported 30–70 μg/m^3 of PM_{10} on roads with trees and 150–320 μg/m^3 of PM_{10} on roads without trees, over 17 days in 2010, as part of a study to understand the role of trees in the city. Sabapathy et al. (2012) reported 100–380 μg/m^3 of PM_{10} and 1.5–12.0 ppm of CO, as part of a study to understand personal exposure levels on select arterial roads in 2010–11. Safai et al. (2012) and Rajeevan et al. (2018) reported black carbon (BC) concentrations of up to 5 μg/m^3.

2.3. Satellite derived data

A combination of satellite derived data, ground measurements, and GEOS-chem global chemical transport model were utilized by Van Donkelaar et al. (2016) to establish global annual surface $PM_{2.5}$ concentrations for all years between 1998 and 2016. We summarized the data extracted from this open database for urban Bengaluru in Fig. 3. This is the only long-term annual average data available for the city. In the absence of ground monitoring data this information can be used as a proxy, with an understanding that this data has inherent modeling uncertainties stemming from emission inventories used in the global chemical model and in the processing of the satellite derived aerosol optical depth. Between 1998 and 2016, $PM_{2.5}$ concentration increased 50%, with an annual average of 29.6 μg/m^3 in 2016 – this is under the national ambient standard of 40 μg/m^3 and 3 times the World Health Organization guideline of 10 μg/m^3.

2.4. Emissions inventory

2.4.1. Methods

Urban emissions inventory at 1-km spatial resolution was established for the Greater Bengaluru region for sources including road/rail/aviation/shipping transport, power generation through diesel generator sets, small and medium scale industries, urban road dust resuspension, domestic cooking/heating/lighting, construction activities, and open waste burning. Regional emission sources, where relevant, are also considered in the modeling exercise including open fires, sea salt, dust storms, biogenic, and lightning, but are not included in the urban emissions inventory calculations presented in this paper.

The methodology for estimating emissions is based on activity data by sector (for example fuel consumed for vehicle exhaust, vehicle km traveled for road dust, waste collected or left behind for open waste

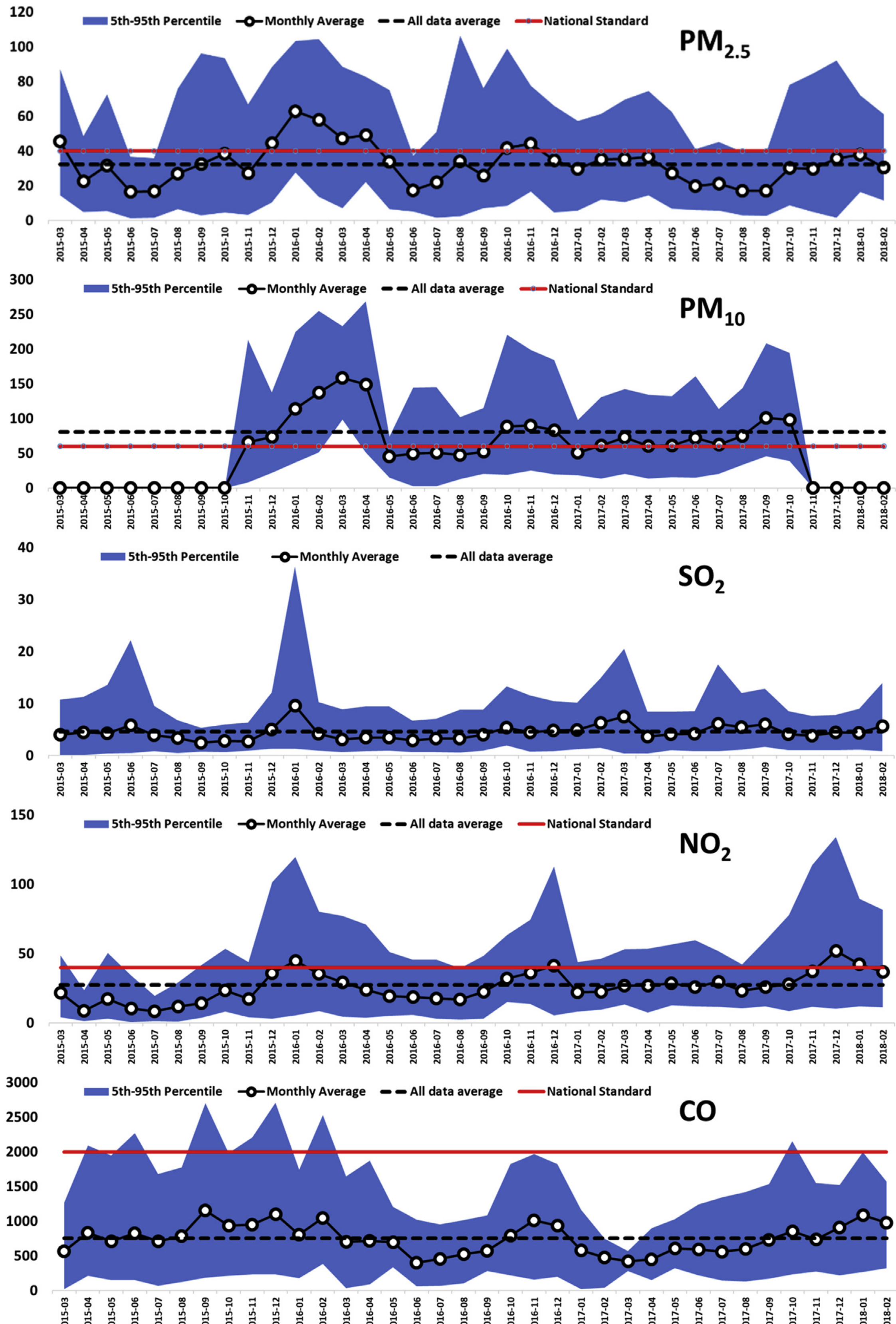

Fig. 2. Variation of 24-hr average ambient concentrations (in μg/m^3) from continuous monitoring stations in Bengaluru between March-2015 and Feb-2018.

