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Air Quality, Emissions, & Source Contributions Analysis for the Greater Bengaluru Region of India

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Send your questions, comments, and suggestions on the methodology and data resources to the program coordinators: simair@urbanemissions.info

ACRONYMS

APnA	Air Pollution Knowledge Assessment (APnA) city program
BC	Black Carbon
BDA	Bangalore Development Authority
BMTC	Bengaluru Metropolitan Transport Corporation
CAMX	Comprehensive Air Quality Model with Extensions
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
DGsets	Diesel Generator sets
HDVs	Heavy Duty Vehicles
IT	Information Technology
km	Kilometer
KSPCB	Karnataka State Pollution Control Board
LDVs	Light Duty Vehicles
NAMP	National Ambient Monitoring Programme
NMVOC	Non-Methane Volatile Organic Compounds
NO_2	Nitrogen Dioxide
NOX	Nitrogen Oxides
OC	Organic Carbon
PM_{10}	Particulate Matter with diameter < 10 μm
$PM_{2.5}$	Particulate Matter with diameter < 2.5 μm
SO_2	Sulfur Dioxide
sq.km	Square kilometers
VOC	Volatile Organic Compounds
WRF	Weather Research Forecasting model
$\mu g/m^3$	micro-grams per cubic meter

EXECUTIVE SUMMARY

Bengaluru – capital of the state of Karnataka is the original 'Silicon Valley' of India. In this report, we present a comprehensive snapshot of the state of air quality in Bengaluru, along with an emissions inventory for all criteria pollutants at 0.01° grid resolution (approximately 1-km), for an urban airshed covering 60 x 60 grids (4,300 sq.km).

For 2015, emission estimates for the city are 31,300 tons of PM2.5, 67,100 tons of PM_{10}, 5,300 tons of SO_2, 56,900 tons of NOX, 335,550 tons of CO, 83,500 tons of NMVOCs, and 10.4 million tons of CO_2. Overall, transport is the key emission source for Bengaluru – vehicle exhaust and on-road dust resuspension account for 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 PM2.5.

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 monthly ranges 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), 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, total 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. This paper discusses the policy measures that can reduce pollution from these sectors and provides a roadmap with quantifiable estimates for an air quality management plan for the city of Bengaluru.

1.0 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, IT campuses, educational institutions, and for people who have made Bengaluru their home (Sudharia 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. We present in FIGURE 1a the urban airshed for the Greater Bengaluru region, extending from 77.3°E to 77.9°E in longitude and 12.7°N to 13.3°N in latitude, along with
5 the main road network of approximately 4,500 km and in FIGURE 1b the built-up area mapped for 1990 and 2014 (Pesaresi et al., 2016), which nearly tripled from 330 sq.km to 850 sq.km.

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. In 2017, a revised master plan was released by the local planning body (BDA), for the year of 2031, suggesting an expansion of 80 sq.km of built up area, restricting commercialization and development encircled by the outer ring road, to ease congestion and related environmental pollution (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.

For the Greater Bengaluru region, the number of studies reporting source emissions and source strengths are limited, with most reporting analysis for the transport sector (Verma et al., 2015; Verma et al., 2017; Kreindler, 2018; 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 burn-

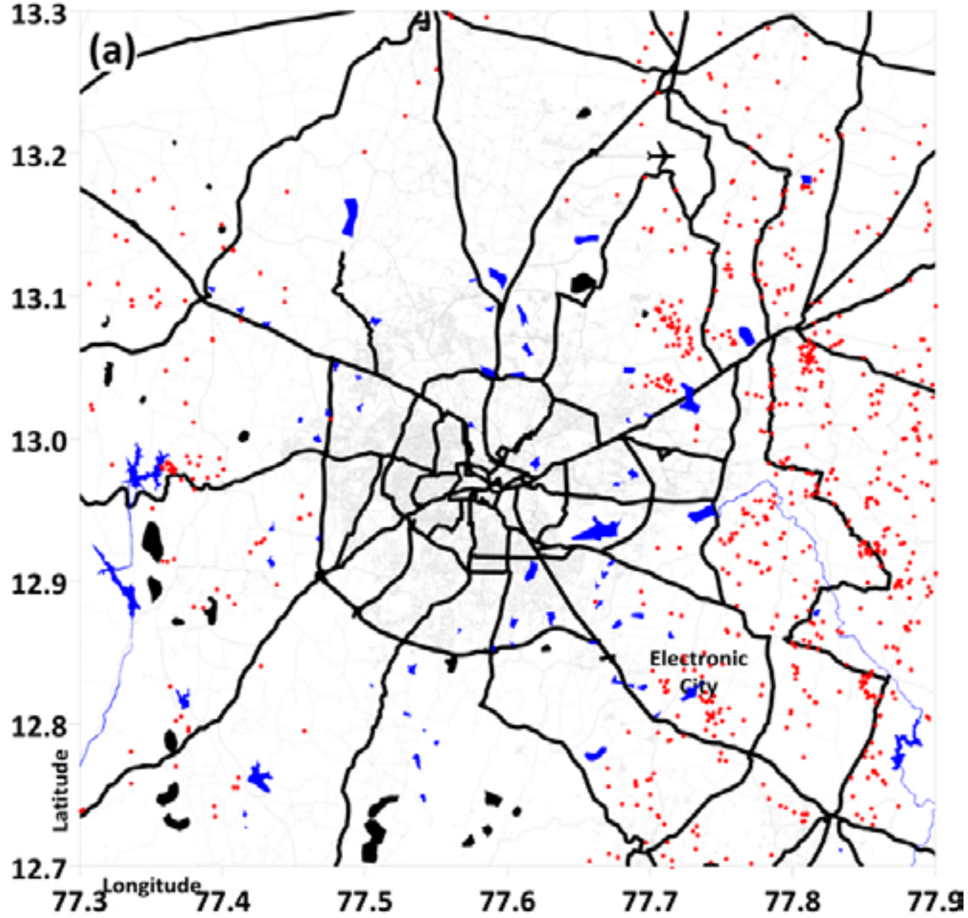


Figure 1a Selected urban airshed for the Greater Bengaluru region including main roads (thick lines), arterial roads (grey lines), water bodies (blue lines), airport (symbol), quarries (black patches), and brick kilns (red dots)

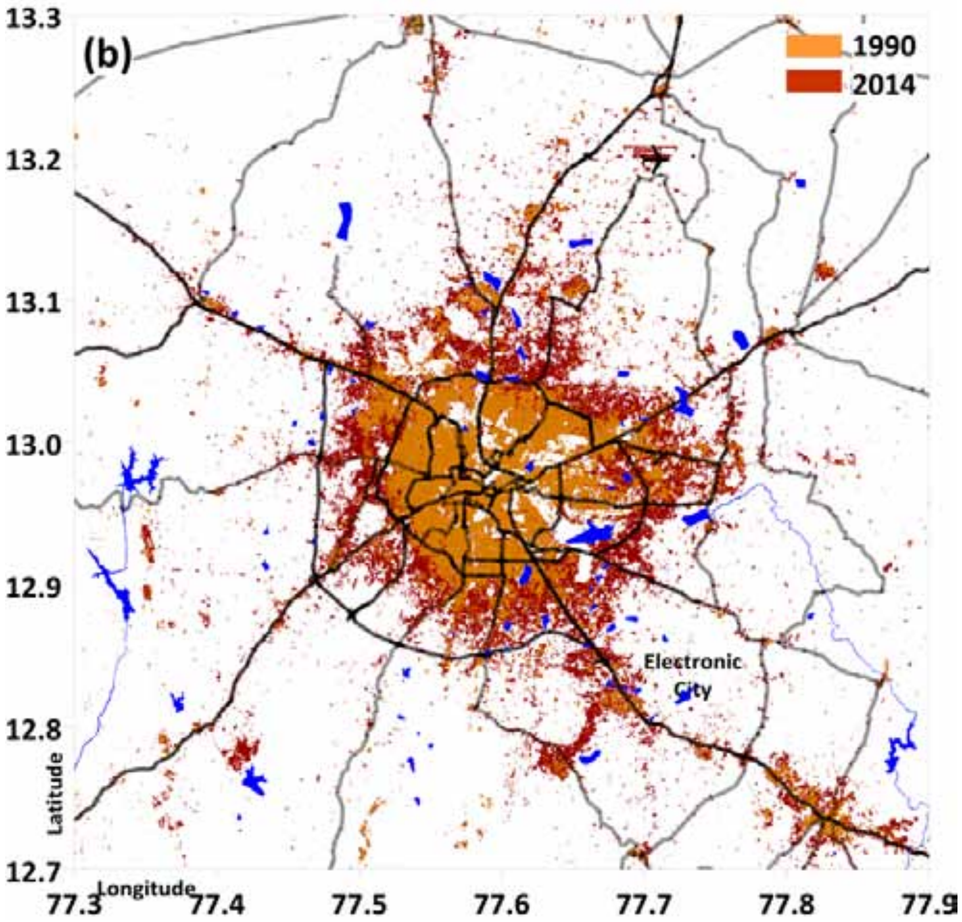


Figure 1b Urban built-up area in 1990 and 2014

ing 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 Central Pollution Control Board (CPCB, New Delhi, India) study remains the only comprehensive assessment of air quality in the city (CPCB, 2010), highlighting source contributions from on-road vehicle exhaust, on-road dust resuspension, construction activities, DGsets, coal and biomass burning in the domestic sector, industries including brick kilns, and open waste burning. This study was based on surveys and pollution samples collected in 2006-07, for receptor model based source apportionment using CMB8.2, emissions inventory development, and dispersion modeling using ISCST3 model (Sharma et al., 2013). In Bengaluru, for an area covering 624 sq.km in 2006, on-road dust was recorded as the major contributor (50%) to PM_{10} pollution.

A combination of satellite derived data, ground measurements, and global chemical transport models 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 database for urban Bengaluru in FIGURE 2. This is the only long-term trend available for the city. Between 1998 6
and 2016, $PM_{2.5}$ concentration increased 50%, with an annual average of 29.6 $\mu g/m^3$ in 2016 – this is under the national ambient standard of 40 $\mu g/m^3$ and 3 times the World Health Organization guideline of 10 $\mu g/m^3$.

