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Monitoring particulate matter in India: recent trends and future outlook

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Abstract

Air quality remains a significant environmental health challenge in India, and large sections of the population live in areas with poor ambient air quality. This article presents a summary of the regulatory monitoring landscape in India, and includes a discussion on measurement methods and other available government data on air pollution. Coarse particulate matter (PM_{10}) concentration data from the national regulatory monitoring network for 12 years (2004–2015) were systematically analyzed to determine broad trends. Less than 1% of all PM_{10} measurements (11 out of 4789) were found to meet the annual average WHO Air Quality Guideline (20 μg/m^3), while 19% of the locations were in compliance with the Indian air quality standards for PM_{10} (60 μg/m^3). Further efforts are necessary to improve measurement coverage and quality including the use of hybrid monitoring systems, harmonized approaches for sampling and data analysis, and easier data accessibility.

Keywords India · Air quality monitoring · Air pollution policy · WHO Air Quality Guidelines · PM_{10} · $PM_{2.5}$

Introduction

Particulate matter (PM) has been identified as one of the most critical environmental risks globally (Brauer et al. 2015) and poor air quality (AQ) including exposure to PM has been associated with morbidity and mortality due to respiratory, cardiovascular, and cerebrovascular diseases (Dockery et al. 1993; Dominici et al. 2006; Pope and Dockery 2006; Brook et al. 2010; Thurston et al. 2016). A significant proportion of the global population lives in areas that exceed the World Health Organization (WHO) Air Quality Guidelines, particularly in low- and middle-income countries (van Donkelaar et al. 2015). PM also has climate effects including its direct role in light scattering and absorption of sunlight and thermal radiation and the indirect role in acting as cloud condensation nuclei (CCN) (Ramanathan and Carmichael 2008), and impacts visibility and general well-being (Levinson 2012; Singh et al. 2017; Zhang et al. 2017).

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$PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) is the specific fraction of the PM that is linked with human health impacts, and is often used as an indicator for air quality within a community, though PM_{10} (particulate matter with an aerodynamic diameter less than 10 μm) is also found to have adverse health outcomes (Ostro et al. 1999; HEI 2011; Stieb et al. 2012; Shah et al. 2013). In India, 99.9% of the country's population resides in areas that exceed the WHO Air Quality Guideline of 10 μg/m³ (annual average), and half of the population resides in areas where the Indian National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ (40 μg/m³) is exceeded (Greenstone et al. 2015; Venkataraman et al. 2018). Per latest Global Burden of Disease (GBD) estimates, the average population-weighted $PM_{2.5}$ concentration is 74.3 μg/m³, and exposure to outdoor (ambient) air pollution is linked to 133.5 deaths per 100,000 people per year (Cohen et al. 2017). Another study estimated that exposure to $PM_{2.5}$ is linked to ~600,000 premature deaths per year in India (Chowdhury and Dey 2016); the status of epidemiological research with respect to air pollution is summarized in Gordon et al. (2018). Despite poor air quality, only a limited amount of data are available on air pollution trends in Indian cities, and there is a significant gap in our understanding of spatio-temporal patterns of air pollutants at the local, regional, and national level. Previous studies have called for better coverage in terms of air pollution monitoring, as well as better QA/QC (quality assurance/quality control) to ensure high-quality data (Guttikunda et al. 2014; Greenstone et al. 2015; Pant et al. 2016). However, to the best of our knowledge, there has been no concerted effort to summarize and evaluate existing regulatory AQ monitoring efforts and analyze associated datasets across India in the last decade. Furthermore, there is a lack of comprehensive information on the types of monitoring networks, and associated data availability across the country.

Considering the above issues and gaps, this manuscript reports on (1) regulatory $PM_{2.5}/PM_{10}$ data availability and key trends throughout India, and (2) current status of the national monitoring networks, plans, and limitations in India. Results of our data analysis and the underlying data are available upon request.

Ambient air quality monitoring in India

Regulatory AQ monitoring, mandated by the Air (Prevention and Control of Pollution) Act of 1981, is conducted in India under the aegis of the Central Pollution Control Board (CPCB) which operates under the Ministry of Environment, Forest and Climate Change (MoEFCC) (Figs. S1, SI). The first set of standards for AQ in India was adopted in 1982 followed by revisions in 1994 and 2009. Originally, there were separate standards for TSP (total suspended particles) and RSPM (respirable suspended particulate

matter, i.e., PM with aerodynamic diameter less than 10 μm; now typically referred to as PM_{10}), for residential, industrial, and sensitive zones. The standards were revised in 2009, including the promulgation of a uniform standard for $PM_{2.5}$ concentration across all location types (http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php) (see Table 1). The standards for $PM_{2.5}$, both 24 h (60 μg/m³) and annual (40 μg/m³), are higher than the WHO Air Quality Guidelines (see Table 1), as well as standards in the USA and Europe. The following section discusses the major monitoring programmes in the country (see Table 2).

National Air Quality Monitoring Programme

The National Air Quality Monitoring Programme (NAMP) is the flagship air quality monitoring programme of the Government of India. As of September 2018, four key pollutants—sulfur dioxide (SO_2), nitrogen dioxide (NO_2), PM_{10}/RSPM, and $PM_{2.5}$—are monitored at 703 AQ stations across 307 cities and towns (http://cpcb.nic.in/monitoring-network-3/). The program is managed by the CPCB in coordination with the State Pollution Control Boards (SPCBs) and UT (union territory) Pollution Control Committees (PCCs). Other national organizations such as NEERI (National Environmental Engineering Research Institute) and regional/local educational institutions are also involved in sample collection and analysis.

Most of these stations (residential and industrial) are located in urban areas, and the coverage in the rural areas is sparse (Balakrishnan et al. 2014; Gordon et al. 2018). This is relevant to note since residential combustion emissions, typically associated with solid fuel use, are a key source of air pollution across the country (Balakrishnan et al. 2013; Venkataraman et al. 2018). Typically, sampling is conducted twice a week, with gas and PM samples collected for 24 h (4-h and 8-h periods respectively) (http://cpcb.nic.in/monitoring-network-3/). Outside of these 4- and 8-h time periods, no data is collected at the manual stations based on publicly available information. To ensure comparative sampling procedures across the NAMP stations, national guidelines have been set for monitoring and include information regarding siting criteria, QA/QC procedures, measurement methods, and data reporting (CPCB 2003; CPCB 2011). In addition to the monitoring sites under NAMP, several states including Maharashtra, Gujarat, Kerala, Odisha, Karnataka, Telangana, and Andhra Pradesh conduct ambient AQ monitoring at additional sites under State Ambient Air Quality Monitoring Programme (SAMP).

