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Evaluation of Particulate Pollution and Health Impacts from Planned Expansion of Coal-Fired Thermal Power Plants in India Using WRF-CAMx Modeling System

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ABSTRACT

Power from coal-fired thermal power plants (TPPs) represents a large percentage of the electricity generated in India. As the demand increases, expansion of the coal-fired TPPs is the most likely scenario, which will lead to an array of environmental and health impacts. The proposed projects in India net a generation capacity of 300 GW through 2030. With limited emission control regulations in place, this will increase the number of health impacts—some from direct particulate matter (PM) emissions and some from secondary PM, especially due to the chemical transformation of sulfur emissions. The WRF-CAMx chemical transport modeling system was utilized to study the impact of these emissions from the planned coal-fired TPPs. The additional 300 GW of projects will result in 3-times the coal consumption and at least 2-times the health impacts (premature mortality and asthma attacks), compared to those estimated for the operational TPPs. The technology to control all criteria pollutant emissions, which could reduce the health impacts linked to ambient $PM_{2.5}$ from the coal-fired TPPs by as much as 50%, is widely available, and the only barrier to implementing these solutions is the lack of a stricter timeline.

Keywords: Dispersion modeling; Environmental regulations; Particulates; Sulfates; Flue gas desulfurization; CAMx; Health impacts.

INTRODUCTION

India has the 5th largest electricity generation sector in the world. Over the next ten years, the power sector must expand to meet the needs of a growing economy. And at least through 2030, coal will remain the primary fuel of choice (Chikkatur *et al.*, 2011; WISE, 2012; Prayas, 2013; GBD-MAPS, 2018; Venkatraman *et al.*, 2018). For the coal-fired thermal power plants (TPPs) operational in 2011–2012, Guttikunda and Jawahar (2014) highlighted the impacts of lack of environmental regulations, contributions to primary and secondary particulate matter (PM) pollution, and the health impacts associated with PM pollution from them (80,000 to 115,000 premature deaths). In 2014, a standing committee headed by the Ministry of Environment Forests and Climate Change (MoEFCC), updated the total PM emissions standard from 150 mg Nm^{-3} to 50 mg Nm^{-3} for all the new coal-fired TPPs, with no change in the regulations for sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury, nor for the already commissioned TPPs (PIB, 2013). In 2015, MoEFCC ratified the new regulations, with a deadline to implement the same by December 2017 (MoEFCC, 2015). At the time of this study, the new regulations are not yet implemented. A comparison of the emission standards between India, China, the United States, the European Union, and Australia are presented in Table 1, along with a summary of the new emission standards.

Given the plans to greatly expand the contribution of coal in Indian power sector, it is vital that decision makers understand the health impacts of air pollution from these coal-fired TPPs and the likely impact of the coal expansion in the power generation sector, if the new emission standards are not implemented to the full extent. This paper extends the analysis presented in Guttikunda and Jawahar (2014) by studying the potential health and air pollution impacts of TPPs that are under construction and planned till year 2030, along with an analysis of their contribution to ambient PM and SO_2 pollution, and the benefits of mandating flue gas desulfurization (FGD) for all the TPPs.

DATA AND METHODS

Planned Coal-Fired Thermal Power Plants

As of June 2018, coal accounts for 57% of installed capacity (197 GW), hydro for 13%, diesel and natural gas for 7.5%, renewables for 20%, and others (including nuclear energy) for 2.5% (NPP, 2018). The location and generation

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Table 1. Summary of emissions standards (all in mg Nm^{-3}) for the coal-fired thermal power plants.

	PM	SO_2	NO_2	Mercury
Old emission standards (in practice as of December, 2017)				
India [a] (for boilers < 210 MW)	350	-	-	-
India [a] (for boilers > 210 MW)	150	-	-	-
New proposed emission standards				
India [a] (for plants installed before 2003)	100	200–600	600	0.03
India [a] (for plants installed between 2003–2016)	50	200–600	300	0.03
India [a] (for plants installed since 2017)	30	100	100	0.03
China [b]	30	100	100	0.03
Australia [b]	50	-	500	-
The European Union [b]	50	200	200	-
The United States [b]	22.5	160	117	0.001

[a] The Gazette of India - REGD. NO. D. L.-33004/99.
[b] http://www.airclim.org/acidnews/china-new-emission-standards-power-plants.

capacity of the operational coal-fired TPPs is presented in Fig. 1. The database of TPPs includes geographical location in latitude and longitude, number of boiler units, coal characteristics, coal consumption rates, and installed control equipment. These details were documented from their respective environmental impact assessment reports and data published by the state electricity boards (public entities) and private operators (MoEFCC, 2010; MoEFCC, 2018; NPP, 2018).

To counter the future electricity demands, McKinsey (2008) estimated the need for 300 GW, based on the growth of India's manufacturing sector, domestic electricity demands, the need for grid connectivity for 125,000 villages, and to suppress the blackouts and the load shedding. Prayas (2011) listed that 700 GW of power generation from coal is in the pipeline, with environmental clearances and project preparations at various stages and stated that if these come online, the necessary demand for electricity in the industrial and the domestic sector will be met with surplus electricity through 2030, barring the environmental and health impacts of the emissions from the new coal-fired power plants.

The database of TPPs under construction, under advance development, under planning and appraisals, and under consideration, are binned for operations between 2016 and 2030, with their likeliness of being operational in 2017, 2020, 2025, and 2030. The temporal distribution of the TPPs is speculative based on the information available in the project documents and their status, dependent on resource, financial, and environmental viability for each plant. The plants with less probability of securing the required clearances are not included in the assessment. Having excluded these, the estimated installed generation capacity for the years 2017, 2020, 2025, and 2030 are 231 GW, 296 GW, 396 GW, and 458 GW, respectively, with new capacity of 300 GW between 2014 and 2030. The planned TPPs are presented in Fig. 2 for 2017, 2020, 2025, and 2030. Not all of these power plants are established as new plants. Some of these are extensions at the existing TPPs. The filled circles in Fig. 2 are overlapping with the existing TPPs.

The totals estimated in this study are less than 700 GW of generation capacity anticipated by Prayas (2011), which is a result of cancellations and withdrawals due to lack of either resource, financial, or environmental clearances. We consider these estimates as conservative. With changes in the coal block allocation strategies and coal import regulations in the coming years, it is likely that more plants could be considered for construction or even the planned TPPs could come under operations faster than anticipated (Prayas, 2013).

Atmospheric Emissions

The total annual emissions were calculated for individual plants, using information on total coal consumed and an emission factor dependent on coal characteristics and the emission control technology for each of the pollutants. The total emissions were established for PM, SO_2, NO_x, carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), and carbon dioxide (CO_2).