As part of the Air Pollution Knowledge Assessment (APnA) city program for Indian cities, we established emissions inventory 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, an assessment for the Greater Bengaluru region in four steps (a) review of the air quality data available from measurements conducted in the city (b) preparation of a multi-pollutant emission inventory at 1-km resolution using data available from multiple sources (c) dispersion modelling for the select urban airshed to estimate the source contributions and (d) concluding with a review of the interventions under implementation and proposed for better air quality in the city of Bengaluru, India.

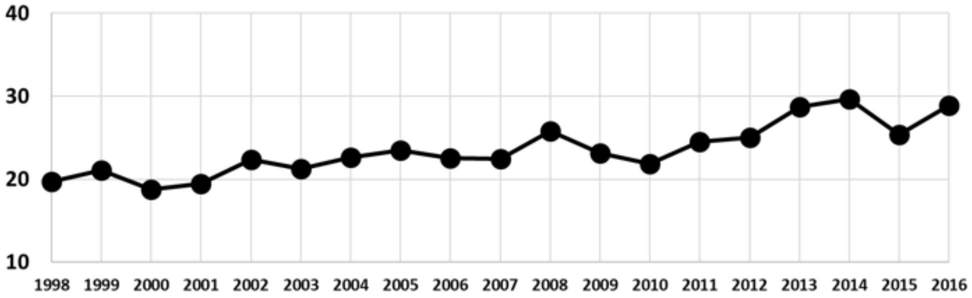
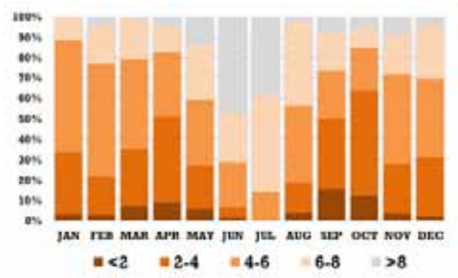
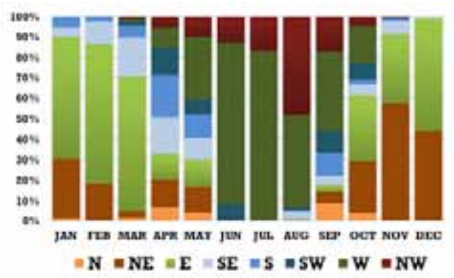


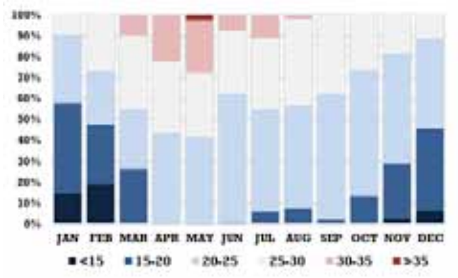
Figure 2 Evolution of $PM_{2.5}$ annual average concentrations (in µg/m³) based on global model simulations, satellite data derived estimates, and an assimilation of on-ground measurements for the period of 1998 and 2016 (Van Donkelaar et al., 2016)



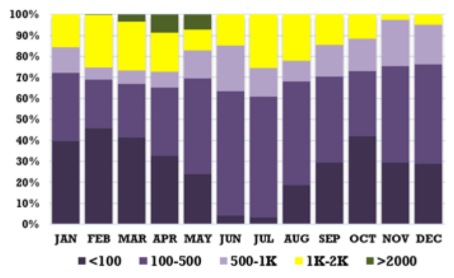
Wind speeds (m/sec)



Wind direction



Temperature (°C)



Mixing height (meters)

2.0 CITY LANDSCAPE & AIR QUALITY

Bengaluru is part of the Deccan Plateau region, distinguished by four seasons. The dry season with clear bright weather between December and February. The summer season from March to May, is followed by the Southwest monsoon from June to September, and a post-monsoon season for October and November. We summarized the variation of daily average meteorological fields (temperature, wind speeds, and mixing height) by month in TABLE 1 and FIGURE 3. The temperatures 7
over Deccan Plateau are very uniform over the months. The mean annual rainfall is 1,000 mm, mostly between June and October. Winds of mostly Westerly between May and September and Easterly for the remaining months, with an annual average mixing height of 769 ± 241 m during the day time and 143.9 ± 111.3 m during the night time, which allows for significant dispersion of emissions and keeps overall pollution levels low.

The Greater Bengaluru region in FIGURE 1, includes the main urban center 4
and the areas with sources of air pollution which could influence the ambient air quality in the city. Rapid urbanization has changed the land-cover and the land-use pattern of the city. A large change is evident 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 transport 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.

These developments in the transport sector and poor urban planning to support the growth, have changed the ambient air quality of Bengaluru city. For the period of 2004–2015 monitoring data from NAMP is available from CPCB for

TABLE 1 Variation in the daily average meteorological fields over the Bengaluru city in 2015 (extracted from WRF simulations using the NCEP reanalysis fields)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mixing height (m)	360 ± 38	461 ± 74	536 ± 90	592 ± 109	519 ± 132	512 ± 80	622 ± 71	480 ± 68	393 ± 53	345 ± 59	326 ± 72	326 ± 71
Wind Speed (m/s)	4.5 ± 1.0	5.1 ± 1.0	4.6 ± 1.1	4.2 ± 1.4	5.5 ± 1.7	8.1 ± 2.8	7.6 ± 1.0	5.5 ± 1.3	4.3 ± 2.1	3.9 ± 1.8	5.2 ± 1.6	5.0 ± 1.5
Temperature (°C)	19.3 ± 1.3	20.5 ± 1.5	23.9 ± 1.1	26.2 ± 1.4	27.0 ± 1.6	24.5 ± 1.4	24.8 ± 0.4	24.4 ± 0.6	24.1 ± 0.8	22.9 ± 0.8	21.5 ± 1.2	20.3 ± 1.4

Figure 3 Variation of (a) wind speeds (b) wind directions (c) temperature and (d) mixing heights by month, presented as percentage of hours in each month in various bins (data is extracted from WRF simulations for the Greater Bengaluru region using NCEP reanalysis fields for 2015)

three pollutants – PM_{10}, SO_2, and NO_2. A summary of 2011–2015 monitoring data is presented in TABLE 2. Impact of the adoption of Bharat IV diesel in Karnataka in 2015 is evident in the SO_2 concentrations. Sulfur content of diesel changed from 350 ppm to 50 ppm. A 25% drop in the NO_2 concentrations can also be linked to change in the transport fuel quality. The PM_{10} concentrations increased 50%, can be linked to growing number of moving vehicles and related dust resuspension and construction activities.

A summary of annual average concentrations at 16 locations monitored by
8 KSPCB in 2016 and 2017 is presented in TABLE 3. $PM_{2.5}$ was added to the list of criteria pollutants in 2009. However, this was included in the monitoring chain only in 2016. On an annual basis, PM_{10} and $PM_{2.5}$ exceed the national ambient standards, approximately 1.5 times. NO_2 is closer to the standard, than any of the other pollutants. SO_2 is the most compliant of all, primarily due to the availability of low-sulfur diesel, relocation of all the industries that rely on coal, and absence of any large coal-fired thermal power plants in the immediate vicinity. 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 also operate continuous monitoring stations, to report air quality information in real time. Prior to 2018, only 5 stations were operational under CPCB. In 2018, 5 new stations were introduced by KSPCB. We summarized the ambient concentrations between
March 2015 and February 2018, from the older stations in FIGURE 4. Data from the 9
new stations is not yet available on the central open data portal operated by CPCB.

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; Chinnaswamy et al., 2016; Thakur, 2017). Some studies collected monitoring data over small periods of time, with various

TABLE 2 Annual average ambient concentrations (in μg/m³) from manual monitoring stations in Bengaluru, 2011-2015

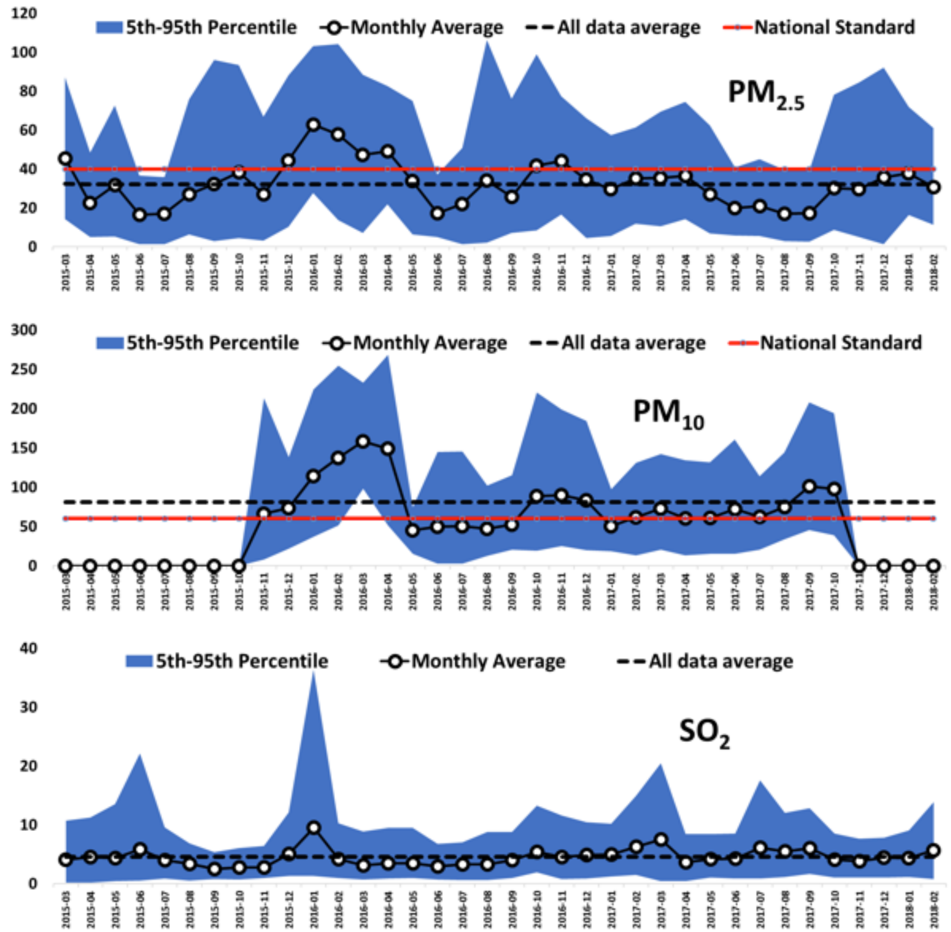
YEAR	SO_2	NO_2	PM_{10}
2011	36.8 ± 30.3	69.7 ± 51.4	221.4 ± 187.5
2012	36.0 ± 21.3	73.5 ± 41.0	275.6 ± 180.8
2013	37.2 ± 24.4	77.0 ± 47.3	314.3 ± 213.4
2014	33.8 ± 19.1	74.7 ± 43.4	333.6 ± 216.3
2015	14.7 ± 8.5	54.0 ± 33.6	349.8 ± 205.8

TABLE 3 Annual average ambient concentrations (in µg/m³) 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	SO2	NO2	PM 10	PM 2.5	NH3	LEAD	CO
1	Export pro park, Whitefield	C, T	2.0	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	0.0	900.0
11	CAAQM S. G. Halli	R	3.7	30.3	45.9		0.0	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

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.