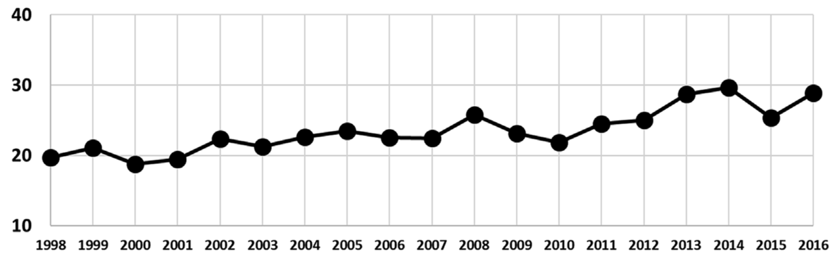

Fig. 3. Evolution of $PM_{2.5}$ annual average concentrations (in µg/m^3) based on global model simulations, satellite data derived estimates, and an assimilation of on-ground measurements for the period between 1998 and 2016 (Van Donkelaar et al., 2016).

burning) and relevant emission factors. The emissions inventory is developed for total PM in four bins (PM_{10} and $PM_{2.5}$, black carbon (BC), organic carbon (OC)), SO_2, nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), and carbon dioxide (CO_2). The overall methods, emission factors, and general assumptions were presented in Guttikunda and Jawahar (2012); Guttikunda and Calori (2013); Guttikunda and Kopakka (2014); Guttikunda and Mohan (2014); Guttikunda and Jawahar (2014); and Goel and Guttikunda (2015). Applicable emission factors for transport, industrial, and domestic sectors were collated from multiple sources (CPCB, 2010; GAINS, 2015; Goel and Guttikunda, 2015; Venkataraman et al., 2018). A copy of the India specific emission factors for all the sectors from GAINS (2015) is available online (registration required).

A library of information was collated for the APnA city program which includes (a) compiled data from - CPCB, state PCBs, Census Bureau, National Sample Survey Office, Ministry of Road Transport and Highways, Ministry of Statistics and Program Implementation, Annual Survey of Industries, Central Electrical Authority, and Municipalities (for Bengaluru from BBMP, BDA). (b) dynamic inputs from - NASA satellite feeds on open fires, dust events, and lightning, meteorological feeds, traffic speed maps (an API 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 (c) linkages to monitoring data from official and unofficial networks to evaluate model performance. Besides the vehicle speed maps, google's API service was also utilized 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, all of which were used as influential layers during the spatial allocation of estimated total emissions to 1-km x 1-km grids. The methods and relevant databases for all key sectors are also documented at Guttikunda et al. (2019) and India-APnA (2017).

2.4.2. Transport sources

A quick expansion of city area, population, and economic activities in the peri-urban areas has resulted in high vehicle ownership rates. Number of vehicles registered per 1000 population, increased from 150 in 1990 to 300 in 2001 and 600 in 2016 (Fig. 4a). Between 1980 and 2016, Bengaluru's vehicle registration increased at an annual growth rate of 10.6%, which is double the annual growth rate observed in New-Delhi over the same period (DES-Delhi, 2016). Personal vehicles comprise of 90% of the total registered vehicles of 6.7 million in 2016 – with two-wheelers (73%), four-wheelers (15%), 3-wheeler auto-rickshaws (4%) and buses, light duty vehicles (LDVs), heavy duty vehicles (HDVs) forming the remaining 8% (MoRTH, 2017). Total registered vehicles in 2006 was 2.8 million. The 2011 national census revealed that 44% and 17% of households in Bengaluru own at least one 2-wheeler and one car respectively (Census-India, 2012).

In the city, most of the traffic growth is concentrated along central districts and the outer suburban areas on the east side. BDA (2012) reported annual traffic growth rates of 2–4% in the central zone, 5–7% in the intermediate zone, and 8–9% in the outer peripheries along the regional roads. The per capita passenger trip rate has increased from 0.82 in 2001 to 1.0 in 2007 and 1.4 in 2011 (DULT, 2011a,b). The public transport mode share reduced significantly from 42% in 2007 to 27% in 2011, despite an increase in the number of buses (Fig. 4b). In 2003, Bengaluru Metropolitan Transport Corporation (BMTC) used to operate 3000 buses for a population of 5.6 million with one bus for 1800 people. In 2016, BMTC operated a fleet of 6400 buses for a population of 11.0 million with one bus for 1700 people (SoE, 2015). This is lower than the international standards (World-Bank, 2006).

We summarized the vehicle speeds for the urban area in Fig. 5. For each 1-km x 1-km grid, distance and duration in traffic was tracked for two random routes. Average route distance for all the urban grids is 6.2 ± 3.9 km per grid. Common features are evident in the plot – with higher vehicle speeds in the morning and late evening; rush hour starting around 9 a.m. and vehicle speeds picking up after 10 p.m. Overall average vehicle speed in the city is 17.1 km/h during the rush hours and 20.3 km/h during the non-rush hours. Within the core urban

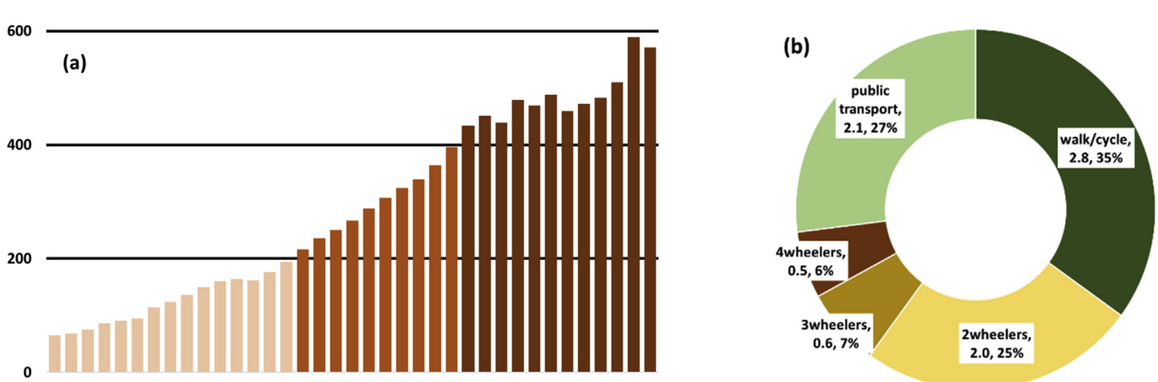

Fig. 4. (a) Number of registered vehicles in Bengaluru per 1000 population between 1980 and 2016 (data - Bangalore traffic police and Ministry of Road Transport and Highways) (b) Number of passenger trips per day in 2011 in the Bengaluru district (data – BMTA).