The regional emission factors for the coal-fired TPPs is summarized in Table 2 in both tons PJ^{-1} and tons hr^{-1} (Guttikunda and Jawahar, 2014). The latter is for comparisons with any data available from online monitoring. Previous studies estimated emissions for all of India and for all the power plants in Asia, and most are estimated for the base year 2000–2005. A serious lack of emissions monitoring data at the stack results in large uncertainty. Under the national ambient monitoring program (NAMP) of India, the large point sources, such as the coal-fired TPPs, are required to conduct continuous emissions monitoring from all the operational stacks for all the criteria pollutants (including other heavy industries like iron and steel, fertilizers, mineral processing, and refineries) (CPCB, 2018). However, the emission rates reported in power plant performance reports are based on intermittent audits and presented as averages or minimum/maximum of the measurements (CEA, 2013, 2017). This makes it harder to compare and/or scrutinize the stack emissions in real time. This is a major barrier linked to lack of protocols on how the monitoring procedures are practiced and how the data is reported to the regulatory agencies.

To understand the uncertainty in emissions rates and total emissions, Monte-Carlo simulations were conducted at the plant level, with normal distribution applied to all the parameters in the emissions calculator. By changing plant size, coal consumption rates, coal characteristics, and

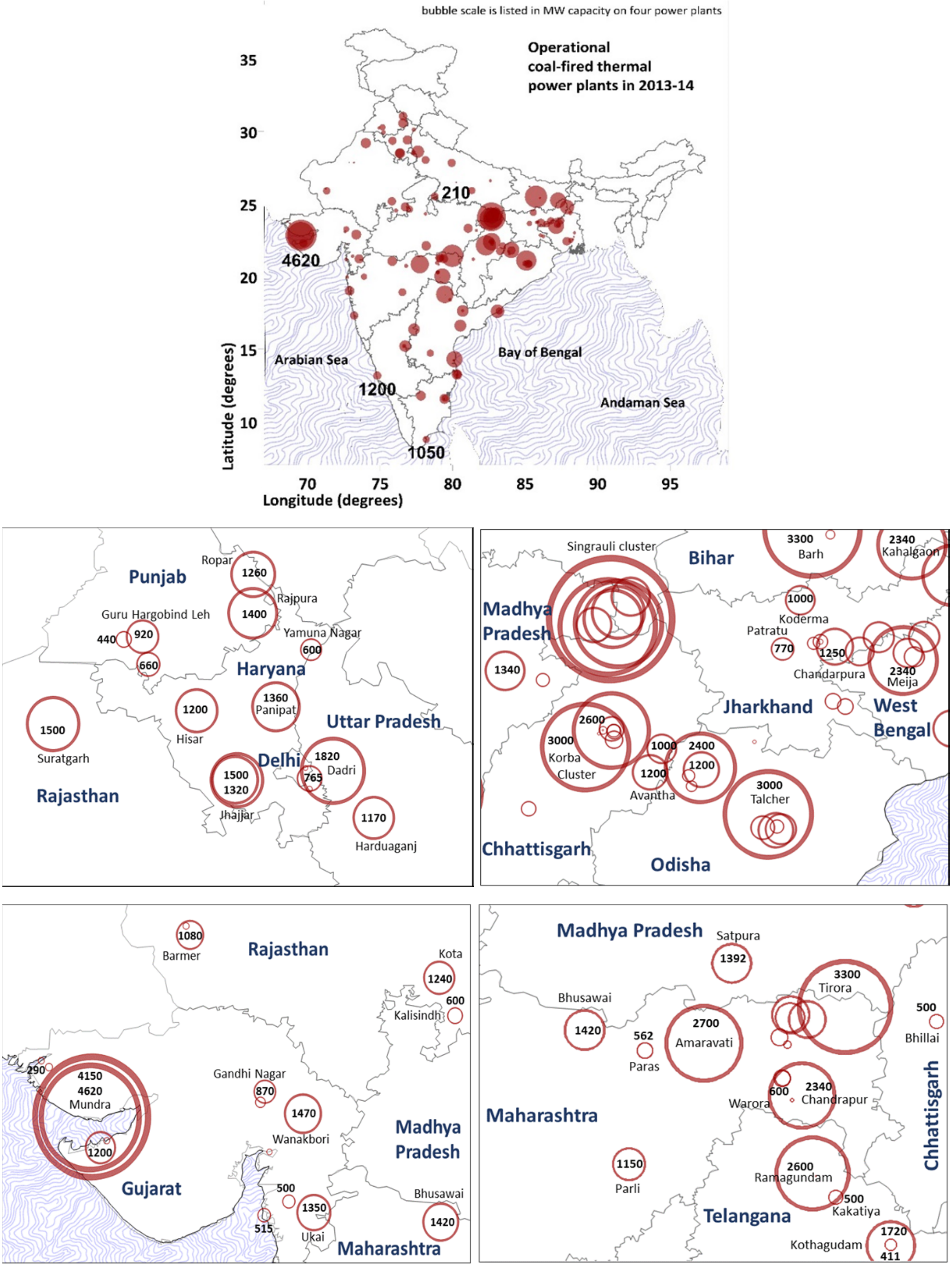

Fig. 1. Installed capacity of the coal-fired TPPs in India. The largest circle is 4620 MW. Note that many of these circles are overlapping due their close proximity. The inlays present details for the four largest clusters.