The CPCB has also set up a network of continuous monitoring stations (Continuous Automatic Air Quality Monitoring Station: CAAQMS) across major cities, and a suite of pollutants including PM ($PM_{2.5}$ and PM_{10}), gases (SO_2, NO_2, NH_3, ground-level ozone (O_3), CO [carbon monoxide]), and BTEX (benzene, toluene, ethylbenzene, and xylene) are measured continuously year-round. Currently, cities

Table 1 Indian National Ambient Air Quality Standards (NAAQS) for PM and related components in India (*TEOM* tapered element oscillating microbalance, *AAS* atomic absorption spectroscopy, *ICP* inductively coupled plasma mass spectrometry, *ED-XRF* energy dispersive x-ray fluorescence, *GC-MS* gas chromatography-mass spectrometry, *FRM* federal reference method, *FEM* federal equivalent method, *lpm* liters per minute)

Pollutant	Unit	Time duration	NAAQS Standard	Recommended measurement method	WHO Air Quality Guidelines
$PM_{2.5}$	$\mu g/m^3$	Annual 24 h	40	*$PM_{2.5}$ Gravimetric measurement*	10
			60	Filter type: PTFE 47 mm	25
PM_{10}		Annual 24 h	60	Volume: 16.7 lpm	20
			100	Instrument: FRM or FEM equipment	50
				PM_{10} Gravimetric measurement Filter type: GFA/ EPM 2000	
				Volume: 1132 lpm	
				Instrument: High-volume sampler	
				Real-time, continuous measurement	
				TEOM/ β-attenuation	
Pb		Annual 24 h	0.50	AAS/ICP on EPM 2000 or equivalent paper /	
			1.0	ED-XRF on PTFE filter	
Particulate BaP	ng/m^3	Annual	1.0	Solvent extraction followed by GC-MS analysis	
As			6.0	AAS/ICP on EPM 2000 or equivalent paper	
Ni			20.0		

with a population of more than one million are prioritized for CAAQM stations, and similar stations are expected to be set up across all state capitals and union territories (http://cpcb.nic.in/Amb_AQ_Monitoring.pdf). As of September 2018, there are 130+ CAAQM stations in more than 65 cities across India (https://app.cpcbccr.com/ccr_docs/caaqms_list_All_India.pdf). Most stations are operated as partnerships between the CPCB and SPCB, with a state and federal cost sharing financial arrangement. Data from the CAAQM stations is also used for determination of the air quality index (AQI), which is publicly available online, via a smartphone app and historical data is archived on the CPCB website. The AQI is calculated using the national AQI methodology, compiled and approved by the CPCB in 2014 (CPCB 2014).

Table 2 Summary of currently operational air quality networks in India

		NAMP/SAMP/ CAAQMS	SAFAR	MAPAN	US Consulate
Purpose	Regulatory	x			
	Research		x	x	
	Other (e.g., public awareness)	x	x		x
Data	Real-time	x	x	x	x
	Manual	x			
Instrument type	High-volume sampler(s)	x			
	BAM (or similar)	x	x	x	x
Pollutant	PM_{10}	x	x	x	
	$PM_{2.5}$	x	x	x	x
Air quality forecast	Yes		x	x	
	No	x			x
Open access to data	Real-time	x			x
	Aggregate	x	x		x
	None			x	
Funding	Government of India	x	x	x	
	Other				x

System of Air Quality and Weather Forecasting and Research

The System of Air Quality and Weather Forecasting and Research (SAFAR) network (http://safar.tropmet.res.in/) was launched in Delhi in 2010 by the Indian Institute of Tropical Meteorology (IITM, Pune) in collaboration with the Indian Meteorological Department (IMD) and the National Centre for Medium Range Weather Forecasting (NCMWRF) and is supported by the Ministry of Earth Sciences (MoES). The program currently runs in Delhi (launched in 2010), Pune (launched in 2013), Mumbai (launched in 2015), and Ahmedabad (launched in 2017) with plans for expansion to Bengaluru, Kolkata, and Chennai. The network has ten air quality monitoring stations (AQMS) in each city equipped with real-time, continuous monitors for a range of pollutants including PM_1, $PM_{2.5}$, PM_{10}, O_3, nitrogen oxides (NO_x), SO_2, black carbon (BC), methane (CH_4), non-methane hydrocarbons (NHMC), VOCs (BTEX) and mercury (Hg), and meteorological variables including solar radiation, rainfall, temperature, relative humidity, wind speed, and direction. At some locations, ammonia (NH_3) is also measured. Like the CPCB network, SAFAR also has a smartphone app, disseminating calculated AQI values for the criteria pollutants (as a city average) and anticipated AQI for the 2 days. This information is also disseminated on real-time display boards in each city. However, it is important to note that the AQI method utilized under this program is different from the national approach approved by the CPCB (see Table S1) (Beig et al. 2015). AQ data from the network are embargoed for 3 years but are available for public use (upon request and justification, submitted to IITM Pune) thereafter.

Modelling Atmospheric Pollution and Networking

The Modelling Atmospheric Pollution and Networking (MAPAN) program is currently operational in ~20 cities across India and is supported by the MoES. Pollutants monitored as part of this program include PM_{10} and $PM_{2.5}$, O_3, CO, NO_x, CO_2, hydrocarbons, BC, and organic carbon (OC). PM monitoring is conducted using β-attenuation method (Met One Instrument Model BAM-1020 in at least two locations (Yadav et al. 2014; http://www.ncess.gov.in/research-groups/atmospheric-processes-atp-group/laboratories/air-quality-monitoring-lab-aqml.html), but it is unclear if the same instrument is used across all sites. Cities included in the network are Pune and Satara (Maharashtra), Thiruvananthapuram (Kerala), Bhubaneshwar (Odisha), Chennai (Tamil Nadu), Jabalpur (Madhya Pradesh), Hyderabad (Telangana), Delhi (NCT of Delhi), Srinagar (Jammu and Kashmir), Udaipur (Rajasthan), Aizwal (Mizoram), Varanasi (Uttar Pradesh), Guwahati and Sonitpur (Assam), and Patiala (Punjab), although this list is likely not comprehensive. In most cities, the air quality monitoring stations are being run in collaboration with local academic/research institutions. Data generated as part of this network are expected to be used for evaluation of the IITM air quality forecasting model, but very limited information is currently available in the public domain.