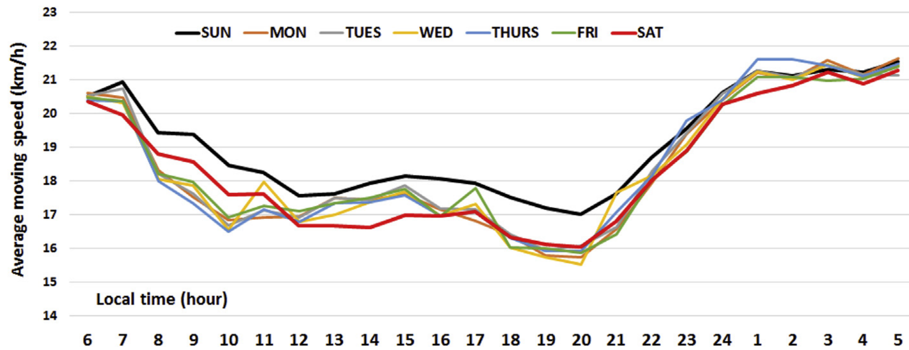

Fig. 5. All vehicle urban average hourly moving speeds (km/h) by weekday. Data is sourced from Google APIs paid service for a period of three weeks.

area (almost in the middle of the modeling domain), day time average vehicle speeds are under 10 km/h. The speeds are the highest on Sunday, which is a public holiday. From Monday to Friday, the diurnal patterns are very similar. On Saturday, there is a delay of 3 h in the morning for the average vehicle speeds to drop further, which is likely due to a reduction in the early morning school traffic and some institutions practicing holiday. The grid level information was used as one of the proxies for spatial allocation of the transport emissions and to adjust the emission loads based on average vehicle speeds in the grid.

In Bengaluru, Phase-1 of the metro rail system called “NAMMA METRO” covers 42 km with expansion expected to reach 114 km by 2020. However, even with the rapid development of the metro rail, the revised master plan projects a congested outlook of traffic by 2031 (BDA, 2017). Latest estimates indicate that the combined trips by public transport, walking and cycling constituted 62% of total trips. However, future business-as-usual forecasts for 2031, indicate a significant shift towards private motor vehicles, accounting for 52% of total trips, with an average traffic speed of 11 km/h.

Movement of goods represent a considerable portion of the urban traffic volume. The main freight strategy for Bengaluru city includes (a) restrictions - on priority corridors, entry of HDVs and LDVs is restricted to between 10 p.m. and 9 a.m. For vehicles violating the restrictions, fines are imposed daily (b) promoting the use of outer-ring roads - the present freight related road network consists of multiple ring roads with nine major radial corridors. (c) development of freight trip generators along the ring road, i.e. truck terminals, integrated freight complexes, warehouses and freight consolidation centers. However, the 2031 master plan does not prioritize freight management improvements. There is limited information available on the number of freight trips and tons carried through the city, to support any improvement. The global estimates suggest that a city could annually generate between 2 and 50 tons per capita freight (World-Bank, 2009). Considering the minimum value, Bengaluru city could generate at least 50,000 tons of freight per day. SoE (2015) reports 20,000 HDVs enter the city every day, of which 10,000 trucks are just passing through. Remaining 10,000 trucks to move 50,000 tons of freight every day is considered a conservative estimate.

Bengaluru city is in the middle of the Deccan plateau and traditionally known to be dusty. While the infrastructure programs focus on building roads, these roads are often left unpaved, increasing the possibility of dust re-suspension when vehicles pass (CPCB, 2010). The emissions inventory includes some dynamic corrections linked to the modeled meteorological data at 1-km^2 grid resolution and 1-h temporal resolution. For example, (a) grids with precipitation over 1 mm/h are adjusted for lesser vehicle movement (b) grids with precipitation over 1 mm/h are adjusted for no dust resuspension on the roads and at the construction sites. The dust resuspension rates are maintained at lower levels, depending on the modeled surface moisture content.

The transport sector emissions also include aviation, for which landing and takeoff (LTO) statistics are obtained from the directorate general of civil aviation (DGCA). Bengaluru airport is the 3rd largest in India (handling 25 million passengers in 2017) and handles 600 LTOs per day serving domestic and international destinations. Besides aircraft operations, other support activities within the airport that result in emissions include baggage handling, shuttling passengers, movement of support staff, catering, and fueling, which require vehicles like buses, tractors, cars, and vans of various sizes. These vehicles are often fueled by diesel. Outside the airport, activities include idling and slow-moving vehicles dropping off or picking up passengers.

2.4.3. *Non-transport sources*

Bengaluru is India's leading IT exporter, 7th largest technological hub in the world and largest in Asia, with 27 special economic zones and has an economic growth of 10.3% (Forbes, 2017). Though there are no heavy industries in the selected urban airshed, there are multiple small-scale industries including engineering, metal, textile, wood, printing, rubber, plastics, food, chemicals, and glass processing. Of the 3400 registered industries in the city, 1600 are under red category, which require pollution inspection every month (MSME, 2017). Although as per CPCB norms, these industries are required to monitor and report pollution levels for all the criteria pollutants, only 124 are maintaining an in-house monitoring station, but this data is not yet in the public domain.

Construction is one of the fastest growing sectors in the city and the demand for bricks is growing. Most of the bricks kilns are located to the east of city (red dots in Fig. 1), majority of them using fixed chimney technology for baking. An example of typical brick kiln in the area, with a stack of approximately 50 feet, is presented in the Supplementary. Unlike the brick kilns in the Indo-Gangetic plain, these are covered kilns, which can be operated throughout the year, with a production capacity of 10,000 to 20,000 bricks per day (Guttikunda and Calori, 2013; Guttikunda et al., 2013; Weyant et al., 2014). There are approximately 700 clamp and fixed chimney brick kilns in the selected airshed, with an estimated production capacity of 1 billion bricks per year, which use field residue, wood, and coal as primary fuel.

At the construction sites, disposal of debris and transport of construction material also contribute to the emission loads. CPCB (2017) mandated sprinklers, green air barriers, and compulsory use of water jets in grinding and stone cutting, which is often missing from constructions sites. Movement of vehicles carrying construction materials create stress on the road infrastructure and dust pollution when operated without a mandatory cover. Karnataka High Court limited the movement of debris carrying vehicles to 6 a.m. and 8 a.m.

Solid waste generation rate in Bengaluru city is 4000 tons/day, which is more than 2-times and 6-times the rate in 2000 and 1988, respectively (Chanakya et al., 2015; SoE, 2015; Chandran and Narayanan, 2016; Ramachandra et al., 2018). Bruhat Bengaluru Mahanagara Palike (BBMP) is responsible for solid waste management in the city and has acquired the following sites for waste processing and land filling - Mavallipura - 100 acres; Mandoor - 135 acres; Kannahalli -

Table 3
Variation in the 24-hr average meteorological fields over the Bengaluru city in 2015 (extracted from WRF simulations using the NCEP reanalysis fields).