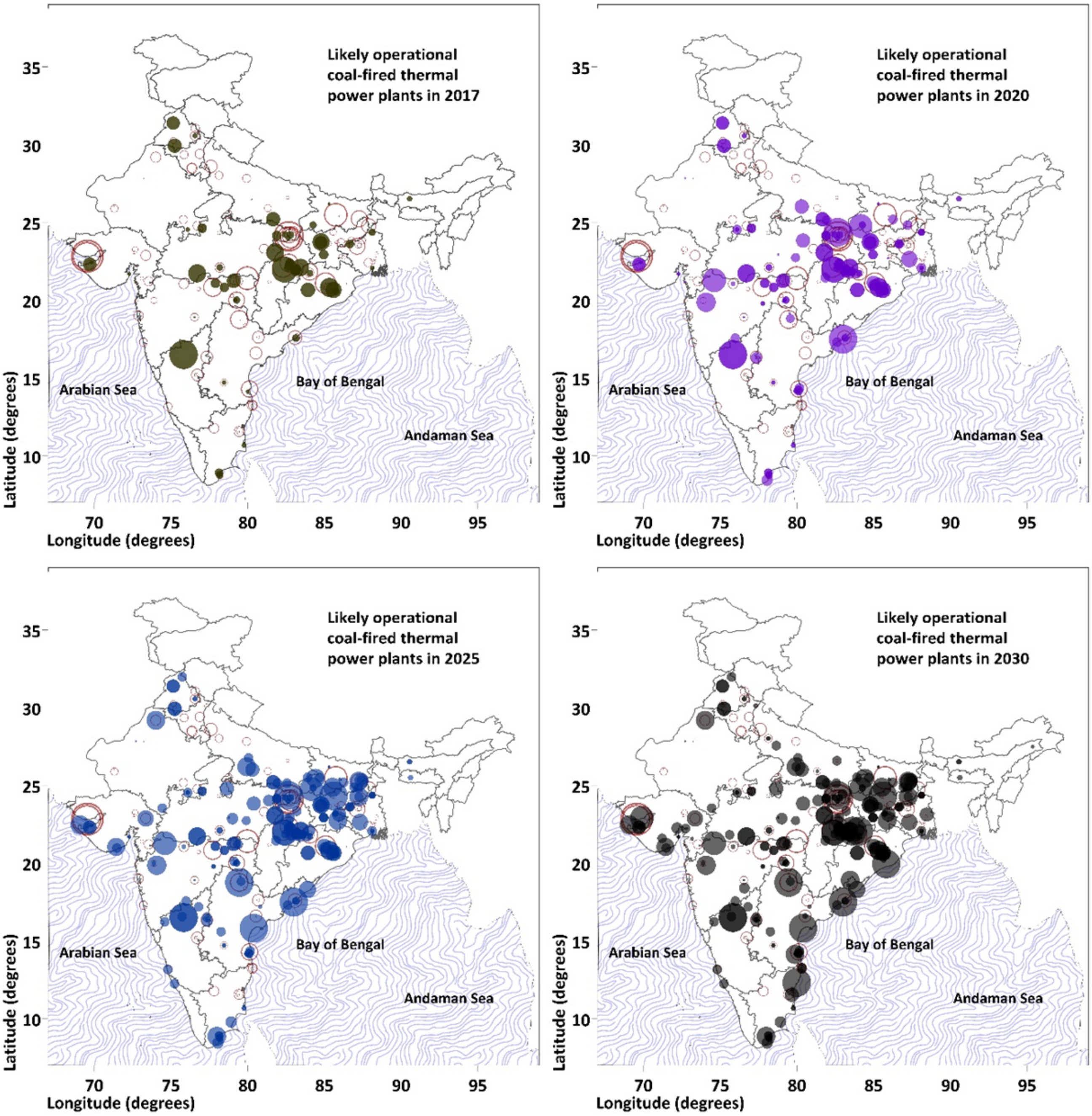

Fig. 2. Proposed locations of the coal-fired TPPs in India through 2030. The brown circles represent the TPPs operational in 2014 (details in Fig. 1) and the second color in each map represents all the new plants and expansions expected after 2014 and likely to be operational in the representative year. The largest circle is 4620 MW. Note that many of these circles are overlapping due their close proximity to other TPPs.

efficiency of emission controls, this exercise led to an evaluation of likely uncertainty in the overall emissions. For example, coal usage at the new power plants operating at super-critical conditions is lower than those observed at the old power plants. For the plants known to operate FGD systems, controls were applied and evaluated for uncertainty. With normal distribution applied to all the parameters, the overall uncertainty gets compounded. The uncertainty was ±34% for total $PM_{2.5}$ emissions, ±18% for total SO_2 emissions, and ±11% for total CO_2 emissions. The lower uncertainty rate for CO_2 emissions is primarily because of lower uncertainty in coal's carbon content than that observed for coal's sulfur content, which originates from both local and foreign mines. These uncertainty rates are similar to those reported for the coal-fired TPPs in China (Chen *et al.*, 2014; Wang *et al.*, 2016). With the availability of stack measurements for individual plants, Chen *et al.* (2014) reported some lower uncertainties, which is also a likely scenario when better data is available from all the stack monitors in India (CPCB, 2018).

Table 2. Regional emission factors database.

Resource	Base year	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC
This study [a, 1]	2011–2012	49–68	90–138	174–192	177–189	100	9
Streets *et al.* (2003) [1]	2000			400–762	219–562		
GAINS (2012) (base) [b, 1]	2000–2005	53–261	18–374	69–1380	100–270		1–15
GAINS (2012) (controlled) [c, 1]	2000–2005	13–27	19–43	27–69	20–54		1–15
Ohara *et al.* (2007) [d, 1]	2000			504	267	154	
Garg *et al.* (2006) [e, 1]	2000		251	367	205	56	
Lu and Streets (2012) [f, 1]	1996–2006				177–410		
This study [g, 2]	2011–2012	0.3–1.4	0.6–2.8	1.0–4.0	0.9–3.7	0.5–2.0	0.05–0.2
Kansal *et al.* (2009) [h, 2]	2004–2005		0.7–1.1	4.0–5.0	1.2–1.8		

[1] units: tons PJ^{-1}.
[2] units: tons hr^{-1}.
[a] the range corresponds to the averages over the states.
[b] base line factors for various technologies without or limited controls, global program.
[c] base line factors with best available control technology for each pollutant, global program.
[d] the emission factor segregation was for China, Japan, and Others in Asia.
[e] calculated as ratios of total emissions and coal consumption corresponding to the power sector, PM factor is for total suspended particulates.
[f] the range corresponds to coal fired boilers with and without low NO_x burner technology, by boiler size.
[g] range corresponds to the estimated average emission rate per plant in each state.
[h] PM factor is for total suspended particulates; based on measurements at one station in Delhi per stack.

The sulfur content in Indian coal varies from as low as 0.1% from the mines in Jharkhand and 0.4% from the mines in Chhattisgarh to a national average of 0.55%. Coal from the mines of Ohio (USA) are known to contain more than 1.5% sulfur and those from the mines of South Africa is up to 4.0% (Cropper *et al.*, 2012; Sadavarte and Venkataraman, 2014). While the sulfur content is lower in Indian coal, the ash content is higher than 40%. The higher uncertainty rate for the PM emissions also stems from uncertainty in control efficiencies. The older power plants with smaller boilers tend to emit more than the modern power plants equipped with electrostatic precipitators (ESPs) with higher control efficiency, partly due to the segregated standard based on the boiler size (Table 1)—as high as 350 mg Nm^{-3} for boiler size < 210 MW and 150 mg Nm^{-3} for boiler size > 210 MW. In 2011–2012, 72% of the operational boilers were of the size ≤ 210 MW (Guttikunda and Jawahar, 2014).