Based on the limited information available from the regulatory stations and the published literature, the data suggests a deteriorating trend for key pollutants like $PM_{2.5}$, PM_{10}, and NO_2 and an improving trend for SO_2. 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.,



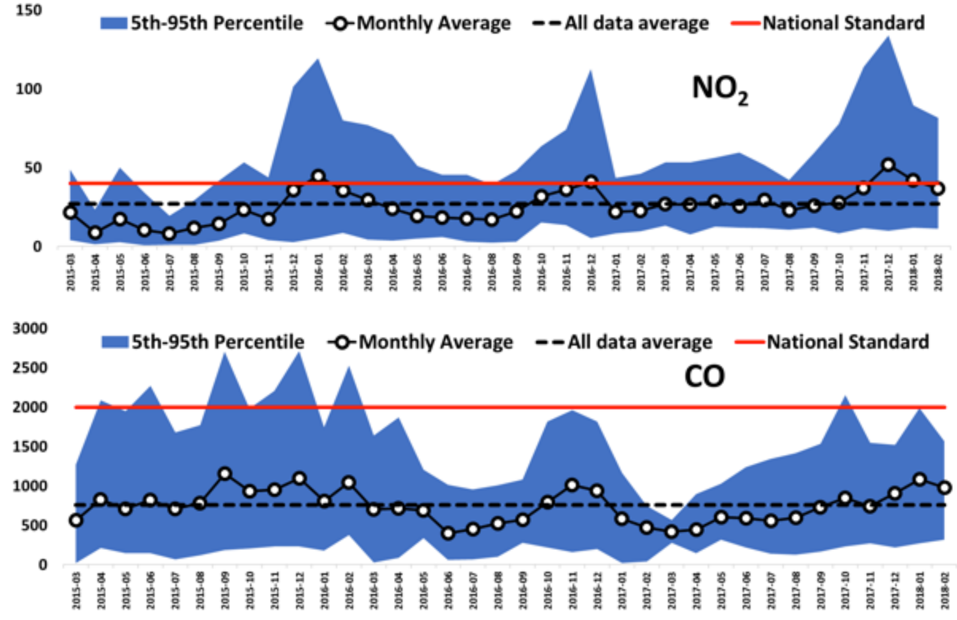


Figure 4 Variation of 24-hr average ambient concentrations (in μg/m^3) from continuous monitoring stations in Bengaluru between March 2015 and February 2018

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, we estimated that the Greater Bengaluru region requires at least 41 continuous monitoring stations to spatially and temporally represent its pollution levels (CPCB, 2003; India-APnA, 2017). An estimate of the spatial spread of these monitors, based on the gridded population and urban-rural landscape is presented in FIGURE 5 – 29 divided between 8 zones of urban Bengaluru, 5 outside these zones but within the district, and 7 outside the district to represent background concentrations.

3.0 SOURCES AND EMISSIONS INVENTORY

3.1 *Transport Sources*

Expansion of city area and population, along with growth in economic activities in the peri-urban areas, has resulted in high vehicle ownership rates. Number of vehicles registered per 1,000 population, increased from 150 in 1990 to 300 in 2001 and
11 600 in 2016 (FIGURE 6a). 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%), auto 3-wheeler auto-rickshaws (4%) and buses, LDVs, 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 the outer suburban areas. 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, 2011). The public transport mode share reduced significantly from 42% in 2007 to 27% in 2011, in

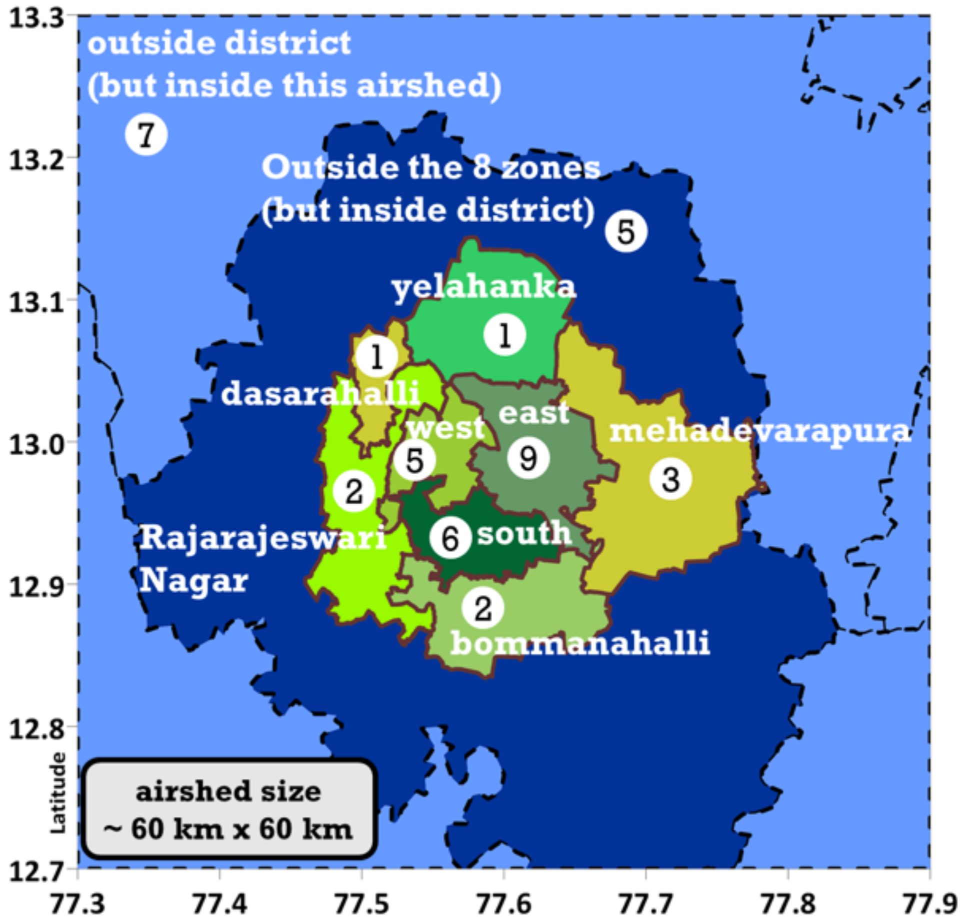


Figure 5 Distribution of required number of minimum continuous monitoring stations in the Greater Bengaluru region

spite of an increase in the number of buses (FIGURE 6b). In 2003, BMTC used to operate 3,000 buses for a population of 5.6 million with one bus for 1,800 people. In 2016, BMTC operated a fleet of 6,400 buses for a population of 11.0 million with one bus for 1,700 people (SoE, 2015). This is lower than the international standards (World Bank, 2006).

In 1999, in collaboration with the Swedish International Development Co-operation Agency, Bengaluru proposed the development of high capacity bus transport system, but dropped the plans in favor of the metro rail systems. Phase-1 of the metro rail system called 'NAMMA METRO' is now operational with 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 in 2011, 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. In traffic terminology, this level of service gets 'F' across all modes, as the peak-hour traffic congestion equilibrium is close to efficiency, with respect to the travel speed externalities (Kreindler, 2018).

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 PM and 9 AM. 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

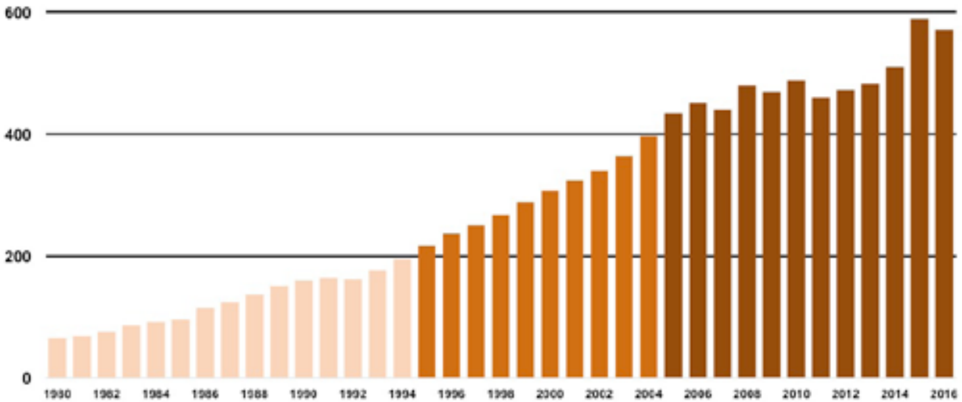


Figure 6a Number of registered vehicles per 1,000 population between 1980 and 2016 (Data source: Bangalore traffic police and Ministry of Road Transport and Highways)

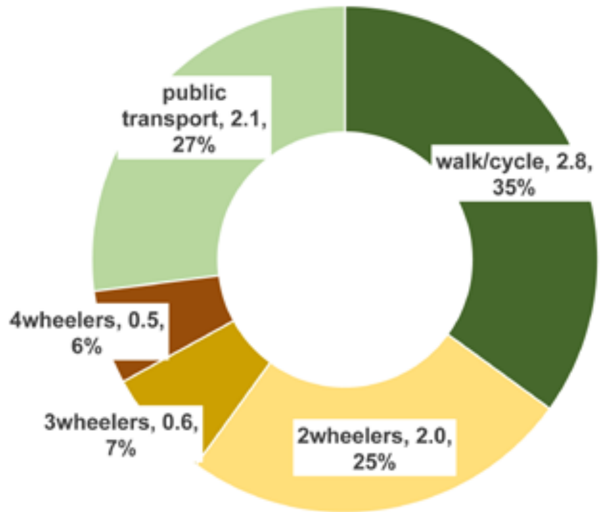


Figure 6b Percentage share of number of passenger trips per day in 2011 in the Greater Bengaluru area (Data source: BMLTA Legend shows category, million trips per day, % share)

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 to 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 as 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 final emissions inventory includes some dynamic corrections linked to the modeled meteorological data at 1 sq.km grid resolution and 1-hour 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; and 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.