	Mixing height (m)	Surface wind speed (m/s)	Surface temperature (C)
January	360 ± 38	4.5 ± 1.0	19.3 ± 1.3
February	461 ± 74	5.1 ± 1.0	20.5 ± 1.5
March	536 ± 90	4.6 ± 1.1	23.9 ± 1.1
April	592 ± 109	4.2 ± 1.4	26.2 ± 1.4
May	519 ± 132	5.5 ± 1.7	27.0 ± 1.6
June	512 ± 80	8.1 ± 2.8	24.5 ± 1.4
July	622 ± 71	7.6 ± 1.0	24.8 ± 0.4
August	480 ± 68	5.5 ± 1.3	24.4 ± 0.6
September	393 ± 53	4.3 ± 2.1	24.1 ± 0.8
October	345 ± 59	3.9 ± 1.8	22.9 ± 0.8
November	326 ± 72	5.2 ± 1.6	21.5 ± 1.2
December	326 ± 71	5.0 ± 1.5	20.3 ± 1.4

29.1 acres; and Kyalasanahalli - 46 acres (ESG, 2018). Most of these landfills are abandoned quarries and operated without any environmental clearances and necessary operations to manage waste, leaching, and other environment related problems. About 70% of the waste management from primary collection to disposal has been outsourced, 30% of the remaining work is carried out by BBMP, which is transported to treatment sites using compactors, tipper trucks, and dumper placers. BBMP established 188 dry waste collection centers to encourage dry waste segregation at source, 7 construction and demolition waste treatment units, 10 mixed waste treatment facilities, 7 landfill sites, and 15 decentralized bio-methanation facilities to process wet waste. Further, bulk waste generators like hotels, restaurants, kalyan mantaps (wedding halls), and apartments, were directed to establish a system to handle municipal solid waste in their premise or through empaneled service providers. Many of the treatment facilities are dysfunctional and hence heaps of waste lying on the roads can be seen across the city. The only measure adopted by the society is open waste burning, which leads to an uncertain amount of toxic air emissions. Also, the heavy duty and the light duty vehicles utilized for waste collection are not maintained regularly, further adding to the emission load from this sector.

There are no power plants in the selected airshed, while the state of Karnataka hosts more than 6.3 GW of coal fired power generation (Guttikunda and Jawahar, 2014; NPP, 2018). Bengaluru has approximately 870,000 registered commercial customers, consuming 4460 million units of electricity per day (BESCOM, 2016). CSE (2018) found that pollution level is up 30% during the usage of DGsets in Delhi and its satellite cities. While power cuts are rare in the city, but often the supply is not at full capacity. Being a commercial hub, the use of DGsets is common at large establishments like hotels, hospitals, restaurants, cinema halls, malls, apartment complexes, institutions, metro rail stations, funeral homes, and more than 10,000 telecom towers.

According to Census-India (2012), 80% urban and 60% rural household's use liquified petroleum gas (LPG) and electricity as their primary fuel for cooking. While kerosene is prohibited, 15–20% of the households continue to use it for cooking and lighting. Rest of the households reported to use biomass, other wood, field residue, coal, and cow-dung. Since 2012, the use of cleaner fuels (LPG and electricity) has increased under the Prathan Mantri Ujjwala Yojana scheme (MoPNG, 2018).

2.5. Modeling $PM_{2.5}$ and PM_{10} concentrations

2.5.1. Chemical transport model

We modeled particulate concentrations utilizing the emissions inventory from this study and the Comprehensive Air Quality Model with Extensions (CAMx) (http://www.camx.com). This is an open-source Eulerian chemical transport model, with detailed advection and scavenging schematics (dry and wet deposition) and supports gas to aerosol conversions via multiple chemical mechanisms (for SO_2 to sulfates, NO_x to nitrates, and VOCs to secondary organic aerosols). In this study, we focused on particulate pollution analysis only, even though multi-pollutant emissions inventory is available for photochemical modeling.

CAMx modeling system was also utilized to establish source contributions to annual and seasonal $PM_{2.5}$ ambient concentrations. One simulation was conducted with all the sources included and multiple simulations were conducted without the individual sectors for which source contributions needed to be calculated. The difference between the sum of individual contributions and the all source simulation is determined as the contribution from sources outside the selected urban airshed. A national scale simulation was conducted over the Indian Subcontinent at 0.25° grid resolution, which was utilized to produce boundary conditions for the Greater Bengaluru region at 1-h temporal resolution (details on national emissions inventory and modeling framework are available online @ http://www.indiaairquality.info). The boundary conditions for the India Subcontinent were obtained from MOZART global chemical transport model, for which a pre-processor module is available with the CAMx modeling system.

2.5.2. Meteorological data

For the designated urban airshed, meteorological data was processed in a nested mode, starting with the global NCEP Reanalysis inputs (NCEP, 2016), downscaled to the Indian Subcontinent at 0.25° resolution and finally arriving at 0.01° resolution via 2 sub-grids within the "Weather Research and Forecasting" (WRF) model (https://www.mmm.ucar.edu/wrf-model-general). The final output from the WRF model is maintained at a temporal resolution of 1-h for each grid. The vertical resolution of the model extends to 12,000 km over 35 layers. There are 12 layers under 1 km to support better vertical mixing of the emissions and average surface layer height is 30 m.

We summarized the variation of daily average meteorological fields (temperature, wind speeds, and mixing height) by month in Table 3. The temperatures over Deccan Plateau are uniform over the months. The mean annual rainfall is 1000 mm, mostly between June and October. Winds of mostly Westerly between May and September and Easterly for the remaining months. High wind speeds throughout the year and an annual average mixing height of 769 ± 241 m during the day time and 143.9 ± 111.3 m during the night time, allows for significantly dispersion of emissions than that observed over North Indian cities where the mixing heights can be under 50 m and low wind speeds for Winter months (Guttikunda and Gurjar, 2012).

3. Results and discussion

3.1. Emissions inventory

3.1.1. Annual emissions

For 2015, the emissions inventory results are summarized in Table 4. For the modeling domain, we estimated 31,300 tons of $PM_{2.5}$, 67,100 tons of PM_{10}, 5300 tons of SO_2, 56,900 tons of NO_x, 335,550 tons of CO, and 83,500 tons of NMVOCs. Under the APnA city program, for 20 Indian cities, average city $PM_{2.5}$ emissions is 22,500 tons/year with a maximum of 94,000 tons/year for the city of Chennai (a metropolitan city with 10 + million population, large vehicle fleet, and large industrial area with a commercial port) and a minimum of 5000 tons/year for the city of Dehradun (hilly, tourist destination) (India-APnA, 2017; Guttikunda et al., 2019).

Overall, transport is the key emission source – in the form of vehicle exhaust and on-road dust resuspension which account for 56% and 70% of total $PM_{2.5}$ and PM_{10} emissions, respectively; followed by industries (17.8% including the brick kilns); open waste burning (11.0%); and domestic cooking, heating, and lighting (6.5%) in case of $PM_{2.5}$. The emission load split leaning towards transport is an indication of how

Table 4
Estimated annual particulate and gaseous pollutant emissions (in tons/year) for the Greater Bengaluru region in Karnataka, India for the base year 2015.