WRF-CAMx Dispersion Model

Atmospheric dispersion modeling was conducted to study the movement of emissions on a regional scale, formation of the secondary sulfate particles (part of $PM_{2.5}$), and contribution of power plant pollution to health impacts. Ni *et al.* (2018) utilized the WRF-Chem model to evaluate the impact of coal-fired TPP emissions in China and Dodla *et al.* (2017) utilized a combination of WRF and HYSPLIT to evaluate the impact of two coal fired TPPs in India. For this study, the ENVIRON Comprehensive Air Quality Model with Extensions (CAMx), an Eulerian photochemical dispersion model, was selected for its modular nature in characterizing and treating the plumes from point sources. The model formulation, advection and scavenging schematics (dry and wet deposition), chemical solvers, and chemical mechanisms are detailed in the model manual. The model includes gas-to-aerosol conversions for SO_2 to sulfates, NO_x to nitrates, and VOCs to secondary organic aerosols and supports plume rise calculations for each power plant using 3-dimentional (3D) meteorological data.

The meteorological data (3D wind, temperature, pressure, relative humidity, precipitation fields, and other parameters necessary for chemical transport modeling) is derived from the National Center for Environmental Prediction (NCEP, 2016) global reanalysis database and processed through WRF meteorological model at 1-hour temporal resolution. To further localize the initial conditions, the model was looped for the first 10 days of January before starting the full-year model calculations. After initializing the model, the emissions from the power plants were utilized to isolate the impacts of these emissions on the ambient $PM_{2.5}$ concentrations. The combination of WRF-CAMx modeling system was also utilized to evaluate the VOC speciation procedures applied to SAPRC chemical mechanism over the Indian subcontinent (Sarkar *et al.*, 2016) and evaluation of the coal-fired TPPs in India (Guttikunda and Jawahar, 2014).

The modeling domain extends from 7°N to 39°N in latitudes and 37°E to 99°E in longitudes at 0.25° grid resolution (Fig. 1). The vertical resolution of the model extends to 12 km stretched over 28 layers, with the lowest layer designated at 30 m and 12 layers within 1 km to advance vertical advection closer to the ground level.

Health Impacts

In India, the estimated morbidity and mortality burden of outdoor air pollution, in terms of work days lost, lost productivity, and loss in terms of gross domestic product, is approximately USD 23.4 billion and 1.7% of national GDP (World Bank, 2012). The direct link between outdoor air pollution and human health has been extensively documented under the Global Burden of Disease (GBD) study for overall impact between 1990 and 2016 (GBD, 2017) and for major polluting sources (GBD-MAPS, 2018), with more than 695,000 and 1,000,000 premature deaths attributed to outdoor air pollution from $PM_{2.5}$ and ozone in 2010 and 2015, respectively. Guttikunda and Jawahar (2014) established that the emissions from the coal-fired TPPs in 2011–2012 could account for 80,000 to 115,000 annual premature deaths, approximately 11.5 to 16.5% of the total estimated premature deaths under the GBD analysis. An updated assessment under GBD-MAPS (2018) estimated 83,000 premature deaths, approximately 7.6% of the total estimated for 2015.

Using the GBD methodology, the total health risk, as mortality, can be quantified to assess the impact of India's planned coal expansion. The GBD methodology accounts for the cases of ischemic heart disease (which can lead to heart attacks), cerebrovascular disease (which can lead to strokes), chronic obstructive pulmonary diseases, lower respiratory infections, and cancers (in trachea, lungs, and bronchitis) (Burnett *et al.*, 2014). Each of these endpoints have established integrated exposure risk (IER) coefficients, sub-divided into age groups, with detailed descriptions at the country level presented in Cohen *et al.* (2017). A combination of all these risks can be summarized as an all-cause mortality supra-linear function for relative risk (RR) of $PM_{2.5}$ pollution (Pope *et al.*, 2015) as the following:

$$RR_i - 1 = 0.4 \times \{1 - \exp[-0.03 \times (\delta C_i)^{0.9}]\} \quad (1)$$

$$\delta E = \sum_{i=1}^{\#grids} \frac{(RR_i - 1)}{(RR_i)} \times \delta POP_i \times IR \quad (2)$$

where δC is the $PM_{2.5}$ concentration at the grid level (including both the primary and secondary contributions), IR is the death incidence rate established as part of the GBD study, and δPOP is the population exposed in each grid. The total concentrations at the grid level are taken from the CAMx simulations for each corresponding year.

Pope *et al.* (2015) utilized the all-cause mortality function to assess how the supra-linear shape of the IER curve influences the health benefits of air pollution abatement policies in the United States. Given the uncertainties in the study calculations from fuel usage, emission factors, and control efficiencies, and to total emissions, which are propagated through a dispersion model (with chemistry module to include secondary contributions) to estimate final $PM_{2.5}$ concentration shares, it was decided to use the all-cause mortality risk function for the end discussion instead of evaluating 5 distinct mortality risk functions.

The total population per grid is extracted from gridded databases (Landscan, 2013; GRUMP, 2015). Most national censuses count populations by measuring where people live rather than where they work or travel. Landscan integrates daytime movements and collective travel habits into a single measure to produce a better representation of where people are located during an average day. This database is available at 30-second resolution, which is aggregated to 0.25° CAMx model resolution.

RESULTS

Atmospheric Emissions

Summary of annual coal consumption and emissions in 2014 and from the planned TPPs in 2030 is presented in Table 3. Additional information for the intermittent years is also available. Between 2014 and 2030:

- Total installed capacity is expected to triple from 159 GW in 2014–2015 to 450 GW in 2030.
- Largest (3-fold) expansions are expected in the states of Andhra Pradesh (including Telangana), Odisha, Chhattisgarh, Bihar, and Jharkhand, all of which have established coal reserves and with the most operational generation capacity in 2014.
- A 2-fold expansion is expected in the states of Karnataka, Madhya Pradesh, Maharashtra, Punjab, Tamil Nadu, and Uttar Pradesh.
- Telangana is the new state carved out of Andhra Pradesh in 2014, which also harbors the largest coal mines, bordering Odisha and Maharashtra, and plans to establish more than 10 GW of coal-fired TPPs to support the planned industrial and domestic electrification plans.
- Coal-fired TPPs in the northeastern states will be commissioned in Assam before 2018 (which is under construction) and in Meghalaya before 2025 (which is under appraisal).
- Total coal consumption is expected to increase 3-times from 660 million tons year^{-1} in 2014 to 1800 million tons year^{-1} in 2030, and accordingly, the CO_2 emissions from 1,590 to 4,320 million tons year^{-1}. This is after taking into consideration that a majority of the newer TPPs are of minimum 660 MW capacity and will operate under super-critical conditions with better performance rates than the existing TPPs. Four TPPs in Odisha are expected to utilize ultra-critical technology, with further improvement to the performance ratios.
- The PM, SO_2, and NO_x emissions will at least double in the same period. This is less than the 3-time increase in generation capacity, primarily due to the introduction of newer boiler technology, utilizing less coal per MWh of electricity generated. With no emission regulations in place for SO_2 and NO_x, these are assumed uncontrolled and allowed to release at the elevated stacks for dispersion. The scenario analysis includes application of FGD systems to further reduce the overall emission rates.