Figure 7a An example brick kiln with a stack (12°52´N and 77°49´E – last accessed on August 21st, 2018)

Figure 7b An example of an abandoned quarry used as a landfill at Bethahalli (13°00´N, 77°25´E – last accessed on August 21st, 2018)

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.

3.2 *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 3,400 registered industries in the city, 1,600 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 cement and bricks is growing. Most of the bricks kilns are located to the east of city (FIGURE 1), majority of them using fixed chimney technology for baking. 4
An example of typical brick kiln in the area, with a stack of approximately 50 feet, is presented in FIGURE 7a. 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). With the proximity of agricultural land, top soil is easily accessible, along with field residue during the harvest season for fuel. Rest of the fuel needs are met mostly by coal. 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.

Solid waste generation rate in Bengaluru city is 4,000 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 Narayan, 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 – 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 4,460 million units of electricity per day (BESCOM, 2016). While power cuts are rare in the city, 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. 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). Other sources of air pollution include seasonal dust events and open field burning.

3.3 *Emissions Inventory*

The emissions inventory at the model resolution (1 km × 1 km) covering anthropogenic and non-anthropogenic sources includes transport (road, rail, and aviation), power generation (from DGsets), small and medium scale industries, dust (urban road resuspension and construction activities), domestic and agricultural sector (cooking, heating, lighting, and pumps), open waste burning, open fires, and where relevant, sea salt, dust storms, biogenic, and lightning.

The methodology for estimating total emissions is based on fuel consumption data and relevant emission factors. The emissions inventory is developed for total PM in two bins (PM_{10} and $PM_{2.5}$), SO_2, NOx, CO, NMVOCs, and CO_2. The overall methods, emission factors, and general assumptions in establishing this inventory are discussed in Guttikunda and Jawahar (2012); Guttikunda and Calori (2013); Guttikunda and Kopakka, (2014); Guttikunda and Mohan (2014); Guttikunda and Jawahar (2014); Goel and Guttikunda (2015) and India-APnA (2017). 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 (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 (c) linkages to monitoring data from official and unofficial networks to evaluate model performance. Besides the vehicle speed maps, Google's paid 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 × 1 km grids. A detailed list of these resources is available @ India-APnA (2017).

For 2015, the emissions inventory results are summarized in TABLE 4, with estimates of 31,300 tons of $PM_{2.5}$, 67,100 tons of PM_{10}, 5,300 tons of SO_2, 56,900 tons of NOx, 335,550 tons of CO, 83,500 tons of NMVOCs, and 10.4 million tons of CO_2. Under the APnA city program, for 20 Indian cities, average total $PM_{2.5}$ emissions is 22,500 tons/year/city 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 5,000 tons/year from the city Dehradun (hilly, tourist destination) (India-APnA, 2017). This total does not include the seasonal open fires, dust storms, or lighting, whose emissions are linked to the on-line calculations at the dispersion modeling stage, designated as regional contributions to the urban air quality.

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

TABLE 4 Estimated particulate and gaseous pollutant emissions inventory for the Greater Bengaluru region in Karnataka, India for the base year 2015

Category	$PM_{2.5}$	PM_{10}	SO_2	NOX	CO	VOC	CO_2
	tons/yr	tons/yr	tons/yr	tons/yr	tons/yr	tons/yr	Million tons/yr
Vehicle exhaust	12,550 (40.1%)	13,200 (19.7%)	1,300 (24.5%)	24,100 (42.4%)	237,300 (70.7%)	70,650 (84.6%)	6.7 (64.1%)
Domestic	2,050 (6.5%)	2,050 (3.0%)	750 (14.2%)	1,400 (2.5%)	20,300 (6.%)	2,350 (2.8%)	1.6 (15.4%)
Industries	2,650 (8.5%)	2,700 (4.0%)	1,650 (31.1%)	16,050 (28.2%)	20,600 (6.1%)	2,900 (3.5%)	1.2 (11.8%)
Dust	6,400 (20.4%)	41,200 (61.4%)					
Waste burning	3,500 (11.2%)	3,700 (5.5%)	100 (1.9%)	100 (0.18%)	16,800 (5.%)	3,400 (4.1%)	0.02 (0.2%)
Generator sets	1,250 (4.0%)	1,350 (2.0%)	100 (1.9%)	11,950 (21.0%)	3,150 (0.94%)	300 (0.36%)	0.54 (5.2%)
Brick kilns	2,900 (9.3%)	2,900 (4.3%)	1,400 (26.4%)	3,300 (5.8%)	37,400 (11.1%)	3,900 (4.7%)	0.33 (3.2%)
Total	31,300	67,100	5,300	56,900	335,550	83,500	10.4

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 $PM_{2.5}$. This is also an indication of how dependent the city is better urban transport mechanisms. 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). Annually, an estimated 200 million liters of diesel is consumed by DGsets in the city.

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 NOx, 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. In 2030, the share of vehicle exhaust and on-road resuspended dust account for 60% and 74% of the total $PM_{2.5}$ and PM_{10} emissions, respectively.

The Greater Bengaluru region extending from 77.3°E to 77.9°E in longitude and 12.7°N to 13.3°N in latitude, is further divided into 60 × 60 grids at 0.01° resolution (approximately 1 km), covering a total area of 4,300 sq.km. We present the
16 gridded emissions inventory for 2015 and is presented in Figure 8. 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.

Total emissions reported in CPCB (2010) are 54.4 tons/day for PM_{10}, 217.4 tons/day for NOx and 14.6 tons/day for SO_2, which translates to 19,900 tons/year, 79,350 tons/year, and 5,300 tons/year, respectively, for the study year 2006. The airshed covered an area of 24 km × 26 km of urban Bengaluru (624 sq.km). Growth patterns presented in the report projected a 100 % increase in the overall emissions of PM_{10} and NOx, between 2007 and 2017.

4.0 PARTICULATE POLLUTION DISPERSION MODELING

For the Greater Bengaluru region, the meteorological data necessary for dispersion modeling at 0.01° resolution was arrived at in nested mode using the 'Weather Research and Forecasting' (WRF) model and NCEP Reanalysis inputs (NCEP, 2016). Urban particulate and gaseous dispersion modeling was conducted utilizing the Comprehensive Air Quality Model with Extensions (CAMx – http://www.camx.com), an open-source Eulerian air quality dispersion model, with detailed advection and scavenging schematics (dry and wet deposition), with chemical solvers for multiple chemical mechanisms, with links to online emission calculations for certain sources (such as sea salt, which is not relevant for Bengaluru), and with chemical modules to support gas to aerosol conversions.

Total modeled $PM_{2.5}$ concentrations for the Greater Bengaluru region is
presented annual averages in FIGURE 9 and as monthly averages in FIGURE 10. This 17, 18
includes secondary particulate concentrations, due to chemical transformation of SO2 to sulfates and NOx to nitrates. The modeled urban average $PM_{2.5}$ is 36.5 ± 9.0 $\mu g/m^3$ (with a domain maximum of 76.2 $\mu g/m^3$), represents approximately 600 urban grid cells of the total 3,600 airshed grid cells. Measured $PM_{2.5}$ average
from 13 manual monitoring stations (TABLE 2) is 47.4 ± 7.5 $\mu g/m^3$, representing 7
approximately 120 grid cells (assuming a monitoring station is representative of a 2-km radius). Measured $PM_{2.5}$ average from 3 continuous monitoring stations
summarized in FIGURE 4 is 32.3 ± 24.2 $\mu g/m^3$. 9

We present a comparison of monthly ranges of modeled and monitored $PM_{2.5}$
and PM_{10} concentrations in FIGURE 11 and FIGURE 12. The model captures the 19
quantitative range and qualitative trend of the measurements for all the months. The months of November to February exhibit the seasonal highs and the monsoonal months of June-August exhibit the lows. In case of PM_{10}, model underperforms during the monsoonal months, likely due to either an overestimation of wet scavenging or an underestimation of dust emissions in the city. Noting that the measurements are available from only 3 continuous stations for $PM_{2.5}$ and 1 continuous station for PM_{10}, this evaluation will be revisited, when data from more