US Embassy/consulate monitoring stations

As part of the AirNow program, the US Department of State operates $PM_{2.5}$ monitors in five major Indian cities—Delhi, Mumbai, Kolkata, Hyderabad, and Chennai—on the premises of the Consulate/Embassy in each city. The data are publically available in near real-time through the AirNow website. AQI values are also published on the website of the Consulate/Embassy; however, it is important to note that the reported AQI value is based on the US air quality standards and uses a different formula, and as such is not directly comparable to the Indian AQI values. The instruments operate at the embassy/consulate grounds, relatively isolated from heavy traffic or industrial sources, and in most cases they provide $PM_{2.5}$ measurements equivalent to an urban location in the cities.

Currently, data from the CAAQM stations are available online (https://app.cpcbccr.com/ccr/#/caaqm-dashboard/caaqm-landing), but data access is often limited and, in some cases, unavailable. Data from the NAMP stations can also be downloaded through the Government of India open data platform (https://data.gov.in/). Most SPCB websites also share ambient air quality data, but there are variations in the type of data available. In most cases, monthly or annual averaged data are posted (most often as pdf files) on the SPCB websites. It must be noted that some states (e.g., Telangana, Tamil Nadu, Uttarakhand, Uttar Pradesh, and Maharashtra) have good data availability on their websites (e.g., Uttarakhand- http://ueppcb.uk.gov.in/pages/display/95-air-quality-data; Maharashtra- http://mpcb.gov.in/envtdata/envtair.php). Third-party organizations including several media outlets have also created data dashboards that allow the public to access the data, and the raw data from the CAAQM stations and the US Embassy/Consulate stations are archived by OpenAQ. Data from SAFAR and MAPAN networks are not available in the public domain currently.

Ambient PM₁₀ concentrations across India

Data collected as part of the NAMP network are released monthly or annually, while the data from the CAAQM stations is accessible in near real-time (https://app.cpcbccr.com/ccr/#/caaqm-dashboard/caaqm-landing). It is important to note that no metadata or QA/QC data are made available, either on the website or in the annual reports. Additionally,

for CAAQM stations, data is often missing for long periods of time often with no description for the reasons behind missing data. In terms of application, data collected as part of the NAMP monitoring network is used for reporting annual trends by the CPCB. Some trend analysis (Kandlikar 2007; Guttikunda and Gurjar 2012; Gurjar et al. 2016) and epidemiology studies (Balakrishnan et al. 2013; Maji et al. 2017) have utilized the data, but there has been limited application of the data elsewhere. Recently, Pande et al. (2018) utilized the PM_{10} data from NAMP stations to correct satellite data-derived estimates (based on AOD) of PM_{10} at the country level.

For this study, annual average PM_{10} data was retrieved from the NAMP stations from 2004 through 2015 from the national data portal and the reports on the CPCB website. Monitoring of $PM_{2.5}$ commenced only after the introduction of the standard in 2009, and as a result, the data availability prior to this is comparatively limited. Although NAMP data was collected before 2004, national-level data was not available. Measurements presented here are from 27 states and 5 UTs at 630 unique monitoring locations as of 2015 (see Table 2). A large number of sites exceed the annual PM_{10} standard ($60~\mu g/m^3$), particularly in the northern and central parts of the country, and in some cases, the concentrations were up to six times higher than the standard.

Only 11 of the 4789 (0.23%) unique PM_{10} annual average measurements meet the annual WHO Air Quality Guideline ($20~\mu g/m^3$) though 895 measurements (19%) met the annual Indian NAAQS ($60~\mu g/m^3$) (see Table 3). Over the 12-year period, only one site (Tekka Bench Ridge, Shimla, Himachal Pradesh) met the WHO AQ guideline in two separate years (2004 and 2005). Two hundred forty-six unique sites, mostly located in southern and eastern India (see SI Fig. S2), met the Indian NAAQS in at least 1 year over the assessment period. On the other hand, five sites (two in Chennai (Tamil Nadu) and one each in Madurai (Tamil Nadu), Shillong (Meghalaya), and Mysore (Karnataka)) met the annual Indian standard each of the 12 years that data is available.

A summary of annual average PM_{10} concentrations shows significant variations across states, with higher concentrations in the northern part of the country. There is little evidence of a PM trend nationally. Over this time, the average number of stations in a state/UT has gone up from 8 to 19, while the PM_{10} concentration has remained more or less constant (Fig. 1). Further, there were no notable trends within individual states; it is difficult to assess state level trends as there are

inconsistencies with monitor distribution (i.e., number of monitoring stations and location of monitors). However, an assessment of PM_{10} monitoring data shows an increasing trend for PM_{10} concentrations across the country in the last few years (Yang et al. 2018). Additionally, between 1998 and 2014, $PM_{2.5}$ concentrations have steadily increased, and the number of districts (per 2011 Census) that exceed the annual average $PM_{2.5}$ standard of $40~\mu/m^3$ increased several fold (van Donkelaar et al. 2015). Further, visibility data (a proxy for air pollution levels) from Indian cities shows an increase in bad visibility days in the last decade (Hu et al. 2017).

Annual average PM_{10} concentrations were higher in Northern India (namely Rajasthan, Uttar Pradesh, Delhi, Jharkhand, and Punjab) compared to the Southern states (Fig. 2), consistent with other measurement, modeling, and satellite findings (Nair et al. 2007; Dey et al. 2012; Saikawa et al. 2017; Shi et al. 2018). Several studies have also reported on the winter haze in the Indo-Gangetic plains in Northern India (Gautam et al. 2007; Ram et al. 2016). The lowest annual average PM_{10} concentration was $9~\mu g/m^3$ at Tekka Bench Ridge (Shimla, Himachal Pradesh) in 2004 while the highest reported annual average PM_{10} concentration at any sites was at Sarora (Raipur, Chattisgarh) in 2011 with the annual concentration of $379~\mu g/m^3$ (annual average varied between 177 and $379~\mu g/m^3$ across sampling years, with an average of $273~\mu g/m^3$). The Tekka Bench Ridge station has been continuously active since 2004 and the annual average concentrations have ranged between 40 and $62~\mu g/m^3$ (average across the years is $42~\mu g/m^3$) except for 2004 ($9~\mu g/m^3$) and 2005 ($17~\mu g/m^3$). Overall, the highest annual average concentration averaged across all monitors in the state/UT in any year was $261~\mu g/m^3$ in Delhi (number of monitoring stations = 9) in 2010. Since 2008, Delhi has consistently been the most polluted state/UT although in the years prior, the northern state of Punjab recorded the highest PM_{10} levels. Several studies have reported high average concentrations for both PM_{10} and $PM_{2.5}$ in Delhi (Chowdhury et al. 2007; Guttikunda and Goel 2013; Pant et al. 2015a, b; Tiwari et al. 2015; Sharma and Dikshit 2016; Maji et al. 2017; Yang et al. 2018). It is important to note that not all sources are the same for both PM_{10} and $PM_{2.5}$, and it is important to consider the data with caution. In the Indian context, dust is a major source for PM_{10}, and there is strong seasonality in the concentrations (Pande et al. 2018; Yang et al. 2018). Studies in India have also indicated that the average $PM_{2.5}/PM_{10}$ ratio is between 0.5 and 0.8 (Kothai et al. 2011; Tiwari et al. 2015).