An important impetus in this analysis is that the emissions and the impacts are studied only from the supply side of the electricity generation and not from the demand side. It is arguable if the proposed list of TPPs through 2030 can meet the demand or not meet the demand or is this surplus. The subjective judgment is based on available information on the supply side for those TPPs which have secured some form of environmental clearance and showed resource and financial arrangement for operations. We expect this to be different in the coming years.

Ambient $PM_{2.5}$ and SO_2 Pollution

The dispersion modeling results for each month were averaged to obtain monthly, seasonal, and annual

Table 3. Total power generation capacity (in GW), annual coal consumption (in million tons) and annual emissions (in ktons for $PM_{2.5}$, SO_2, NO_x, and CO; and in million tons for CO_2) from the coal-fired TPPs in 2014 and 2030 in India at the state level.

State	2014							2030						
	GW	Coal	$PM_{2.5}$	SO_2	NO_x	CO	CO_2	GW	Coal	$PM_{2.5}$	SO_2	NO_x	CO	CO_2
Andhra Pradesh	8.9	35	21	172	160	129	85	37.1	141	94	687	514	513	338
Assam								1.3	5	3	25	34	19	12
Bihar	6.2	25	30	120	107	89	59	30.2	117	83	572	560	427	282
Chhattisgarh	11.1	46	57	223	250	166	110	50.1	200	149	973	1,008	726	479
Delhi	0.8	4	12	17	23	13	9	0.8	4	12	17	23	13	9
Gujarat	15.9	63	107	309	275	231	152	37.7	143	173	699	557	522	344
Haryana	6.0	25	15	124	165	92	61	6.6	28	16	135	170	101	67
Jharkhand	6.2	27	28	129	172	97	64	29.4	113	93	553	511	412	272
Karnataka	5.5	23	32	93	151	85	56	18.9	73	61	319	317	267	176
Kerala								1.3	5	3	23	11	17	11
Madhya Pradesh	12.4	51	30	250	281	186	123	34.6	138	87	673	653	502	331
Maharashtra	21.3	87	78	373	449	316	209	42.4	171	144	764	860	622	410
Meghalaya								0.8	3	2	15	20	11	7
Odisha	11.0	47	36	229	305	171	113	44.3	173	151	682	810	631	416
Punjab	4.7	20	11	95	117	71	47	11.0	44	26	217	228	162	107
Rajasthan	7.4	30	62	148	167	111	73	14.9	58	101	282	235	210	139
Tamilnadu	9.1	39	40	189	252	141	93	26.9	104	92	453	461	379	250
Telangana	5.3	22	17	110	146	82	54	10.0	39	35	192	197	143	95
Uttar Pradesh	15.3	65	64	317	423	237	156	36.3	143	110	699	715	522	344
West Bengal	11.9	51	56	247	330	185	122	23.2	96	82	467	558	349	230
Grand Total	159.1	660	695	3,147	3,774	2,402	1,584	457.9	1,799	1,514	8,447	8,440	6,547	4,318

concentration maps. The modeled annual average $PM_{2.5}$ and SO_2 concentrations due to emissions from coal-fired TPPs are presented in Figs. 3 and 4 (monthly and seasonal maps were also constructed). The total $PM_{2.5}$ includes both primary and secondary contributions. The largest impact is felt over most of central-east India including states of Maharashtra, Madhya Pradesh, Chhattisgarh, and Orissa, which harbor the largest clusters of coal-fired power plants. Similar observations are reported based on satellite measurements of column NO_2 concentrations (Lu and Streets, 2012; Prasad *et al.*, 2012).

The collective impact of the TPPs over each state is presented in Table 4, as population weighted concentrations, which is indicative of the pollution load observed in each state, irrespective of the size of the installed capacity in that state. The model grid size is 0.25° (~25 km × 25 km). Due to this coarse spatial coverage, these numbers cannot be directly compared to the data from the ambient monitoring stations, which only represent their immediate vicinity. These concentrations highlight the role of the long-range transport of high-stack emissions. For example, the northeastern states of Assam, Nagaland, Mizoram, Manipur, Meghalaya, Arunachal Pradesh, Tripura, and Sikkim; the smaller states, Goa, Puducherry, and Delhi; and the hilly states, Uttarakhand and Himachal Pradesh, do not operate any coal-fired TPPs within their administrative boundaries and yet experience a significant amount of pollution originating from them. The cities with no TPPs or the cities not located near a TPP also experience impact of TPP emissions. For example, major cities in the Korba region (of Chhattisgarh), Ranchi, Jamshedpur, Rourkela, Jabalpur, Nagpur, and Raipur (capital of Chhattisgarh); major cities in the Mundra region, Jamnagar (major industrial port), Rajkot, and Ahmedabad (300 km away, with two TPPs of 1000 MW in the city); and the city of Delhi, with large TPPs within 100 km of radius, experience the impact of these emissions.

The impact of long-range transport is often underestimated in the environmental impact assessment reports filed by the individual power plants to secure environmental clearance necessary for commissioning a power plant. This is due to a technical requirement that the impact assessments are conducted only for an influential radius of 10 km from the stacks, while the impact of these emissions can be tracked to distances as far as 300 km from the source region, depending on the meteorological conditions. The movement of the elevated emissions is illustrated using meteorology of two days for three months in Fig. 5 for four clusters: (a) Korba cluster (in-land), (b) Jhajjar cluster (in-land), (c) Mundra cluster (coastal), and (d) Mumbai cluster (coastal). The forward trajectories are drawn for 24 hours, with a puff released at a height of 300 m every hour and tracking its movement for the next 48 hours. The lines represent only the horizontal movement of the puffs and do not include any information on vertical mixing of pollution. The release height was set at 300 m, considering the large power plants in these clusters are mandated to have stacks of minimum 275 m and allowing 25 m for additional minimum plume rise. The animated forward trajectories are also available for each of these clusters for all months, and for convenience, we are presenting only three months. An important point illustrated through these forward