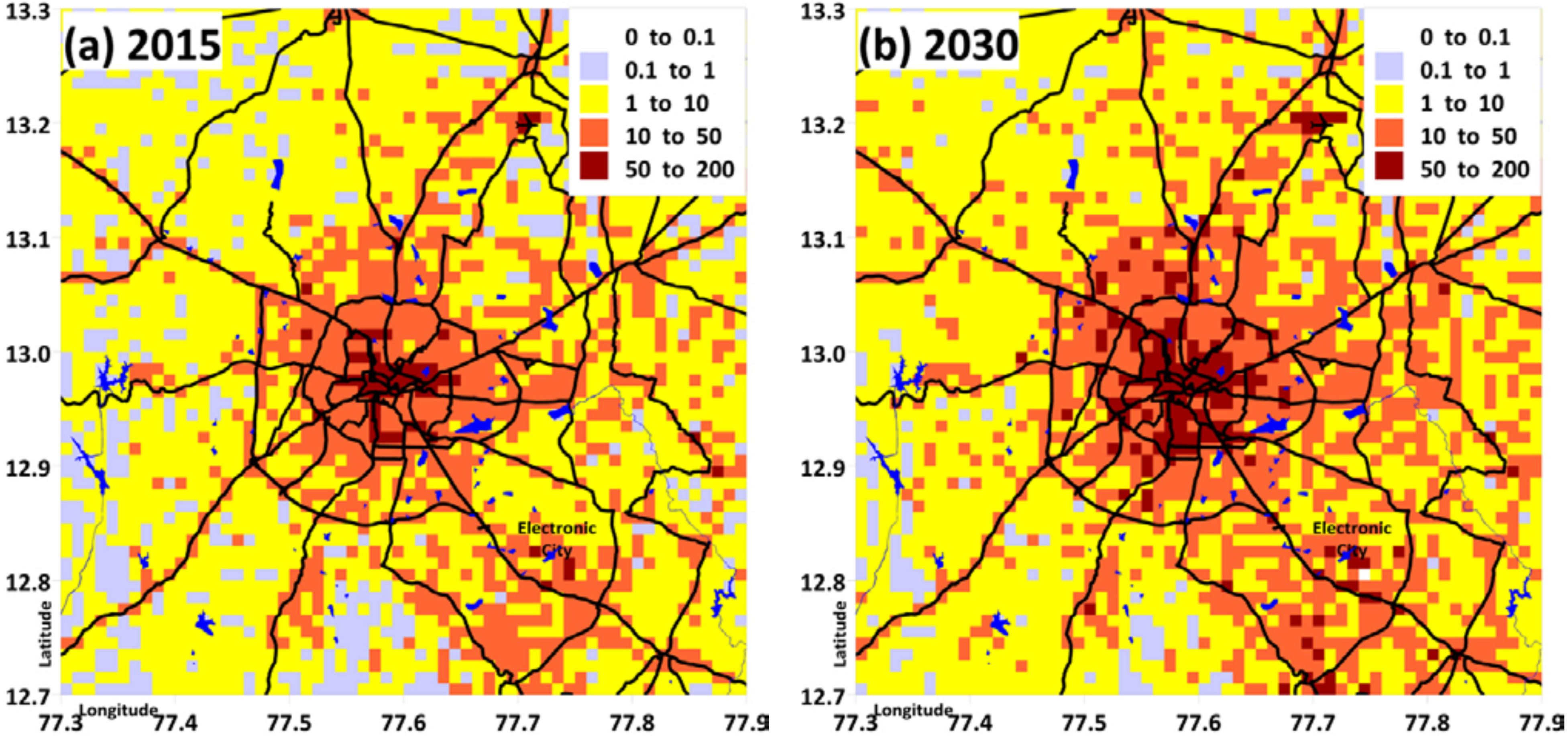


Figure 8 Gridded annual $PM_{2.5}$ emissions (in tons/year/grid) for the Greater Bengaluru region for (a) 2015 (b) 2030, at 0.01° (approximately 1 km) spatial resolution

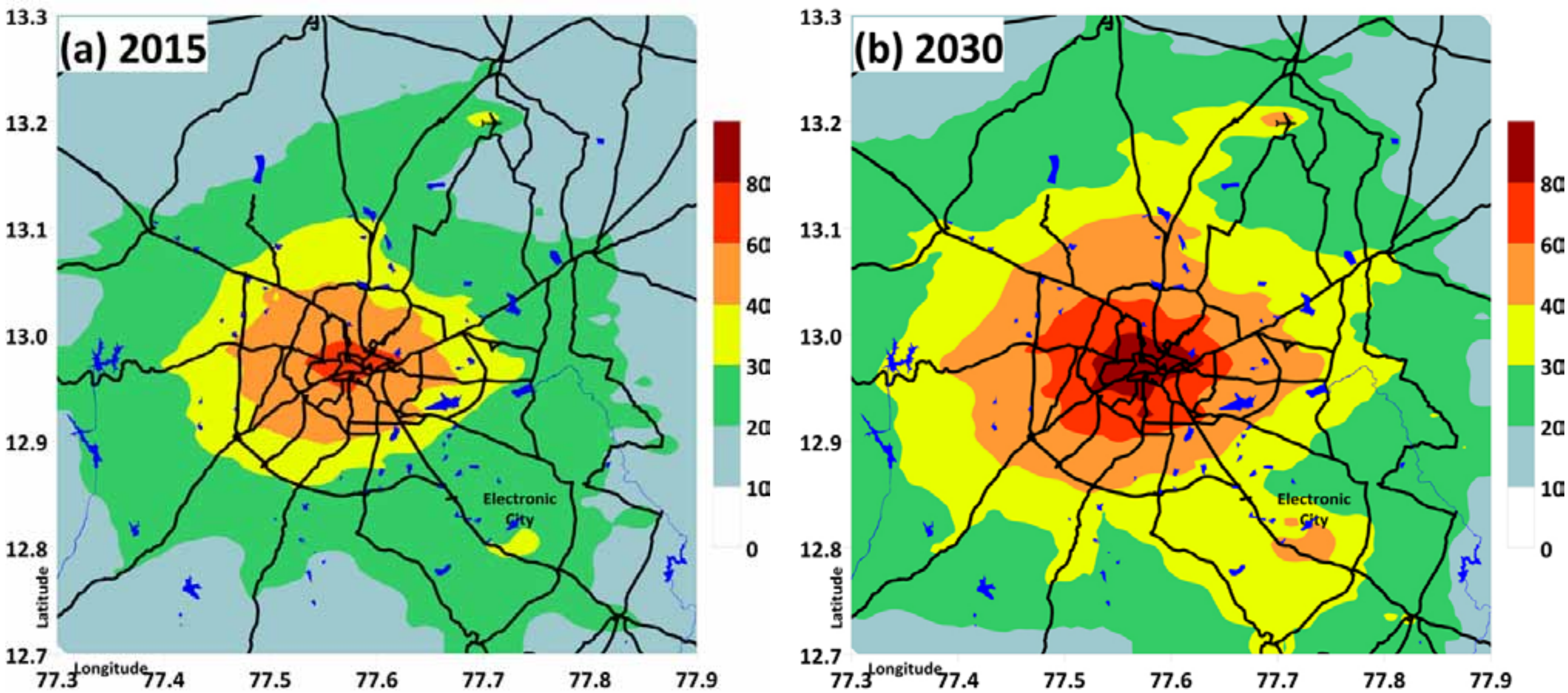
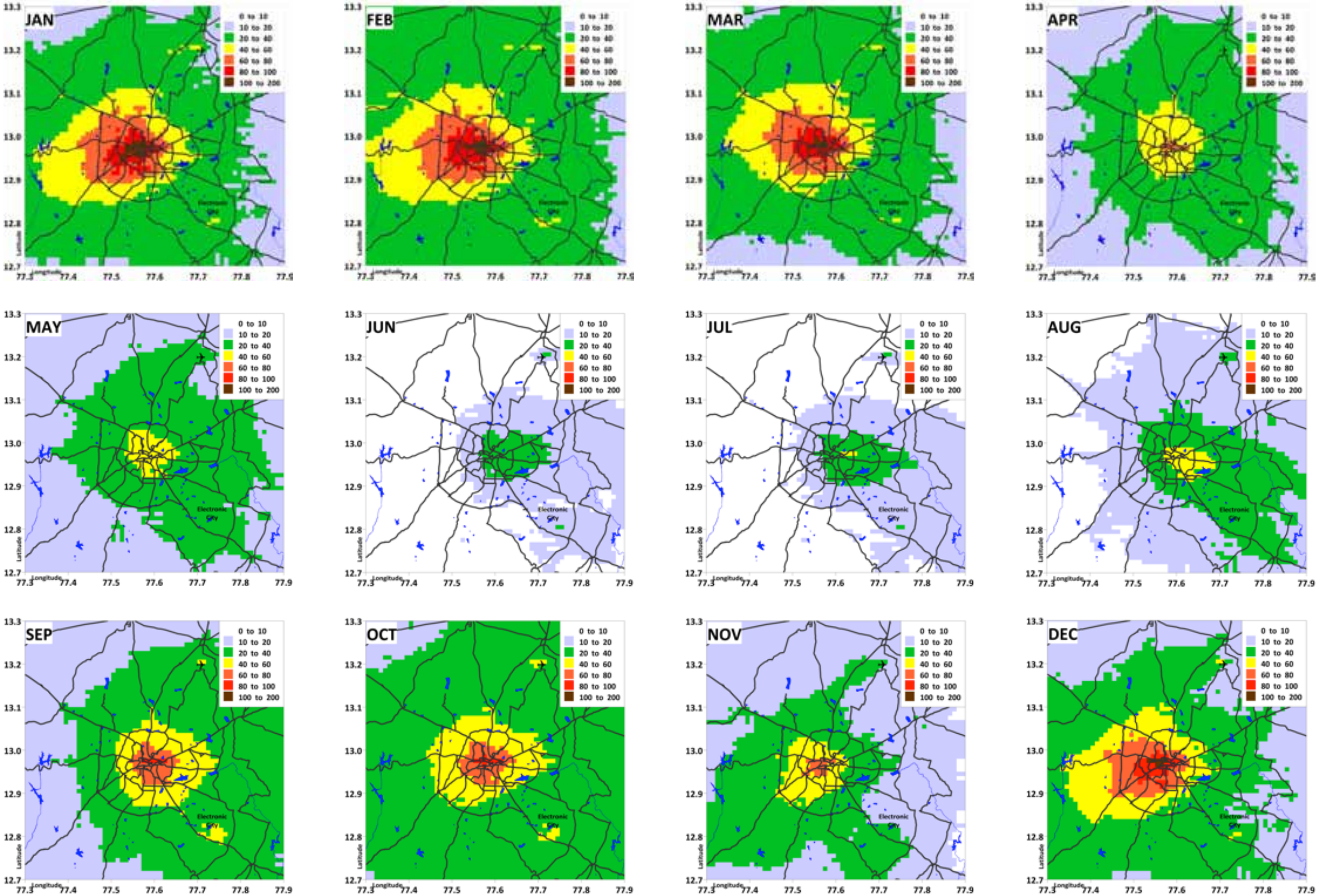


Figure 9 Modeled annual average $PM_{2.5}$ concentrations in μg/m³ in (a) 2015 and (b) 2030

Figure 10
WRF-CAMx modeled monthly average $PM_{2.5}$ concentrations (in µg/m³) in 2015