Table 3 Number of annual average PM_{10} measurements attaining the Indian NAAQS ($60~\mu g/m^3$) and WHO Guideline ($20~\mu g/m^3$)

	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	Total
WHO Air Quality Guideline	0	0	0	0	3	0	0	0	0	0	6	2	11
Indian NAAQS	107	107	107	78	86	79	53	53	61	62	62	40	895
Total Sites	555	517	506	472	482	432	369	342	335	306	247	210	4789

Fig. 1 Average PM_{10} concentrations (panel A) and monitoring stations (panel B) based on NAMP data from 2004 to 2014
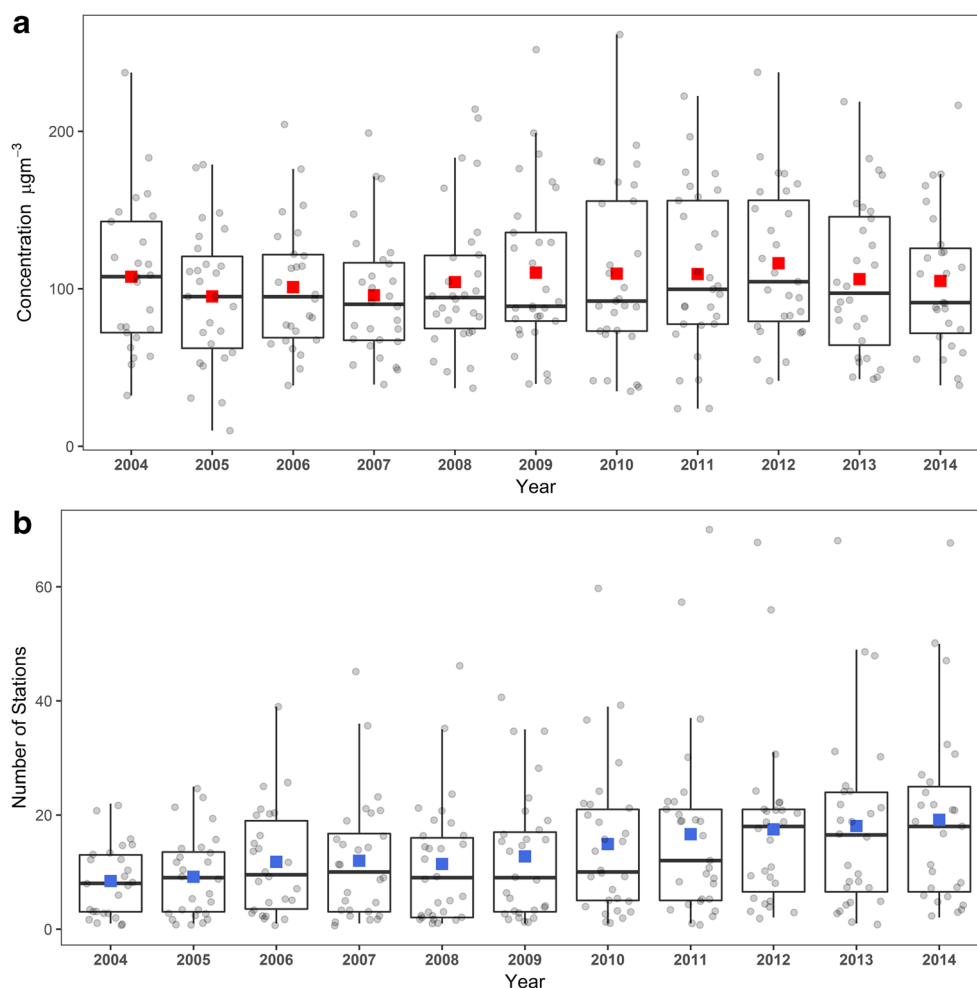
Observations from this dataset also align with available information on PM sources characteristics for the country
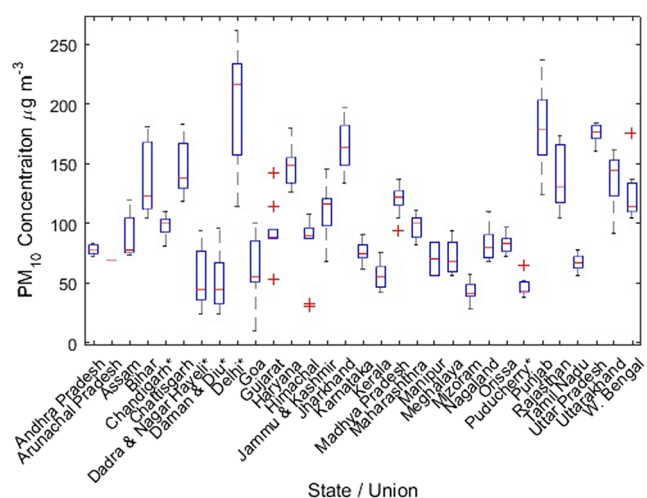

Fig. 2 Annual average PM_{10} concentrations at state/UT-level based on NAMP data from 2004 to 2015. [Note: Locations of monitors (industrial vs residential and other sites) tend to vary significantly from state to state. This figure should only be used for a general understanding of average pollution levels in urban India]

(dominant sources being residential biomass burning, dust, fossil fuel and biomass burning, and waste burning (including crop residue)) (Pant and Harrison 2012; Guttikunda et al. 2014; Wiedinmyer et al. 2014; Pandey et al. 2014; Sadavarte and Venkataraman 2014; Karagulian et al. 2015; Gargava and Rajagopalan 2015; Gurjar et al. 2016). In a recent global modeling assessment for energy-related sources of PM_{10}, residential and industrial sectors were reported to be the largest contributors followed by power and transportation for India (Winijkul et al. 2015), and another study reported residential biomass fuel emissions to be the biggest contributor to ambient $PM_{2.5}$ levels across India followed by combustion of agricultural residue (particularly in Northern India where in situ waste burning is a common practice) (Venkataraman et al. 2018). Non-exhaust emissions, including resuspended dust and brake, and tire emissions can also play a significant role in PM_{10} emissions (Pant et al. 2015a, b; Nagpure et al. 2016).