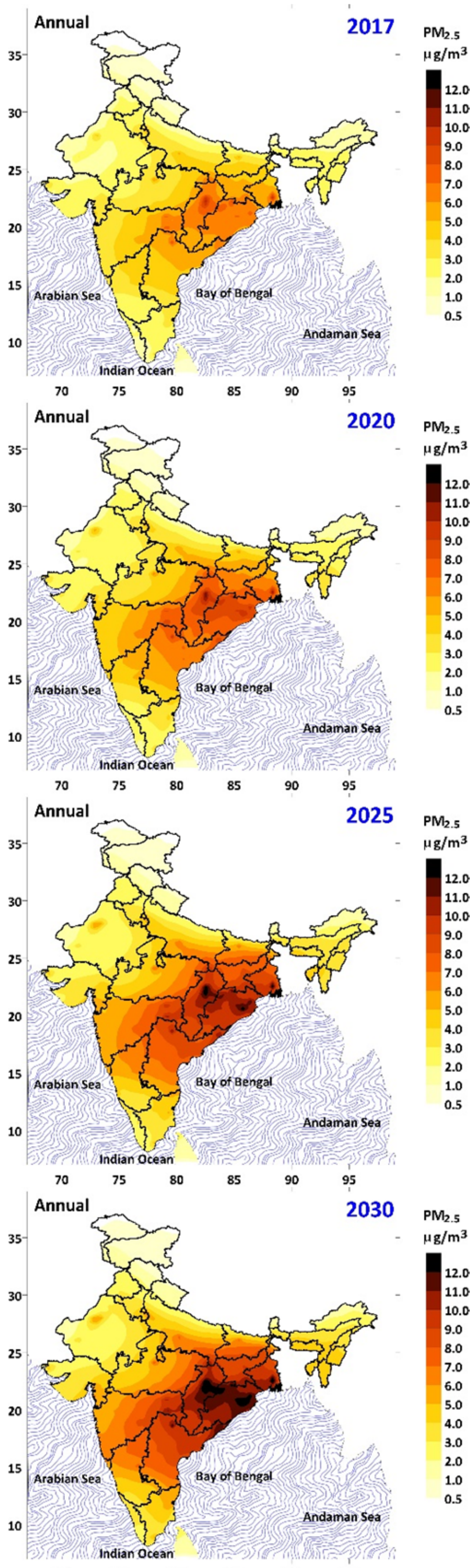

Fig. 3. Modelled annual average $PM_{2.5}$ oncentrations (µg m^{-3}) from the planned coal-fired TPPs in India through 2030.

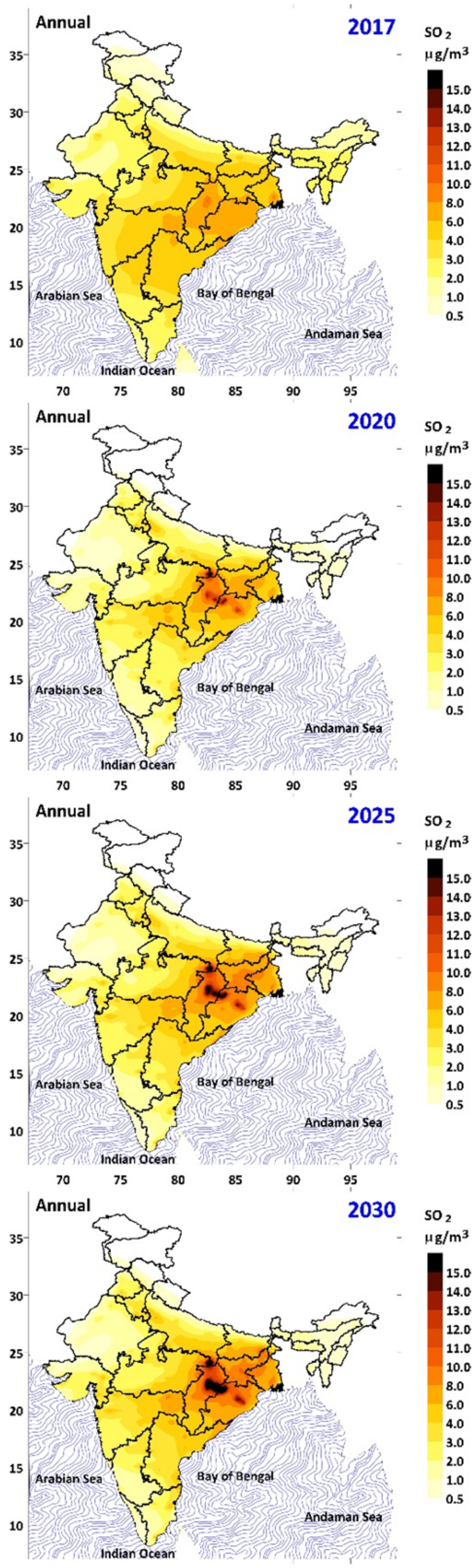

Fig. 4. Modelled annual average SO_2 concentrations (µg m^{-3}) from the planned coal-fired TPPs in India through 2030.

Table 4. Modelled state average $PM_{2.5}$ concentrations (indicative of the pollution load) due to the emissions from the planned expansion of coal-fired TPPs in India. The concentrations are in µg m^{-3} and the data represents - population weighted state average concentration ± standard deviation of concentrations for all grids covering the state and (in the brackets - maximum concentration among the grids covering the state).