Category	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC
Vehicle exhaust	12,550 (40.1%)	13,200 (19.7%)	1300 (24.5%)	24,100 (42.4%)	237,300 (70.7%)	70,650 (84.6%)
Domestic	2050 (6.5%)	2050 (3.0%)	750 (14.2%)	1400 (2.5%)	20,300 (6.%)	2350 (2.8%)
Industries	2650 (8.5%)	2700 (4.0%)	1650 (31.1%)	16,050 (28.2%)	20,600 (6.1%)	2900 (3.5%)
Dust	6400 (20.4%)	41,200 (61.4%)				
Waste burning	3500 (11.2%)	3700 (5.5%)	100 (1.9%)	100 (0.18%)	16,800 (5.%)	3400 (4.1%)
Generator sets	1250 (4.0%)	1350 (2.0%)	100 (1.9%)	11,950 (21.0%)	3150 (0.94%)	300 (0.36%)
Brick kilns	2900 (9.3%)	2900 (4.3%)	1400 (26.4%)	3300 (5.8%)	37,400 (11.1%)	3900 (4.7%)
Total	**31,300**	**67,100**	**5300**	**56,900**	**335,550**	**83,500**

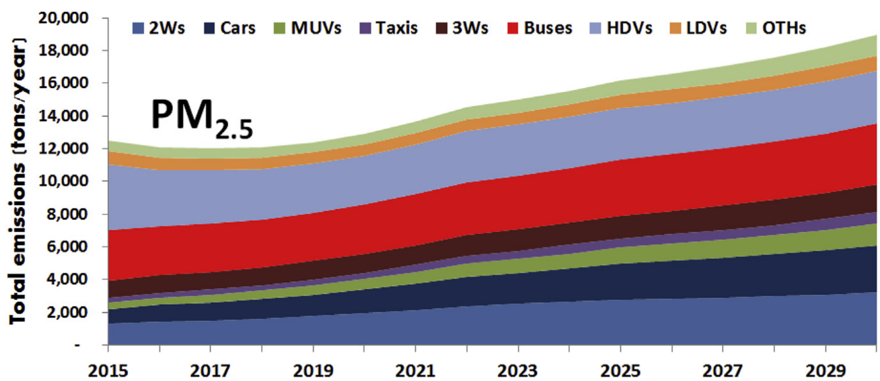

Fig. 6. Estimated vehicle exhaust emissions inventory by vehicle mode for the period of 2015–2030 for the Greater Bengaluru area.

much the city needs a better urban transport planning. Within the transport sector, more than 70% of $PM_{2.5}$ emissions originate from a small fraction of diesel operated vehicles (some 4-wheelers including taxis, buses, HDVs, and LDVs).

Estimated total emissions of $PM_{2.5}$, SO_2, and NO_x for the period of 2015–2030 are presented in the Supplementary. Under the business as usual scenario, in 2030, we estimate an increase of 54% in $PM_{2.5}$, 70% in PM_{10}, 35% in SO_2, 55% in NO_x, 107% in CO, and 133% in VOC annual emissions for the region. This is after considering the proposed urban transport and household energy mix improvements. Largest increases are expected in the transport sector – 50% from vehicle exhaust and 80% from road re-suspension dust and construction dust. While an improvement in the fuel standards is expected to lower the overall transport emissions, a gradual increase in the number of vehicles and vehicle km traveled is nullifying those benefits over time. These estimates are for business as usual conditions. For vehicle exhaust, there is a proposal for the introduction of Bharat-VI fuel standards nationwide, but the timeline is not set. Among the pollutants, SO_2 will have a 4-fold drop in the total emissions when the new fuel standards are implemented. In 2030, the share of vehicle exhaust and on-road re-suspended dust account for 60% and 74% of the total $PM_{2.5}$ and PM_{10} emissions, respectively. Projected $PM_{2.5}$ emissions for vehicle exhaust by vehicle mode is presented in presented in Fig. 6. Largest increases are expected from the personal transport linked to increasing vehicle km traveled and slower vehicle speeds in the city.

The emissions inventory in CPCB (2010) covered an area of 24 km × 26 km of urban Bengaluru (624 km^2) with reported totals of 54.4 tons/day for PM_{10}, 217.4 tons/day for NO_x and 14.6 tons/day for SO_2, which translates to 19,900 tons/year, 79,350 tons/year, and 5300 tons/year, respectively, for the study year 2006 and projected a 100% increase in emissions of PM_{10} and NO_x between 2006 and 2017 (a ten year horizon at the time of the study). Overall, there has been a 300% increase in PM_{10} emissions between CPCB (2010) estimates and our estimates. This is primarily due to an exponential increase in the construction activity and associated dust emissions. Overall, the NO_x emissions have lowered despite an increase in the vehicle count due to gradual introduction of better vehicle and fuel standards since 2006. Bharat-III (equivalent of Euro III) standards were introduced in 2010 and Bharat-IV standards were introduced in 2015. For comparison, the modeling domain in this study covers an area of 4300 km^2.

The annual emissions inventory is based on bottom-up sector specific activity data and information on emission factors from secondary sources (India-APnA, 2017; Guttikunda et al., 2019). For the estimates presented in Table 4 we summarize the uncertainties below. For vehicle exhaust emissions, the largest uncertainty margin is in vehicle km traveled and vehicle age distribution with an uncertainty of ± 20% for passenger, public, and freight transport vehicles. A series of fuel station surveys like those conducted in Delhi (Goel et al., 2015) are planned to better understand this variability with age of the vehicle. The dust re-suspension is linked to the silt loading on the roads originating from tire wear and tear, construction dust, natural wind erosion, and dry deposition of particles. This has an uncertainty of ± 25%. In the brick manufacturing sector, we assumed a constant production rate per kiln, which has 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 from a small sample of telephone surveys to hotels, hospitals, large institutions, and apartment complexes, with an uncertainty of ± 30%.