Year-on-year trend analysis was not conducted; if absolute changes in PM_{10} concentrations are considered, there is a wide variation in trends across states. Overall, the number of monitoring stations has changed (in most cases, there has been an increase in the number of monitoring stations) over time, and

it is expected that changes in demography and socio-economic patterns would have impacted the emission patterns (Fig. 3). However, it is hard to make significant conclusions regarding pollutant concentrations from these datasets since there has been a shift in the type of stations setup under NAMP during the study period. While detailed information is not available, there has been an increase in the number of residential/urban monitoring stations in the last decade.

There are limitations and uncertainties associated with this dataset that have not been explicitly defined for each station; all measurements are gravimetric, and while there is a protocol for sample collection and analysis, in the absence of QA/QC data or information on laboratory inter-comparisons, it is hard to interpret the quality of the data across the country. Further, most measurements occur over 24 h (8-h period) two to three times a week, presumably during the day. This likely underestimates the true PM_{10} concentration as nighttime concentrations often exceed daytime concentrations, and the 8-h

sampling period does not capture the temporal variability of the pollutant.

Aerosol optical depth (AOD) measurements made on-board satellites offer another opportunity for estimation of PM concentrations. Chowdhury and Dey (2016) estimated $PM_{2.5}$ concentrations at the district level in India using daily columnar AOD data from Multiangle Imaging SpectroRadiometer (MISR) and associated modeling exercises that combines the AOD data with emission inventories and ground monitoring data using chemical transport models. Based on this dataset, Kinnaur (Himachal Pradesh, 3.7 μg/m^3) had the lowest annual average $PM_{2.5}$ concentration while the highest concentration was observed in Delhi (148 μg/m^3). These observations are in broad agreement with the reported trends for PM_{10} data from the NAMP network as discussed above.

Station density and coverage

The NAMP network currently has 700 stations and the network has come a long way since 1984 when it was first launched with seven stations in Northern India. The CPCB has provided detailed siting criteria for monitoring stations and included considerations such as size of the area, population, and pollutant sources (CPCB 2003). The guidelines also refer to a greater need for making measurements near traffic (diesel vehicles) and industries since these are major sources of PM.

However, for a country with a population of ~1.2 billion, this amounts to one pollution monitoring station for every ~2 million people. Given the spatial heterogeneity of pollutant concentrations in India, in part due to mixed land-use (Tiwari 2002), the data should be improved (e.g., better coverage, clear metadata, and QA/QC) to better support pragmatic regulatory assessment or epidemiology studies. There is a wide variation in the number of monitoring stations across states often irrespective of the PM levels or population density (Fig. 4). Additionally, in several states including Manipur and Arunachal Pradesh in North-eastern India, station density is very poor and only 2–5 years of data is currently available. For comparison, there are 87 monitoring stations for PM_{10} and 32 for $PM_{2.5}$ in the Greater London region, UK (Mittal and Fuller 2017), a city of 9 million. To better characterize air pollution in Indian cities, there is a need to introduce more monitoring stations, especially in densely populated urban centers. As per the review of CPCB (IIM 2010), a total of 3000 stations were expected to be established in Class I (population of one million or more) and II (population of 50,000 to 99,999) cities and towns by 2022, and 100 CAAQM stations by 2012. However, there are currently 703 stations across the country, and 130 + CAAQM stations are operational as of September 2018.

It is also important to consider that this dataset largely represents the air quality for urban and peri-urban India, since the NAMP network does not include monitoring stations in rural areas (Balakrishnan et al. 2014). Given the significant
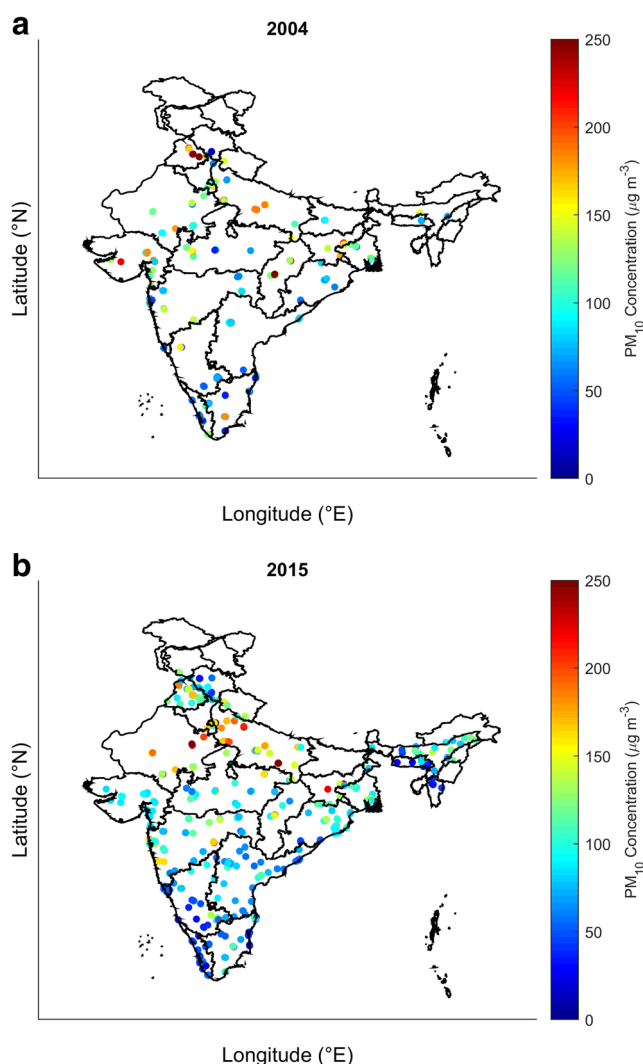