State	2017	2020	2025	2030
Andhra Pradesh	4.9 ± 0.9 (8.5)	6.1 ± 1.1 (9.8)	7.5 ± 1.3 (11.6)	8.4 ± 1.5 (13)
Arunachal Pradesh	1.6 ± 0.3 (2.0)	2.0 ± 0.4 (2.4)	2.5 ± 0.5 (3.0)	2.9 ± 0.6 (3.5)
Assam	2.1 ± 0.3 (2.6)	2.6 ± 0.4 (3.2)	3.3 ± 0.5 (4.1)	3.8 ± 0.6 (4.6)
Bihar	3.7 ± 1.0 (6.0)	4.3 ± 1.2 (6.5)	5.5 ± 1.7 (7.7)	6.1 ± 1.9 (8.8)
Chhattisgarh	6.6 ± 0.9 (12.7)	8.0 ± 1.0 (14.0)	9.6 ± 1.1 (16.0)	10.6 ± 1.2 (16.9)
Delhi	4.1 ± 1.0 (5.8)	4.3 ± 1.0 (6.0)	4.7 ± 1.0 (6.4)	5.0 ± 1.0 (6.8)
Goa	3.6 ± 0.1 (3.8)	4.4 ± 0.1 (4.6)	5.4 ± 0.1 (5.6)	6.0 ± 0.1 (6.2)
Gujarat	3.0 ± 0.7 (5.7)	3.3 ± 0.8 (6.2)	3.9 ± 0.9 (7.0)	4.2 ± 1 (7.5)
Haryana	3.3 ± 0.7 (5.8)	3.5 ± 0.7 (6.0)	3.9 ± 0.8 (6.4)	4.2 ± 0.8 (6.8)
Himachal Pradesh	1.4 ± 0.4 (2.1)	1.5 ± 0.4 (2.2)	1.8 ± 0.5 (2.5)	1.9 ± 0.6 (2.7)
Jammu & Kashmir	0.9 ± 0.2 (1.4)	1.0 ± 0.3 (1.5)	1.2 ± 0.3 (1.8)	1.2 ± 0.3 (1.9)
Jharkhand	5.2 ± 0.7 (10.1)	6.2 ± 0.9 (11.5)	8.0 ± 0.9 (13.3)	8.8 ± 0.9 (14.3)
Karnataka	3.3 ± 0.8 (5.5)	4.1 ± 1.0 (6.4)	5.1 ± 1.2 (7.5)	5.7 ± 1.3 (8.2)
Kerala	1.9 ± 0.2 (2.6)	2.3 ± 0.3 (3.2)	2.9 ± 0.4 (4.0)	3.3 ± 0.4 (4.5)
Madhya Pradesh	3.7 ± 0.9 (8.2)	4.4 ± 1.2 (8.7)	5.2 ± 1.4 (10.0)	5.6 ± 1.5 (10.8)
Maharashtra	4.4 ± 0.9 (9.3)	5.2 ± 1.1 (10.6)	6.3 ± 1.3 (12.1)	6.8 ± 1.4 (12.9)
Manipur	2.4 ± 0.1 (2.6)	2.9 ± 0.1 (3.2)	3.7 ± 0.2 (4)	4.1 ± 0.2 (4.5)
Meghalaya	2.4 ± 0.1 (2.8)	2.9 ± 0.1 (3.3)	3.8 ± 0.2 (4.4)	4.3 ± 0.2 (5.0)
Mizoram	2.5 ± 0.1 (2.6)	3.1 ± 0.1 (3.2)	3.9 ± 0.1 (4)	4.4 ± 0.1 (4.5)
Nagaland	2.1 ± 0.1 (2.4)	2.6 ± 0.2 (2.9)	3.2 ± 0.2 (3.7)	3.7 ± 0.2 (4.2)
Odisha	6.4 ± 0.6 (10.1)	8.1 ± 0.7 (11.5)	10.1 ± 0.9 (13.6)	11.2 ± 0.9 (15.0)
Punjab	1.9 ± 0.3 (2.7)	2.1 ± 0.3 (2.8)	2.4 ± 0.4 (3.2)	2.6 ± 0.4 (3.4)
Rajasthan	2.4 ± 0.6 (6.3)	2.7 ± 0.7 (7.6)	3.1 ± 0.8 (8.1)	3.3 ± 0.8 (8.2)
Sikkim	1.4 ± 0.3 (1.6)	1.7 ± 0.4 (1.9)	2.1 ± 0.5 (2.4)	2.3 ± 0.6 (2.6)
Tamilnadu	2.6 ± 0.5 (5.2)	3.1 ± 0.7 (5.6)	3.9 ± 0.8 (6.3)	4.4 ± 0.9 (6.8)
Tripura	2.6 ± 0.1 (2.8)	3.2 ± 0.1 (3.4)	4.2 ± 0.1 (4.4)	4.7 ± 0.2 (5.0)
Uttar Pradesh	3.2 ± 1.1 (7.4)	3.6 ± 1.4 (8.6)	4.3 ± 1.6 (10.0)	4.7 ± 1.8 (10.8)
Uttarakhand	1.4 ± 0.3 (1.8)	1.6 ± 0.4 (2.0)	1.9 ± 0.4 (2.3)	2.0 ± 0.5 (2.5)
West Bengal	6.0 ± 1.6 (12.9)	7.1 ± 1.9 (14.1)	8.8 ± 2.3 (16.0)	9.7 ± 2.6 (17.0)

trajectories is that the high-stack emissions affects the regions far away from the source, even if the pollution levels are diluted, and this should be accounted for in the environmental and health assessments.

Health Impacts

A summary of the health impacts associated with the planned coal-fired TPP expansion in India is presented in Table 5. The total premature mortality due to the emissions from coal-fired TPPs is expected to at least double, reaching 186,500 to 229,500 annually, and the associated asthma cases reaching 42.7 million in 2030. For the future years, we assumed 1.1% net annual growth rate in the population (starting with the latest census projections), with the total population reaching 1.5 billion. For a higher growth rate of 1.3%, the total premature mortality due to the emissions from coal-fired TPPs could be as high as 238,000 annually in 2030.

These results are further disaggregated at the state level in Table 6. The most populated states of Maharashtra, Uttar Pradesh, Bihar, Andhra Pradesh (including Telangana), Odisha, Madhya Pradesh, and West Bengal, which harbor the largest clusters of the power plants, are listed with the most number of premature deaths associated with the emissions from coal-fired TPPs. Gujarat and Chhattisgarh, despite large clusters, register lower health impacts for two reasons—lower population density in the state and long-range transport of the emissions. In case of Gujarat and other coastal states, land-sea breeze is an advantage during some months. A large amount of the emissions from the states of Bihar, Chhattisgarh, Madhya Pradesh, Maharashtra, and Andhra Pradesh get deposited within the states or in the neighboring states. Of the northeastern states, Assam is the most populated and immediate to the mainland, with significant health impacts. These estimates do not include the health impacts of the TPP emissions in the neighboring countries—Nepal, Pakistan, Bangladesh, and Sri Lanka.