3.1.2. Gridded emissions

The gridded $PM_{2.5}$ emissions inventory for 2015 and 2030 is presented in Fig. 7. For convenience only $PM_{2.5}$ is presented in this paper. The proposed urban development plan (BDA, 2017) centered around augmentation of infrastructure in and around the city, is expected to at least double the number of hot spots for emissions. We utilized multiple layers of spatial proxies to grid the estimated sectoral emissions to 0.01° grids. The details of the methodology are described in Guttikunda and Jawahar (2012) and Guttikunda et al. (2019) and the layers of information involved in this step are listed in the Supplementary. For example, for the road transport emissions - layers of road density maps of highway, main arterial roads, feeder roads, and others; population

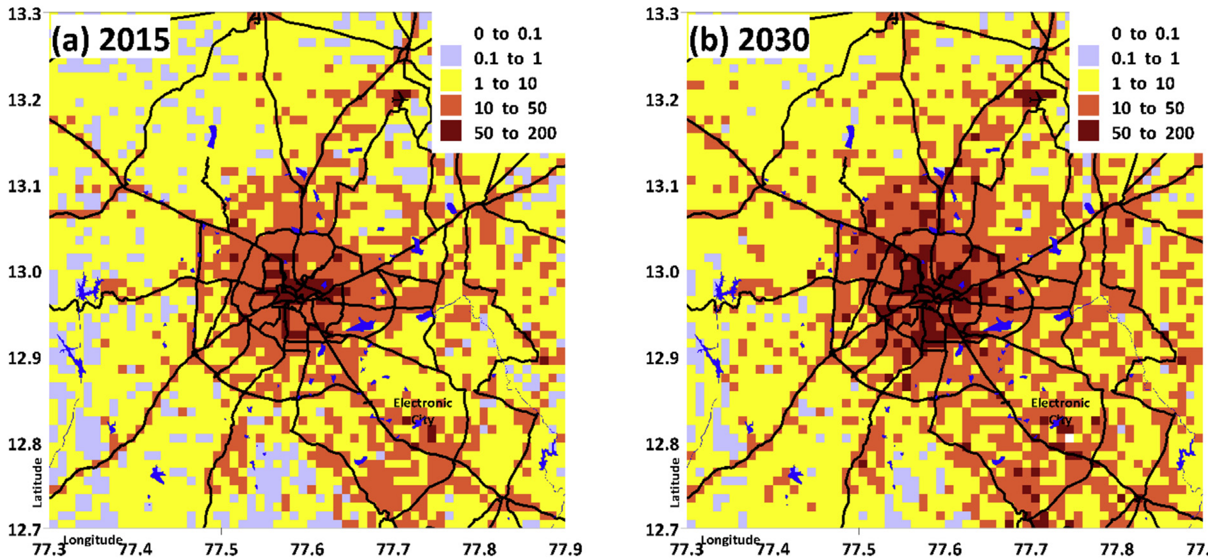

Fig. 7. Gridded annual $PM_{2.5}$ emissions (in tons/year/grid) for the Greater Bengaluru region for (a) 2015 (b) 2030, at 0.01° (approximately 1-km) spatial resolution.

density at the grid level; the urban extent of the grid; information on commercial activity in each of the grids in the form of hotels, hospitals, markets, industrial estates, apartment complexes (this information was gathered from google maps API service) and the vehicle speed data presented in Fig. 5, are used as a proxy to ascertain vehicle density spatially and temporally. For the industrial sector, including the brick kilns, emission loads are assigned to the grid where the sources are. The domestic sector, open waste burning, and construction activities follow the population density map.

3.2. Particulate pollution

3.2.1. Modeled concentrations for 2015

Annual average $PM_{2.5}$ concentration map is presented in Fig. 8 and the monthly average concentration maps are presented in Fig. 9. This summary includes secondary particulate concentrations. The modeled annual urban average $PM_{2.5}$ is 36.5 ± 9.0 μg/m^3 (domain maximum is 76.2 μg/m^3) – this is representative of approximately 600 urban grid cells (of all 3600 grid cells in the modeling domain). Measured annual average from 13 manual monitoring stations (Table 2) is 47.4 ± 7.5 μg/m^3, representing approximately 120 grid cells (assuming a monitoring station is representative of a 2-km radius). Measured annual average from 3 continuous monitoring stations summarized in Fig. 3 is 32.3 ± 24.2 μg/m^3. Estimated annual average based on satellite AOD data and global chemical transport modeling is 29.6 μg/m^3 – this represents an average for the entire city district. Among India's big cities, Bengaluru is considered one of the cleaner cities, because of it low $PM_{2.5}$ concentrations, closer to the national annual ambient standard of 40 μg/m^3. Monthly average $PM_{2.5}$ concentration maps are presented in Fig. 9. Summer months (May to August) overlap with the rainy season dropping the concentrations to under 40 μg/m^3 throughout the city.

3.2.2. Comparison with ambient measurements

We present in Fig. 10 a comparison of range of 24-hr average $PM_{2.5}$ concentrations by month for monitored concentrations from all stations and modeled concentrations over the urban area. We present in Fig. 11 a comparison of 24-hr average monitored concentrations against modeled concentrations extracted for 25 grid cells surrounding the stations. The comparisons are presented here to ascertain some confidence in the emissions inventory and chemical transport modeling analysis for the Greater Bengaluru region. We acknowledge that the monitoring data available is limited – only 3 continuous stations reported $PM_{2.5}$ data for the study period, covering 60% of the days. This

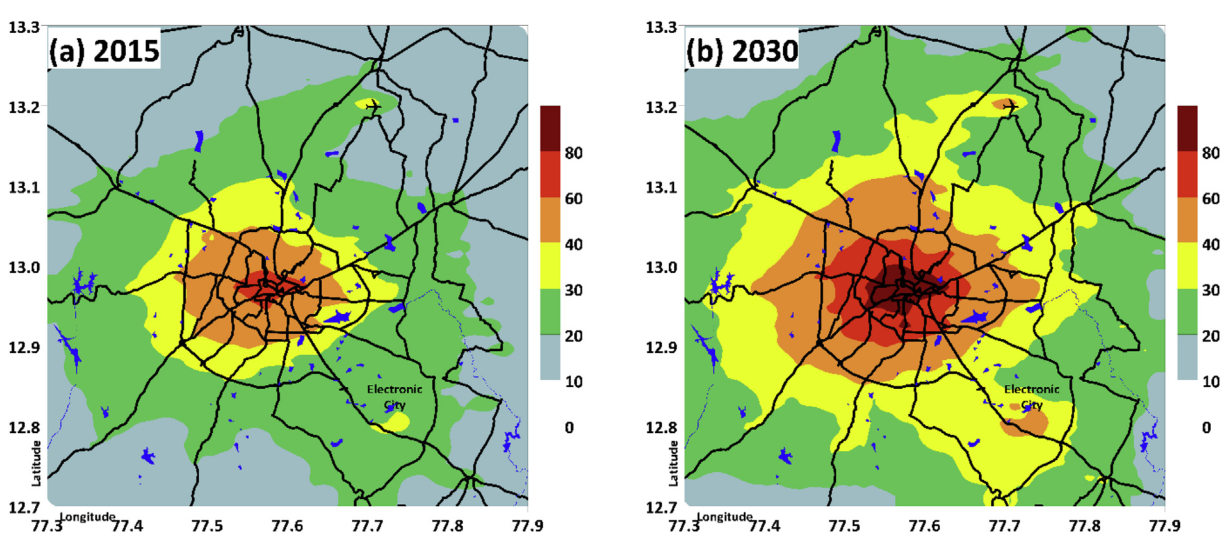

Fig. 8. Modeled annual average $PM_{2.5}$ concentrations in μg/m^3 in (a) 2015 and (b) 2030.