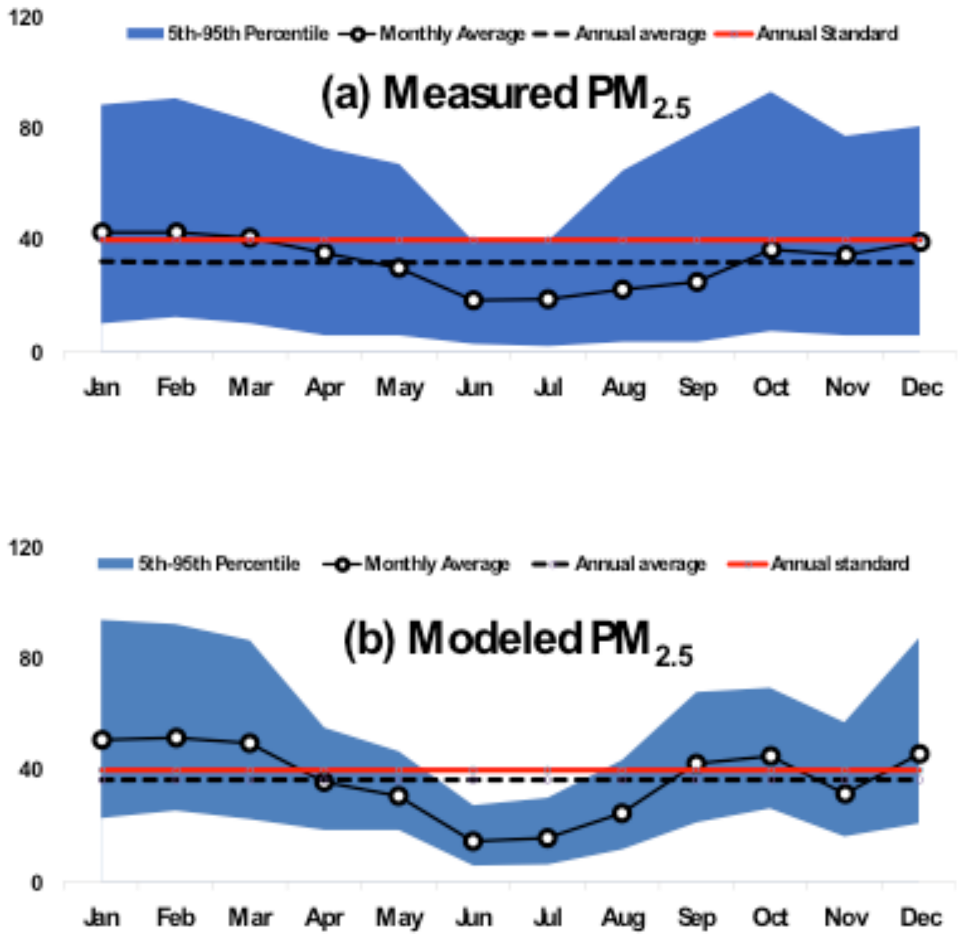


Figure 11 Comparison of $PM_{2.5}$ concentrations (in µg/m³) (a) ranges measured over each month from 3 continuous monitoring stations in Bengaluru between 2016 and 2017 (b) ranges modeled over each month for 600 urban grids (of 1 sq.km each) in Bengaluru for 2015

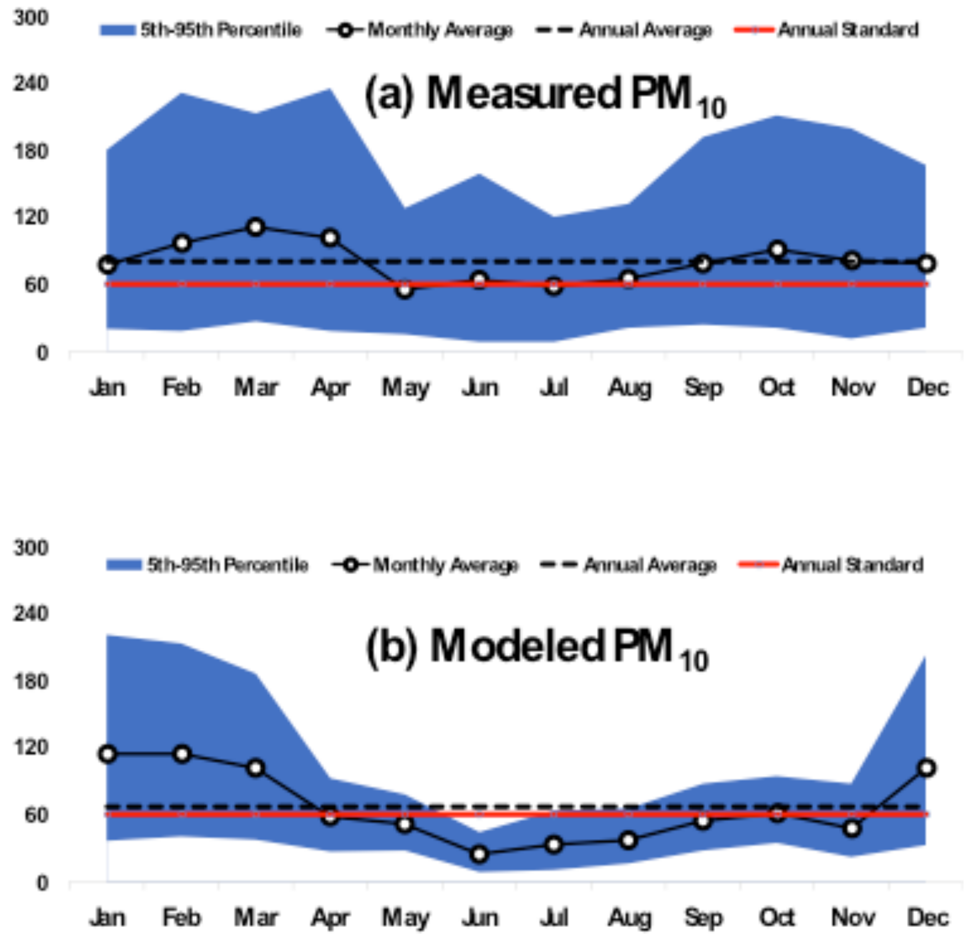


Figure 12 Comparison of PM_{10} concentrations (in µg/m³) (a) ranges measured over each month from 1 continuous monitoring station in Bengaluru between 2016 and 2017 (b) ranges modeled over each month for 600 urban grids (of 1 sq.km each) in Bengaluru for 2015

stations is available for scrutiny.

WRF-CAMx modeling system was also utilized to establish source contributions – from the local emissions inventory (presented in this report) and from the emissions outside the selected urban airshed. To account for long-range transport contributions and for activities outside the designated urban airshed, two model runs are conducted. A national scale simulation was conducted over the Indian Subcontinent at 0.25° grid resolution (details on national emissions inventory and modeling framework are available online @ http://www.indiaairquality.info), which was utilized to produce boundary conditions for the Greater Bengaluru region at 1-hour temporal resolution. The boundary conditions for the India Subcontinent were obtained from MOZART global model, for which a pre-processor module is available with the CAMx dispersion modeling system. The modeled source contri-
21 butions (TABLE 5) highlight 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. 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.

5.0 AIR POLLUTION POLICY REVIEW

While overall air pollution levels in Bengaluru are less than those observed in

Delhi and while 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.

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.

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

TABLE 5 Modeled percentage source contributions from the WRF-CAMX simulations for the Greater Bengaluru region