Fig. 3 Variability in PM_{10} concentrations at NAMP stations in **a** 2004 and **b** 2015. [Note the higher concentrations in the Indo-Gangetic Plains, i.e., north India]
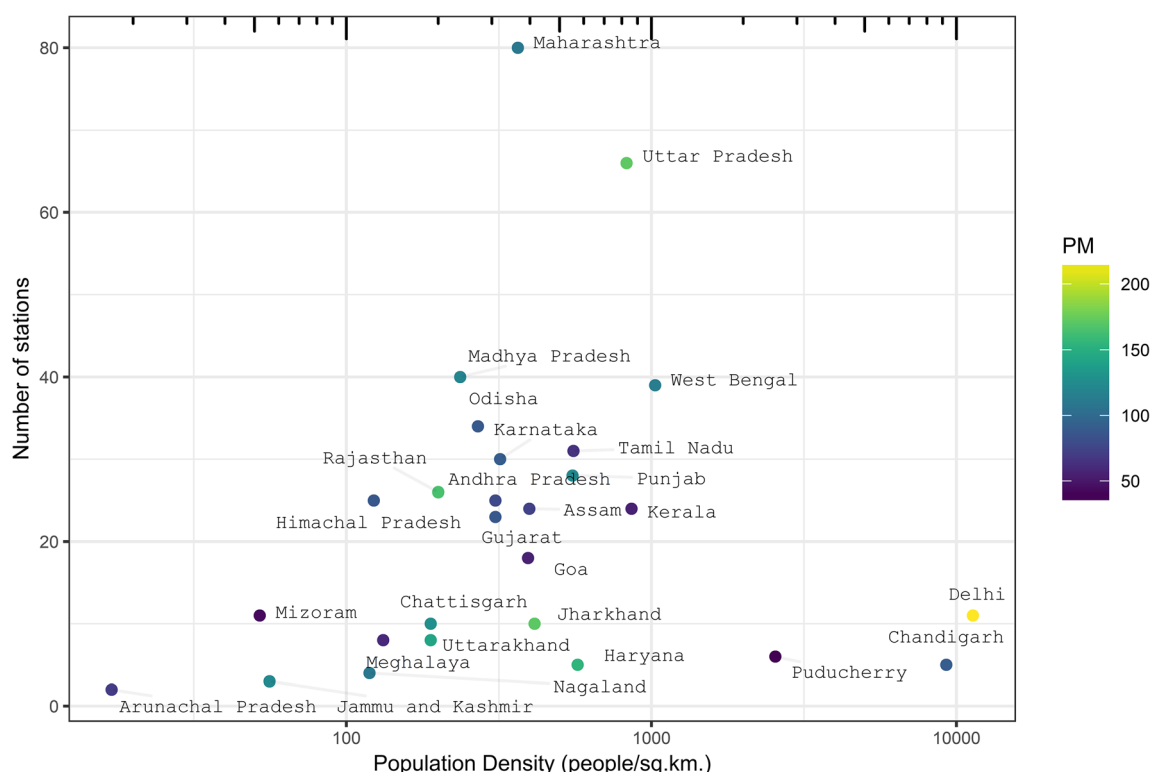
Fig. 4 Average population density and average PM_{10} concentrations (in $\mu g/m^3$) across states and the corresponding number of current NAMP monitoring stations [as of 2017] (following states/UTs are not included: Dadra and Nagar Haveli, Daman and Diu, Tripura, Manipur, Sikkim, Bihar, Telangana, Lakshadweep, Andaman and Nicobar Islands)

human health burden associated with exposure to household air pollution, much of which occurs in rural areas, lack of data from rural areas could in fact be contributing to exposure misclassification in large-scale modeling and epidemiological studies. However, several new research projects are focusing on generating integrated ambient and indoor data on PM in rural parts of the country (Balakrishnan et al. 2015; Tonne et al. 2017).

Finally, from the perspective of air quality monitoring and assessment, it is important to establish regional monitoring stations for measurement of particle concentrations and compositional analysis at background levels. Data from such stations can be useful in assessment of long-term trends as well as in source apportionment analyses, particularly with reference to understanding the contribution of regional and local sources. Additionally, such stations can provide valuable data on improving our understanding of regional transport of aerosols. Currently, there are no regional monitoring stations within the regulatory (NAMP) network.

Data quality

A majority of the air pollution monitoring stations across the country are operated manually and it is unclear how the 8-h samples are used for regulatory purposes of assessing whether locations are meeting the 24-h NAAQS, since an 8-h sample only captures a snapshot of the actual levels. Further, it is likely that singular pollution episodes are either not accounted for, or have an undue influence on the measurements resulting in under- or over-reporting of PM_{10} concentrations. Manual monitoring also results in a delay in data collection, transmission, and availability, although the increasing number of CAAQMS are allowing data to be streamed to the CPCB website in near real-time overcoming some of the aforementioned concerns. A case in point is Delhi, the capital city, which has the most extensive AQ monitoring network in the country. Between 2004 and 2015, data capture for PM_{10} across ten sites (assuming 104 observations/year) varied between 12 and 74% (Fig. 5).

A rigorous QA/QC procedure is vital to ensure that the results are comparable, reliable, and reproducible. The measurement and reporting protocols need to be consistent over time, and any biases due to instrument drift need to be accounted for in the analysis. A number of documents refer to QA/QC procedures for the NAMP monitoring stations (CPCB 2003; CPCB 2011); however, there is no information on data ratification and quality control for the NAMP monitoring sites, which suggests these data should be interpreted with caution. There is a Pollution Assessment, Monitoring and Survey (PAMS) program, but no information on data QA/QC
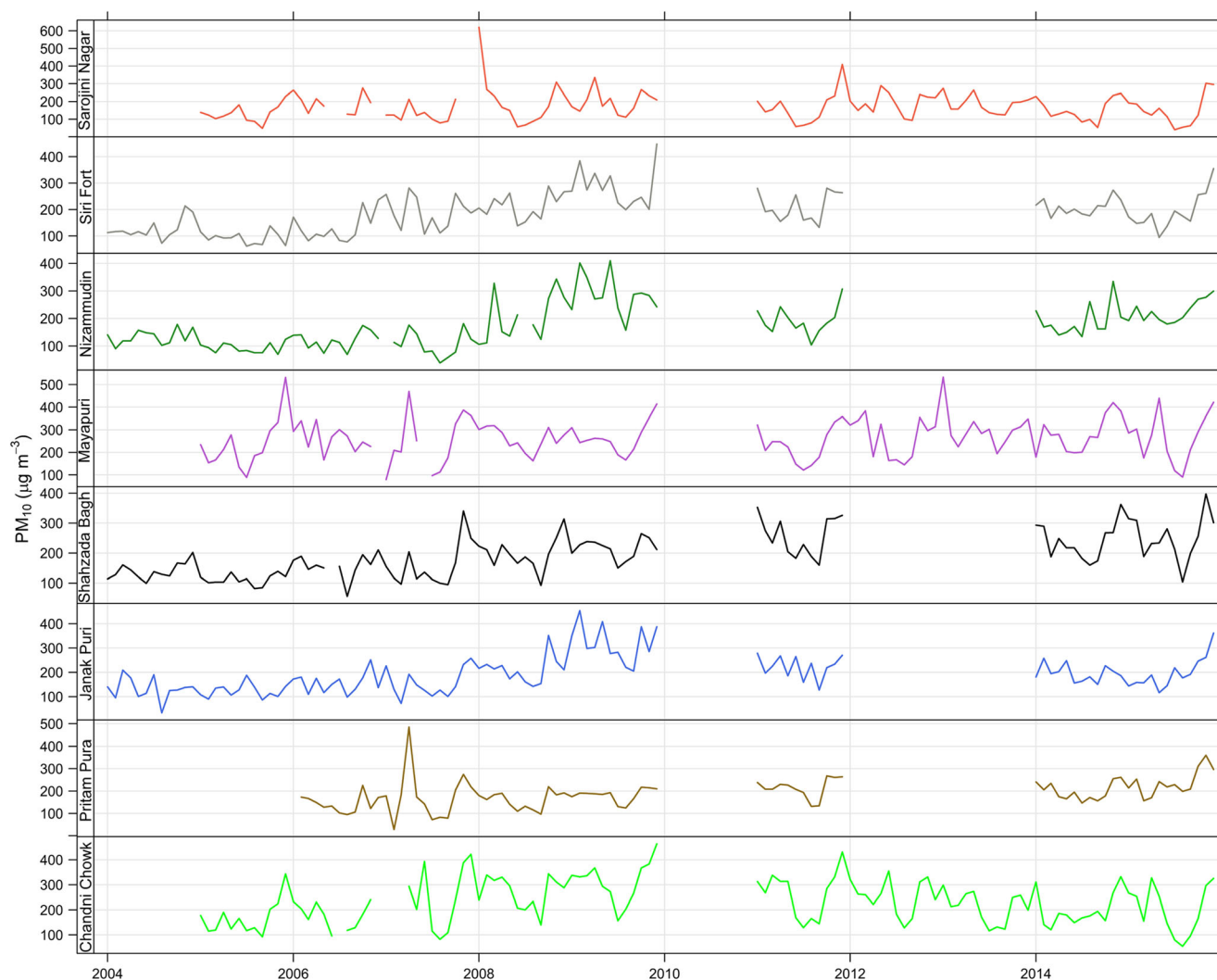
Fig. 5 Monthly average PM$_{10}$ concentration across ten stations in Delhi based on data retrieved for 2004 through 2015 [based on manual monitoring data reported by the CPCB]