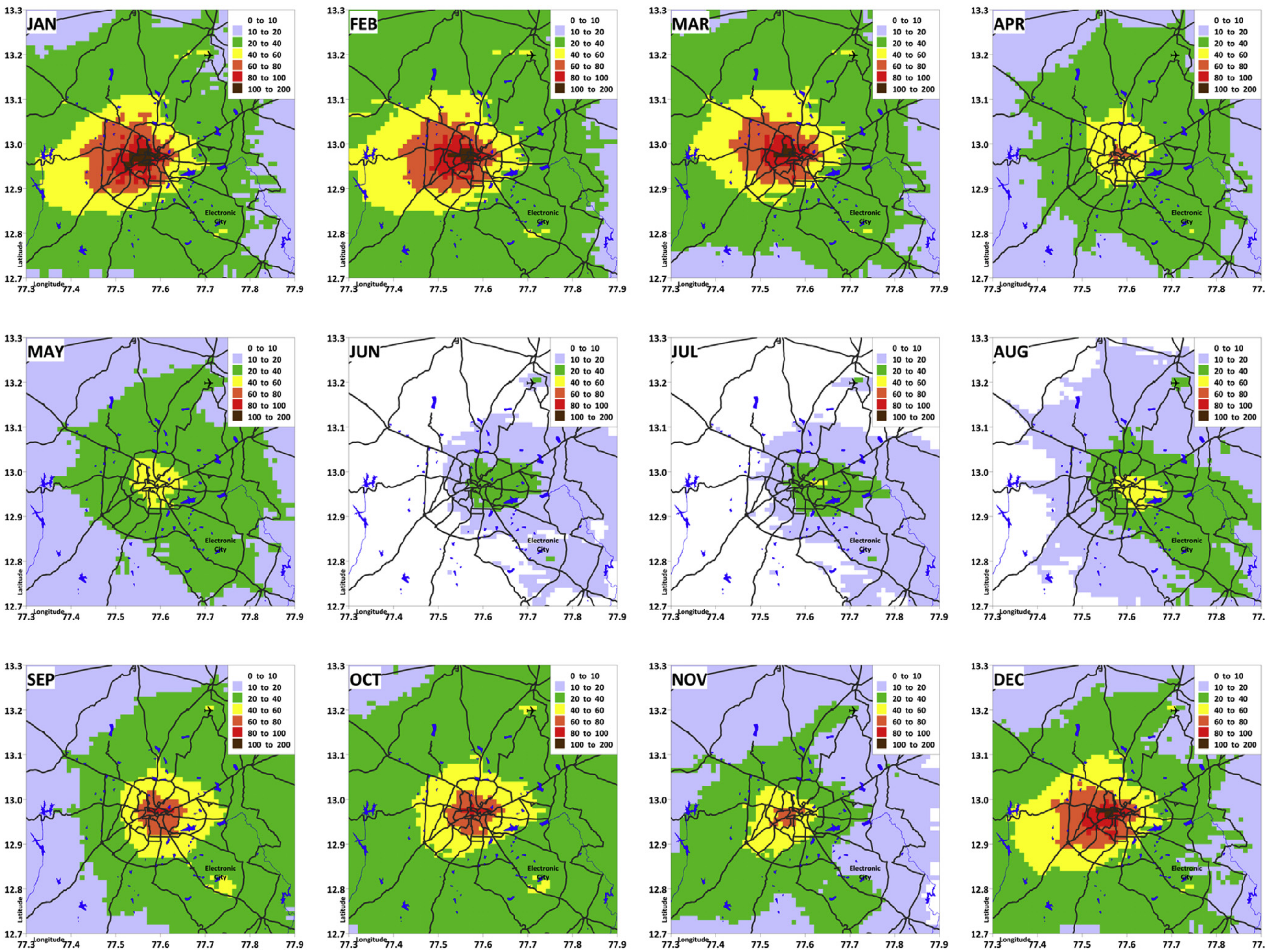

Fig. 9. Modeled monthly average $PM_{2.5}$ concentration (in μg/m^3) for the Greater Bengaluru region.

evaluation has limited scope at this stage and will be revisited, when data from the new stations are available for scrutiny and evaluation of the spatial disaggregation of the emissions. The model captures the quantitative range and qualitative trend of the measurements for all the months. The modeled day to day averages in and around the monitoring stations are higher. The months of November to February exhibit the seasonal highs and the monsoonal months of June–August exhibit the lows.

There is a need for more continuous monitoring stations in the city to better assess these trends. The manual stations provide samples for further analysis, such as chemical speciation and receptor modeling based source apportionment (CPCB, 2010; Sharma et al., 2013), but are limited in providing details on diurnal and seasonal cycles, which is key to support an air quality management plan. Based on the thumb rules designed by CPCB for Indian cities, we estimated that the Greater Bengaluru region requires at least 41 continuous monitoring stations to spatially and temporally represent its pollution levels (India-APnA, 2017; Pant et al., 2018). The thumb rules are detailed in CPCB (2003) which takes into consideration the district total population, urban extent, and landuse types. A likely spatial spread of these monitors, based on the gridded population and urban-rural landscape for the modeling domain is presented in the Supplementary. Of the estimated 41 stations,

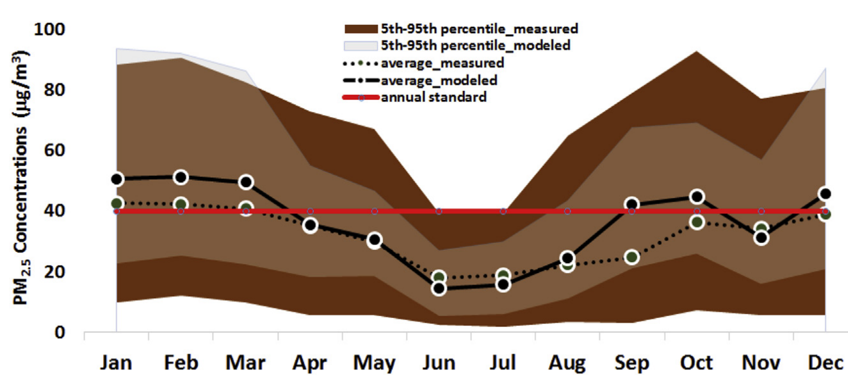

Fig. 10. Comparison of range of 24-hr average $PM_{2.5}$ concentrations (in μg/m^3) by month. Measurements data is an average of data from all the continuous monitoring stations Modeled data represents an average for 600 urban grids (of 1-km^2 each) in Bengaluru.