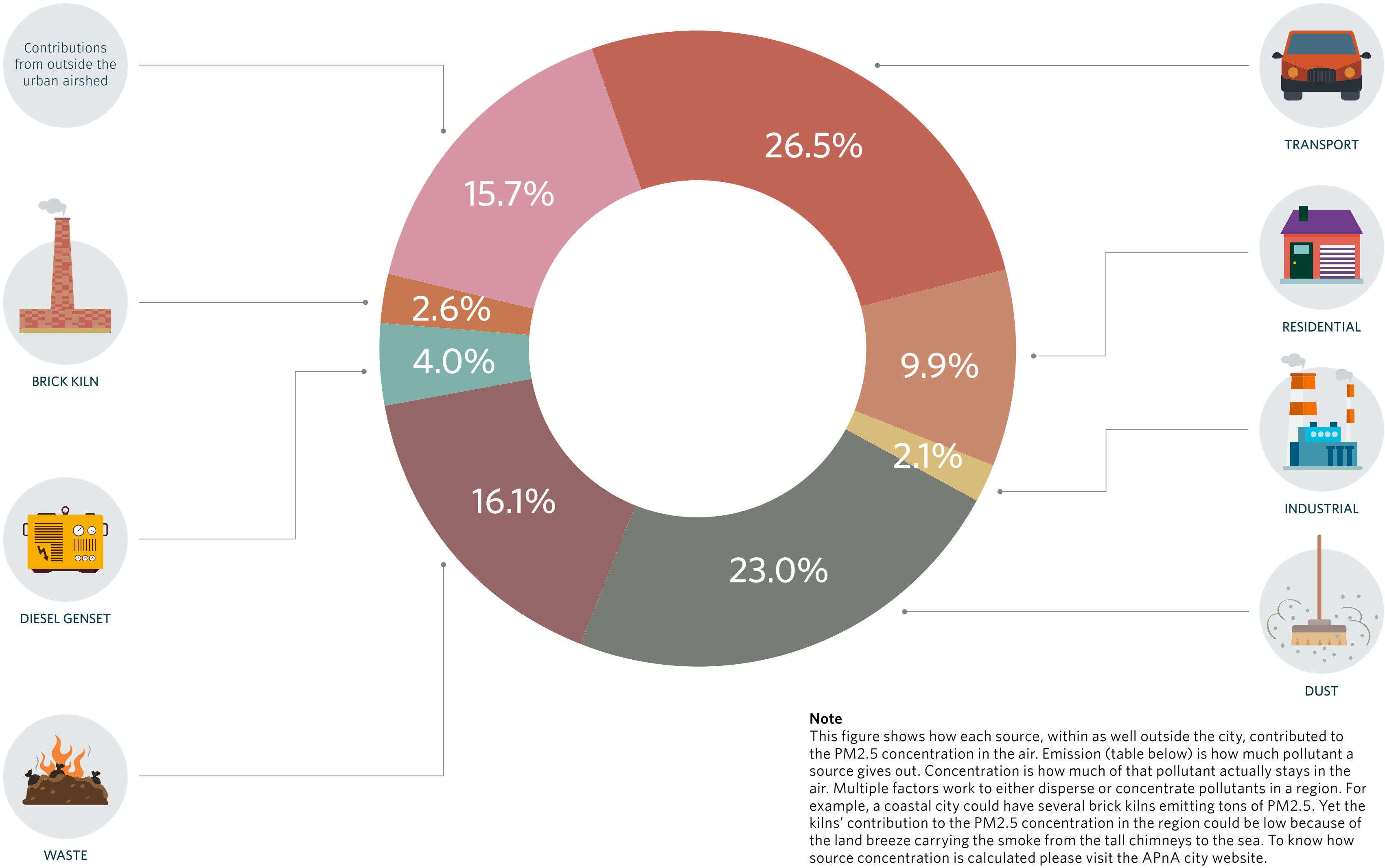
	Domestic	Transport	Dust	Brick kilns	Industries	Open waste burning	Diesel generator sets	Outside
January	9.3 ± 9.2	21.2 ± 9.1	35.5 ± 22.5	4.3 ± 2.2	1.4 ± 2.4	10.8 ± 11.0	3.1 ± 2.3	14.4 ± 2.7
February	8.6 ± 8.5	19.7 ± 8.5	33.6 ± 21.5	4.3 ± 2.2	1.1 ± 2.3	10.7 ± 11.3	2.5 ± 2.5	19.3 ± 8.9
March	9.1 ± 7.9	23.2 ± 9.4	32.4 ± 18.6	4.0 ± 2.2	1.4 ± 2.5	13.3 ± 12.4	2.8 ± 2.3	13.8 ± 1.8
April	6.8 ± 4.6	30.9 ± 9.8	17.9 ± 7.6	1.4 ± 1.8	2.2 ± 2.9	16.1 ± 12.0	3.9 ± 2.2	20.6 ± 3.6
May	6.8 ± 4.8	29.8 ± 9.2	14.9 ± 6.1	1.5 ± 1.3	2.0 ± 3.2	15.6 ± 11.8	3.9 ± 2.2	25.3 ± 6.6
June	8.1 ± 7.6	37.2 ± 14.5	15.7 ± 7.5	1.0 ± 1.4	1.4 ± 5.1	19.7 ± 19.3	5.2 ± 3.7	11.6 ± 1.7
July	6.7 ± 6.6	31.2 ± 12.4	26.1 ± 13.9	0.9 ± 1.2	1.2 ± 4.7	16.8 ± 17.7	4.1 ± 3.1	13.1 ± 2.9
August	8.3 ± 7.2	35.3 ± 12.5	13.0 ± 6.6	1.0 ± 1.2	2.0 ± 4.8	17.5 ± 16.8	4.9 ± 3.3	17.8 ± 9.8
September	9.5 ± 6.3	38.2 ± 11.7	9.8 ± 3.7	1.5 ± 1.2	2.3 ± 3.7	17.8 ± 13.3	5.6 ± 2.9	15.3 ± 6.7
October	10.7 ± 7.6	33.0 ± 19.2	10.3 ± 4.3	2.3 ± 1.2	1.7 ± 3.6	16.5 ± 13.1	4.6 ± 2.5	20.7 ± 7.8
November	11.6 ± 11.0	32.1 ± 13.5	13.6 ± 7.7	3.3 ± 1.8	1.6 ± 3.9	16.2 ± 16.2	4.4 ± 3.3	17.1 ± 1.4
December	9.0 ± 9.3	21.5 ± 9.4	34.2 ± 22.1	5.1 ± 2.3	0.8 ± 3.6	11.0 ± 11.9	3.0 ± 2.5	15.2 ± 1.4
Annual	8.9 ± 6.8	28.1 ± 8.9	22.9 ± 11.6	2.9 ± 1.5	1.5 ± 3.8	14.4 ± 11.5	3.8 ± 2.2	17.2 ± 5.6

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.

For the transport sector, timely upgradation of automobile technology, improvement in fuel quality, expansion of urban public transportation system, promotion of sustainable modes (walking and cycling) and integrated traffic management, are the most feasible options for better air quality.

- Promotion of cleaner fuel standards and tighter emission standards reduce overall emissions. Bharat IV (equivalent of Euro IV) standard fuel was introduced in 2015 in the city, which resulted in a 60% drop in SO_2 pollution levels (TABLE 1). Nationwide, Bharat IV was adopted nationwide in 2017 and a ban 7
was imposed on sale of vehicles with older vehicle standards. The vehicles already sold continue to operate using the new fuel. Bharat VI (equivalent of Euro VI) is proposed for nationwide adoption in 2020. This fuel (with a sulfur content of 10 ppm – 40 less than the current 50 ppm standard) is now (2018) available only in Delhi. Often these improvements in pollutant emissions are short-lived, because of gradual increase in the number of vehicles and their usage. For sustained benefits, along with improvement in fuel and engine standards, urban planning should also include options to reduce use of personal vehicles.

PM$_{2.5}$ CONCENTRATION : SOURCE-WISE PERCENTAGE SHARE IN 2015



Note
This figure shows how each source, within as well outside the city, contributed to the PM2.5 concentration in the air. Emission (table below) is how much pollutant a source gives out. Concentration is how much of that pollutant actually stays in the air. Multiple factors work to either disperse or concentrate pollutants in a region. For example, a coastal city could have several brick kilns emitting tons of PM2.5. Yet the kilns' contribution to the PM2.5 concentration in the region could be low because of the land breeze carrying the smoke from the tall chimneys to the sea. To know how source concentration is calculated please visit the APnA city website.

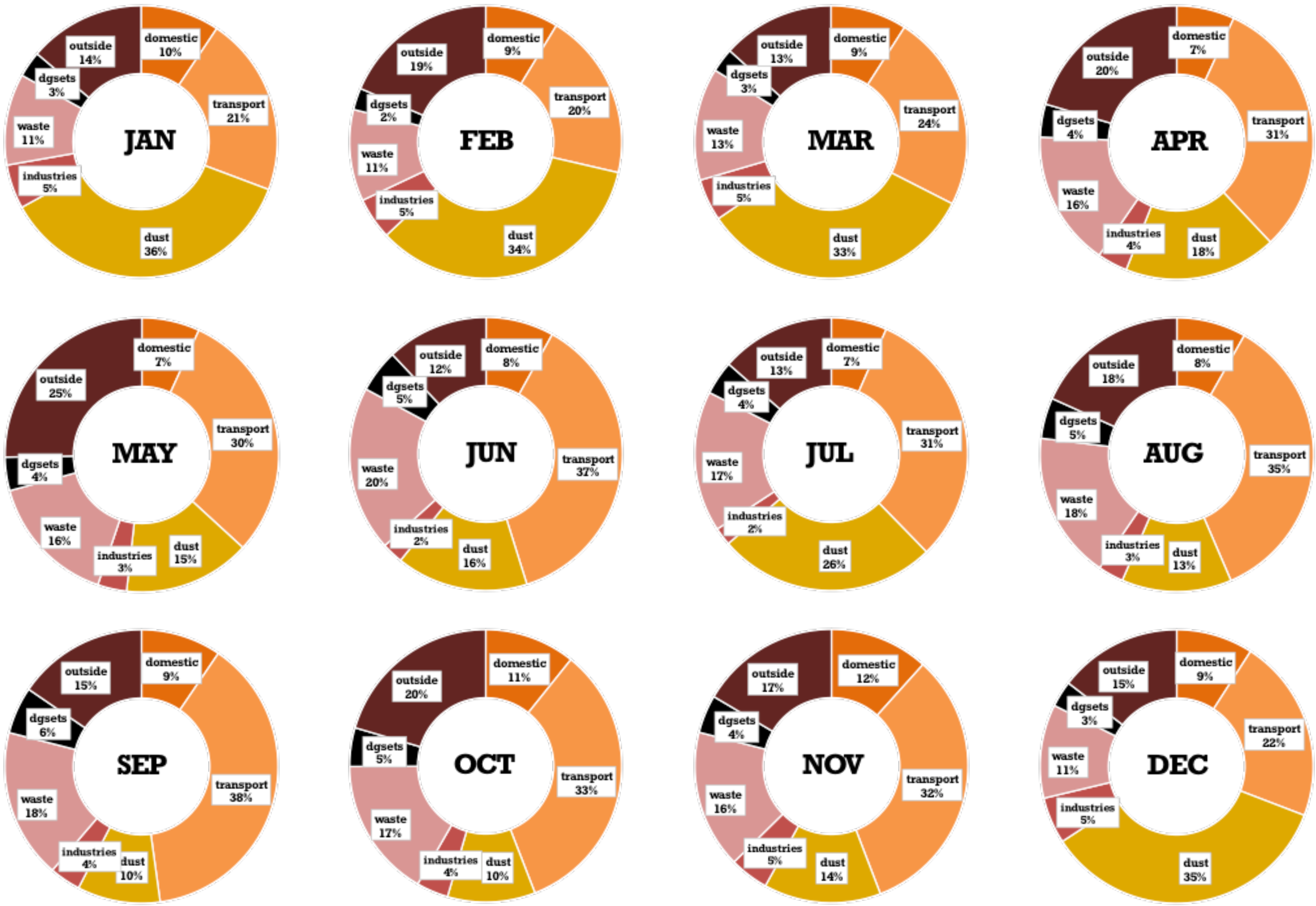


Figure 14 Percentage source contributions to modeled ambient $PM_{2.5}$ concentrations over the Greater Bengaluru region, in 2015 (industries includes brick kilns)

- All the vehicles are required obtain the 'pollution under control' (PUC) certificate every 6 months, which measures (a) tailpipe emission rates for CO and VOCs at engine idle speed and at high engine idle speed at 2000 rpm (lambda testing) for petrol and CNG vehicles and (b) mean Hartridge Smoke Units (HSU) measured using free acceleration test for diesel vehicles. These tests do not reflect the on-road driving conditions of cruising, idling, accelerating, and decelerating; making it difficult to judge if a vehicle is truly fit to get the PUC certificate. A change in the testing procedure is required, where the vehicles are tested using a localized driving cycle on a chassis dynamometer and for the pollutants which are critical in the city (like $PM_{2.5}$ and NO2 in Bengaluru). For the same reason, the emission rates measured for CO and VOC are not admissible for emission inventory calculations, but they do provide information on the engine deterioration trends (Goel et al., 2015). As vehicle ages, owners tend to use the vehicle without the certificate or get a certificate at irregular periods. Introducing schemes like 'NO PUC CERTIFICATE – NO FUEL' can help strengthen the inspection and maintenance programs.