is available publicly. In case of SAFAR, a detailed QA/QC protocol is listed on the website, but neither the air quality data nor the QA/QC is publicly available. Similarly, there is no publicly accessible information for the MAPAN network.

Traceable quality assurance requires clear and reproducible procedures which are implemented with scientific rigor and need trained technicians and scientists to operate these networks. In the Indian scenario, the issue of QA/QC is also tied to the technical capacity at the central and station pollution boards, and the zonal offices and laboratories. This includes both the personnel and the infrastructure available to them for sampling and analysis. The CPCB review (IIM 2010) also alluded to the issue of lack of technical capacity and limited opportunities for capacity building. Further, funding available to the central and state pollution control boards is often limited and does not account for resources required for research and analysis, thereby limiting rigorous data analysis and its direct application in policymaking.

Future outlook for air quality data in India

Air pollution remains a leading environmental concern in India, and a review of current monitoring and data management strategies indicates lack of consistency across different networks (e.g., differences in methodologies for estimation of AQI). Given the very high levels of PM in many parts of the country, India has also been in the international spotlight with several cities listed among the worst in terms of air quality, and increasingly, there is public pressure for action on air pollution. Lack of centralized databases on air quality has rendered it difficult to utilize available data for long-term trends analysis studies, and in cases where the data is used, there is significant uncertainty associated with final observations or outcomes. Recent efforts such as open-access availability of long-term datasets from NAMP stations is a welcome step and will undoubtedly spur and facilitate work on the topic. Significant improvements have been made with respect to

air quality monitoring in India in the last two decades, and efforts are underway to further strengthen the national monitoring program, with a focus on setting up CAAQMS across major cities. Given the significant health burden associated with exposure to PM in India, strengthening the regulatory air quality monitoring networks in India would provide greater support for both air quality management, higher order scientific inquiry, and epidemiological analysis activities. Here, we provide recommendations to further strengthen India's air quality monitoring networks:

[1] *Improvement in data quality and data access*: Third-party data evaluation, annual instrument inter-comparisons and calibration can be used for data assessment. In the UK, for example, all regulatory monitoring data collected as part of the Automatic Urban and Rural Network (AURN) is ratified through Ricardo AEA, an independent agency whereas in the USA, state and local monitoring agencies follow specifically developed standard operating procedures [SOPs] (often in consultation with external contractors such as Sonoma Technology or RTI International). The National Physical Laboratory of India (NPL) has been leading the charge in gas and PM calibrations (http://www.nplindia.in/gas-metrology). In addition, it is important to collect and release metadata (i.e., descriptive information about datasets) to ensure better cataloging and context-relevant usage of data. In addition, information about the performance of the monitoring networks through key metrics such as annual data capture rate and instrument calibration and performance evaluation should be archived and released.

[2] *Harmonized approaches for sampling and data analysis*: Appropriate siting of AQ monitoring stations can help meet the regulatory requirements of AQ monitoring and can also be leveraged for exposure and health assessment studies. Thus, it is crucial to setup monitoring stations based on where they are needed, and not merely where they can be conveniently located. It would be useful to create a national guidance document on siting of AQ stations across a range of environments including urban (roadside, industrial, commercial, residential), rural, and regional monitoring areas. Regional monitoring stations to measure background air pollution levels can be particularly helpful in determining the contribution of regional transport of aerosols. Several studies have reported significant contributions from non-local sources at the city as well regional level (Dey and Di Girolamo 2010). Data generated through the wide network of monitoring programs should also be utilized actively in designing strategies for pollution control, and for measuring the impact of specific interventions.

One point of consideration for new monitoring sites is the migration of people from rural to urban areas and an increase in the in situ urban populations in India (Bhagat 2017). At the same time, recent trends indicate that the net rural to urban migration constitute only a third of the total increase in urban populations (Bhagat 2017). Dey et al. (2012) reported no correlation between annual $PM_{2.5}$ (based on satellite retrieval) and population size but changes in the cities' design and infrastructure coupled with changes in demographics are likely to impact both pollution sources and exposures, and consequently, the health impact estimates. As new monitoring stations are planned, such demographic changes can help to make the monitoring networks representative.