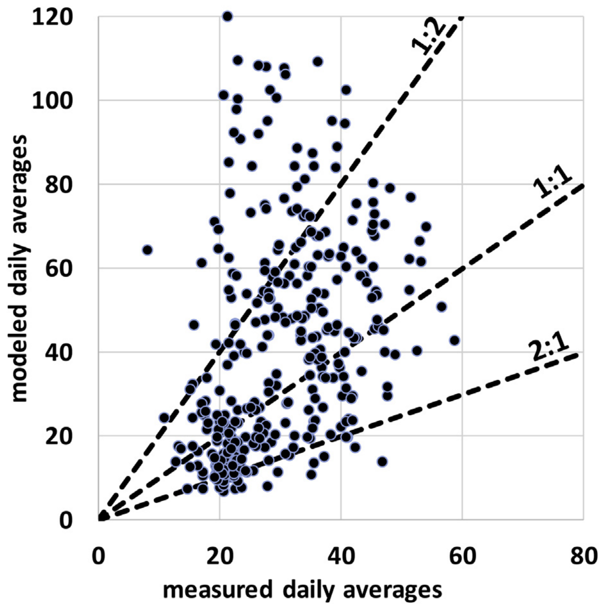

Fig. 11. Comparison of 24-hr average $PM_{2.5}$ concentrations (in $\mu g/m^3$) from the continuous monitoring stations against the modeled concentrations from 25 (1-km^2) grids surrounding the stations in Bengaluru.

Table 5
Modeled annual average percentage source contributions for the Greater Bengaluru region (average and standard deviation is for the variation among the annual average contribution estimated at the grid level for all the urban grids).

Domestic (includes cooking, heating, and lighting)	8.9 ± 6.8%
Transport (includes road, rail, and aviation)	28.1 ± 8.9%
Dust (includes on road dust resuspension and construction activities)	22.9 ± 11.6%
Brick kilns	2.9 ± 1.5%
Industries	1.5 ± 3.8%
Open waste burning	14.4 ± 11.5%
Diesel generator sets	3.8 ± 2.2%
Outside (modeled as the influence of the boundary conditions to the urban airshed)	17.2 ± 5.6%

29 stations are expected in 8 urban zones of Bengaluru, 5 stations outside these zones but within the district, and 7 stations outside the district to represent background concentrations.

3.2.3. Modeled source contributions

The modeled annual average source contributions are presented in Table 5 and a summary by month is presented in Fig. 12. Annual averages highlight the vehicle exhaust (28%), dust (including on-road resuspended dust and construction activities) (23%), and open waste burning (14%) as the key air pollution sources. These are also the 3 key sources highlighted in CPCB (2010) and Sharma et al. (2013). Other sources include DGsets, domestic cooking and heating, and industries. While a large cluster of brick kilns is included in the modeling airshed, their contribution is limited only due to the advantage of yearlong strong westerly winds, which tend to disperse the kiln emissions away from the city center. The monthly variation is strong for the domestic and the dust sectors. As the temperatures drops between October–December, a small increment is evident in the domestic heating sector. Similarly, a drop is evident in the dust contributions during the monsoonal months. The regional impacts are also strong, with an estimated 17% of the ambient annual $PM_{2.5}$ pollution originating outside the urban airshed - this contribution is mostly from domestic, industrial (including brick kilns), and freight movement activities outside the urban airshed and seasonal open biomass fires. A tabular representation of these source contributions by month is included in the Supplementary.

3.2.4. Modeled concentrations for 2030

While overall air pollution levels in Bengaluru are less than those observed in Delhi and Bengaluru is not listed among the top polluted cities in the world (WHO, 2018), it is important to note that, if the emissions are left unchecked at the current growth rates, we are expecting at least 50% increase in the local emissions and a doubling of ambient $PM_{2.5}$ pollution levels in 2030 (presented in Fig. 8). The emission projections to 2030 are under business as usual scenario, without considering any interventions for the future years.

There are several proposals made by the local authorities to help reduce the emission loads from various sectors, but there is no time bound target or an implementation plan. For example KSPCB proposed measures to regulate emissions from the on-road vehicles, such as (a) limit on number of new vehicle registrations (b) ban on entry of HDVs not delivering in the city (c) ban on commercial and passenger 3-wheeler autorickshaws in central business district (d) ban on use of vehicles more than 15 year old (e) denial of fuel for vehicles without a PUC certificate (f) integrated traffic demand management including intelligent traffic systems (ITS) integrating all public transport modes (g) conversion of all passenger 3-wheeler autorickshaws and taxis to CNG (h) a change in the PUC center technology and (i) create a public awareness campaign. Evaluation of these interventions will be considered as a follow up to this baseline presentation.

Overall, transport sector remains the key to better air quality in the city. The institutional mandate for improving transport system is spread around multiple authorities which includes BBMP, Bangalore Development Authority (BDA), Bangalore Metropolitan Region Development Authority (BMRDA), Bangalore Metropolitan Transport Corporation (BMTC), Karnataka Urban Infrastructure Development and Finance Corporation (KUIDFC), Public Works Department, Motor Vehicles Department, Bangalore International Airport Area Planning Authority (BIAAPA), Revenue Department, Regional Transport Offices, Bangalore, Pollution Control Board, Police Department and more importantly Bangalore Metropolitan Land Transport Authority, which coordinates planning of urban transport projects and integrated management of urban transport systems. This is a governance nightmare, which needs to be addressed at the institutional level, to allow for better traffic demand management in the city.

4. Conclusions

A comprehensive source apportionment study for the city of Bengaluru, using the bottom-up (via emissions inventory) and the top-down (via sampling and chemical analysis) techniques was started in 2006 (CPCB, 2010). In this paper, we presented an updated bottom-up emissions inventory for the base year 2015 and $PM_{2.5}$ source apportionment based on chemical transport modeling for local and non-local sources. While the information available to prepare an action plan is available (for example, the common sources that contribute to the ambient pollution and at what level), a repeat of a complimentary top-down chemical analysis will help strengthen the on-ground understanding of the sources and prepare an effective air quality management plan. There is also a need to strengthen the overall ambient air monitoring capacity in the city, to better understand the spatial and temporal trends and to monitor progress of any of the measures to come. While the regulatory focus is on particulate pollution, the same databases will be utilized for understanding the influence of changing landuse patterns and emission sources on regional photochemistry and for establishing an open-access air quality forecasting system reporting pollution levels for the next 3 days.

Fig. 12. Modeled monthly average source contributions to modeled $PM_{2.5}$ concentrations for the Greater Bengaluru region.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2019.01.002.

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