- Regulations like conversion of in-use 3-wheelers that are registered after 1991 to bi-fuel mode (LPG and petrol) should be encouraged, with a complete ban on the diesel operated autorickshaws. There are around 35,000 3-wheelers, running with unauthorized LPG kits and detachable cylinders, which require mandated conversion to authorized kits with fixed cylinders.

- Among the economic measures, restricting the number of new vehicle sales and registrations, allowed for a shift in vehicle ownership and travel mode choices in Beijing, Shanghai and Guangzhou (Huo et al., 2015); and congestion pricing in the central districts of Singapore, London, and Stockholm, allowed for reducing peak hour road congestion and pollution levels (Gu et al., 2018). Both the measures require the city to provide citywide alternate mode of transport (road and rail), to encourage any shift from the personal mode of transport – this is the key for success in all the examples. While the metro rail systems are partly operational and more under construction, the city requires an aggressive promotion of the bus-transit systems, along with first and last mile connectivity through walking and cycling infrastructure. In 2018, only 4.2% of total commuters are using the metro rail. For the growing population and the changing landuse patterns, city could use at least 12,000 buses to provide safe, reliable, and clean transport.

- In Bengaluru, two major initiatives toward green transportation are electric vehicle (EV) and metro rail. The central government is planning to achieve 30% EV by 2030, which will help reduce in-city on-road emissions. A shift from diesel based public transport to EV will reduce 42% of annual carbon emissions from the sector (CSTEP, 2018). However, developing infrastructure for charging stations, power availability, and battery capacity to achieve 30 % EV will take time.

- With urban sprawl already spread beyond the current core ring road and outer ring roads, the government proposed three more ring roads - peripheral (PRR), intermediate (IRR), and satellite township (STRR) (BDA, 2017). The new ring roads will act as a bypass for some freight moving vehicles and disperse the emissions from HDVs within the airshed. Besides the freight movement, passenger movement could benefit from the augmentation of conventional commuter rail system, for which feasibility was assessed in 1983, but overlooked in favor of the new metro rail systems (DULT, 2012).

- On-road resuspended dust is a major component of $PM_{2.5}$ and PM_{10} pollution in the city, with most of the road sweeping conducted manually, and often before the rush hours in the morning. Wet sweeping and mechanical sweepers could help either suppress resuspension due wet road surface or capture the dust to nullify resuspension (Amato et al., 2010).

For the non-transport sector, tighter emission regulations, followed by monitoring and enforcement, are the likely options to result in a reduction in pollutant emissions.

- CSE (2018) found that pollution level is up 30% during the usage of DGsets in Delhi and its satellite cities. Uninterrupted (24/7) power supply is the clear option to reduce the use of DGsets at various commercial establishments. Promotion of solar energy by major industries and commercial establishments will be instrumental in capping diesel consumption, along with promotion of energy efficiency norms to reduce electricity consumption and promotion of LPG/CNG to replace diesel. Emission norms for new DGsets were issued in 2015.

- As per the order by National Green Tribunal in 2016, waste burning is banned throughout the country. With only 30% of the urban waste going to the landfills, efficient waste management practices will help lower the open waste burning emissions in Bengaluru. Increasing the landfill capacity, as planned, will help. However, BBMP may have to consider running decentralized waste segregation and handling systems by ward, to maintain the sector efficiently (Chanakya et al., 2015).

- Construction sector contributes to environmental pollution in multiple ways – at the construction sites, disposal of debris, transport of construction material, and noise pollution. 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 AM and 8 AM.

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 and published in 2010 (CPCB, 2010). In this report, we presented a bottom-up analysis, laying out an updated emissions estimate for all the known sectors. While the information is available to prepare an action plan (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. KSPCB is putting a team of local organizations together to study pollution source contributions and to better understand the potential to control emissions from various sectors. 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.

The emissions inventory established for the Greater Bengaluru region is for all criteria pollutants and gridded at 1-km resolution, suitable for full chemical transport modeling. In this report, we presented an analysis of the particulate pollution measured and modeled for the city. While the regulatory focus is on particulate pollution, given the changing mix of emission sources, pollutants like NO_2, NO, CO, VOCs, and Ozone, are expected to rise and will need a similar emission control plan. The same databases will be utilized to understand 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.

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Phase 1 cities

Agra
Amritsar
Bengaluru
Bhopal
Bhubaneshwar
Chandigarh
Chennai
Coimbatore
Dehradun
Indore
Jaipur
Kanpur
Kochi
Ludhiana
Nagpur
Patna
Pune
Raipur
Ranchi
Varanasi

Phase 2 cities

Agartala
Ahmedabad
Allahabad
Asansol
Aurangabad
Belgaum-Dharwad
Dhanbad
Guwahati-Dispur
Gwalior
Hyderabad
Imphal
Jamshedpur
Jodhpur
Kolkata
Kota
Lucknow
Madurai
Mumbai
Nashik
Panjim
Puducherry
Rajkot
Shimla
Srinagar
Surat
Thiruvananthapuram
Tiruchirapally
Vadodara
Vijaywada
Vishakhapatnam

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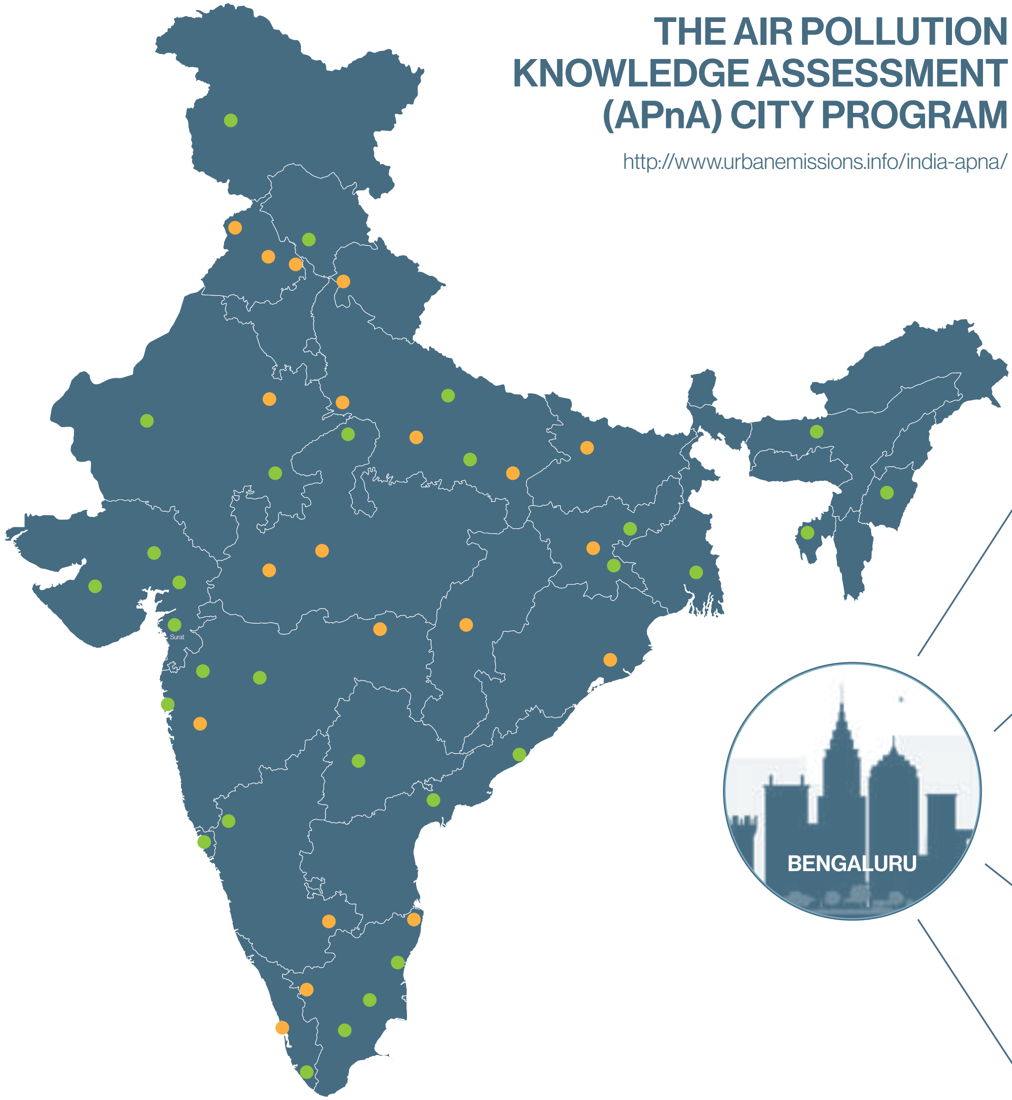


APnA CITY
PROGRAM

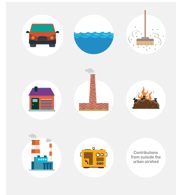
THE AIR POLLUTION KNOWLEDGE ASSESSMENT (APnA) CITY PROGRAM

http://www.urbanemissions.info/india-apna/

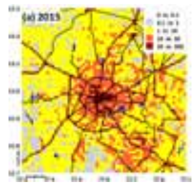
CLEARING THE AIR WITH DATA

Supporting long-term policy making by establishing baselines for air pollution in a city.

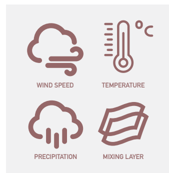
1 → **Compile an emissions inventory:**
Cover major sources for each city, anthropogenic and natural (by sector and by fuel). →



2 → **Create a spatial map of emissions for each pollutant:**
Spatially grid the emission inventory at 0.01° grid resolution in longitude and latitude.
Spatial resolution - 1km x 1km for city and 25km x 25km for national.
Pollutants covered: PM2.5, PM10, SO2, NOx, CO and VOCs →



3 → **Construct meteorological fields:**
Use WRF meteorological model and NCEP Reanalysis data. →



4 → **Use a dispersion model to estimate concentration of pollutants:**
CAMx urban-regional chemical transport model. Dispersion by source for each city. →