[3] *Use of hybrid monitoring networks*: Low-cost sensors offer an opportunity to generate high-resolution data at a lower cost, and with fewer deployment and access limitations (Snyder et al. 2013). A number of community projects have been launched worldwide for crowd-funded air pollution measurements, and while such sensors can be useful in designing citizen science projects and generating novel data, there are still a number of uncertainties associated with the accuracy of measurements using low-cost sensors (Lewis and Edwards 2016; Clements et al. 2017). So far, such monitors have not been proven to provide long-term, accurate data without systematic calibration (Lewis and Edwards 2016; Rai et al. 2017). Efforts are underway to improve precision among such sensors, and latest analyses are supporting the case for deployment of well-designed low-cost sensors for measurement of air pollution at the city level. If designed carefully, such networks can provide valuable data on spatial variability of pollutants and help in identification of hyperlocal pollution hotspots. Additionally, such instruments can be used as indicative instruments to define and design more efficient regulatory monitoring networks.

In India, several independent low-cost sensor-based AQ networks have been launched in recent years, and such networks have been instrumental in improving public awareness. However, in the absence of reliable calibration, and other QA/QC, it is unlikely that these data can be used for research or regulatory applications in the near future.

[4] *Utilizing alternative approaches to fill data gaps*: One avenue for improving our understanding of spatial and temporal patterns of PM is the use of satellite data. Data on aerosol optical depth (AOD) is typically collected via satellite overpass measurements (e.g., MODIS- https://modis.gsfc.nasa.gov/) and can be used for AQ applications such as forecasting, tracking pollution sources, and plumes, and as input/evaluation for AQ models (Duncan et al. 2014). Several recent studies have reported $PM_{2.5}$ concentration estimates based on satellite AOD retrieval and subsequent modeling using chemical transport models (CTMs) (van Donkelaar et al. 2010;

Dey et al. 2012; Brauer et al. 2015), and have contributed in improving our understanding of global pollution patterns, especially in areas where ground monitoring is not conducted, or historical data is not available. There are still certain limitations, including inadequate bias-correction based on local data, obtaining surface level measurements (since AOD is a columnar measurement), and limited datasets (data retrieval is only possible on clear sky days). However, current results indicate that satellite data can be very useful in generating annual estimates for $PM_{2.5}$, especially in areas with limited ground monitoring, both for long-term trend analysis, and for health impact assessments, but not for hour by hour or day to day measurements. MISR observations have additional information on PM physical properties including aerosol size and shape. Additional satellite observations of gas-phase species, particularly PM precursors (e.g., HCHO (formaldehyde), NO_2, and SO_2), can provide spatio-temporal information that can be related to PM levels and sources. A recent analysis by Pande et al. (2018) utilized AOD datasets to estimate PM_{10} concentrations and all-cause mortality associated with PM_{10} exposures at the national level.

[5] *Air Quality Forecasting and Early Warning Systems*: Given the high frequency of pollution episodes, it is important to have early warning systems which can be used for alerting the public and broadcasting public health advisories in urban and rural areas. In addition to generating forecasts, designing public communications programs to spread this information along with guidance on what the public should (or should not do) through apps, social media, and mass media (e.g., radio, TV and print) in local languages would be useful.

- SAFAR has been instrumental in providing advance information about the AQ levels in four cities, but similar systems based on high-quality data are needed across the country. Additionally, it is important to monitor data quality, and reliability of forecasts in the long term, which is currently lacking.
- In 2017, Urban Emissions, a private organization, launched an independent AQ forecasting system where modeled hourly average concentration and a 24-h moving average concentrations are simulated for the next 72 h, using the Weather Research and Forecasting (WRF) meteorological model and the GFS meteorological fields and the CAMx chemical transport modeling system (Skamarock et al. 2008). The data are available in the form of maps on an open-access portal (http://www.indiaairquality.info).

[6] *Increase in expenditure and capacity building efforts*: To further improve the country's AQ monitoring network, increased funding can help extend data collection. Such data should not be limited to PM mass, but include speciation to help quantify the impacts of specific sources and can be immensely useful not only for regulatory monitoring, but also for detailed health impact studies, source apportionment analyses, and assessment of policy interventions. Similar recommendations have also been made elsewhere (Doraiswamy et al. 2017). For example, India is set to introduce Bharat Stage VI fuel standards (comparable to Euro VI) by 2020, and this is expected to result in a decline in PM levels. With speciation data, it will be much easier to characterize changes in the emissions' profile after this national policy is introduced. At a local level, speciation data, when collected over a long term, can be helpful in measuring the impact of specific policy interventions (e.g., odd-even vehicle policy in New Delhi) in terms of reduction of specific PM constituents.

Cities with a population of at least one million currently account for ~30% of the country's population, and as per CPCB plans, the goal is to install CAAQMS (including all criteria pollutants and meteorological parameters) in all state capitals and cities with population of one million or more (see the "National Air Quality Monitoring Programme" section). A number of these cities are currently undertaking large infrastructure projects under the SMART City initiative or the Urban Renewal Mission and have received federal aid. Given the significant health burden associated with exposure to ambient air pollution, setting up, and operating CAAQM stations is a useful investment to get accurate, reliable, and real-time information on air quality. Using CPCB siting criteria, an average city of one million plus residents requires ~25 CAAQM stations, and if this number is extrapolated across 60 cities, a total of ~1500 stations would be required (CPCB 2003). The average cost of a CAAQM station is ~INR one crore (~USD 0.15 million) with ~10% for annual maintenance costs (estimates based on figures reported for a station to be commissioned in 2017 by the CPCB). This would require an initial investment in the order of INR 3000 crores (~USD 0.5 billion) due to capital and operational costs (INR one crore per site for installation and INR one crore per site for maintenance for 10 years). On top of this, costs associated with infrastructure, personnel, and training need to be accounted for; and this can be estimated as an additional INR 3000 crore (~USD 0.5 billion); to cover other miscellaneous costs, an additional 50% is added to this resulting in a total of INR 7500 crores. These estimates indicate that the average cost of running the CAAQM station network in each city over a 10-year period would amount to ~INR 12.5 crores per year (~USD 2 million/year) (see Table S2 for an estimate of monitoring stations across Indian states). In comparison, the cost for the metro train infrastructure in major cities ranges

between INR 16,000 and 100,000 crores INR (~USD 2.5–15 billion). It is important to note that these estimates are based on a broad calculation and are subject to change over time.

Finally, increased opportunities for collaboration between the central and state pollution control boards, and local academic and research institutions, could also benefit pollution mitigation efforts. Creating a system where research and policymaking are better integrated and promoting research and development at the pollution control boards can help fill the gaps.

Compliance with ethical standards

Conflicts of interest Dr. Sarath Guttikunda is one of the founders of Urban Emissions, organization releasing air quality forecasts for Indian districts on an open-access platform.

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