EMISSION REGULATIONS AND CONTROLS

It is ironic that SO_2 is the only pollutant reported with concentrations under the national ambient air quality standard in India (Guttikunda *et al.*, 2014). This is misleading since all the monitors under NAMP are in the cities and this under-represents pollution unmonitored outside urban areas, where the main sources of SO_2 are located. Two of

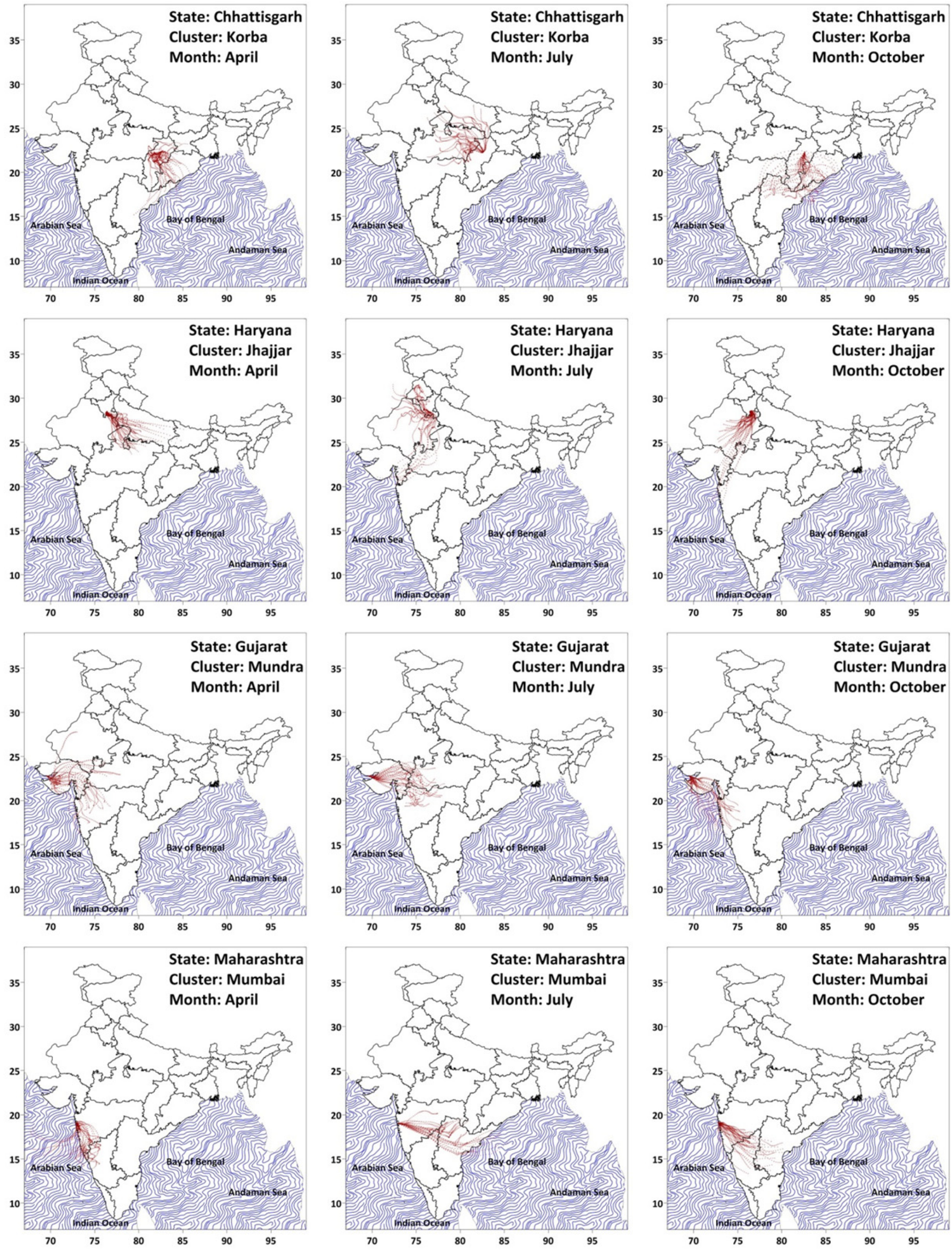

Fig. 5. 48 hour forward trajectories drawn over the Korba (Chhattisgarh), Jhajjar (Haryana), Mundra (Gujarat), and Mumbai (Maharashtra) power plant clusters to illustrate the movement of the emissions for three months, using the NOAA HYSPLIT trajectory model.

Table 5. Anticipated health impacts due to ambient $PM_{2.5}$ pollution from the planned coal-fired TPPs in India.

	Premature mortality	Asthma attacks
Year 2017	112,500–126,000	23.4 million
Year 2020	132,500–153,500	28.4 million
Year 2025	164,000–197,500	36.7 million
Year 2030	186,500–229,500	42.7 million

Table 6. Anticipated health impacts by state due to ambient $PM_{2.5}$ pollution from the planned coal-fired TPPs and the total population from Census-2011 in India.

State	Total population	Estimated premature mortality due to coal-fired power plant emissions				
	Census-2011	2014	2017	2020	2025	2030
Andhra Pradesh	90.6	7,210–7,880	9,870–11,510	12,170–14,810	15,170–19,280	17,510–22,840
Arunachal Pradesh	2.1	50–60	70–70	90–90	110–110	130 - 140
Assam	30.4	1,220–1,300	1,780–1,780	2,160–2,230	2,800–3,020	3,300–3,650
Bihar	103.5	7,530–7,970	9,450–10,440	11,070–12,600	14,410–17,260	16,410–20,030
Chhattisgarh	26.8	2,800–3,230	3,870–4,780	4,610–5,920	5,600–7,500	6,340–8,680
Delhi	11.8	1,300–1,400	1,520–1,700	1,640–1,840	1,880–2,150	2,090–2,420
Goa	1.4	90–90	120–130	140–160	180–210	200–240
Gujarat	60.1	3,390–3,410	4,300–4,540	4,880–5,260	5,890–6,530	6,690–7,540
Haryana	28.7	1,710–1,760	2,080–2,220	2,260–2,430	2,630–2,900	2,940–3,280
Himachal Pradesh	8.3	190–220	250–280	280–300	350–370	390–410
Jammu & Kashmir	12.8	230–290	310–360	340–400	420–480	480–530
Jharkhand	35.6	3,120–3,460	4,120–4,840	4,940–6,030	6,340–8,130	7,190–9,420
Karnataka	63.0	3,850–3,940	5,170–5,600	6,340–7,140	7,940–9,300	9,160–10,960
Kerala	34.3	1,190–1,280	1,610–1,660	2,000–2,010	2,530–2,660	2,980–3,200
Madhya Pradesh	77.6	5,170–5,410	6,790–7,510	7,970–9,080	9,700–11,430	10,940–13,090
Maharashtra	116.0	8,530–9,150	11,580–13,200	13,860–16,360	16,870–20,630	19,010–23,640
Manipur	3.2	130–140	180–180	220–230	280–310	330–370
Meghalaya	3.8	140–140	190–190	230–240	300–330	350–390
Mizoram	1.3	60–60	70–80	90–100	110–130	130–150
Nagaland	2.9	90–100	130–130	160–160	200–210	230–260
Odisha	44.9	4,330–4,920	6,100–7,480	7,560–9,740	9,380–12,670	10,740–14,880
Punjab	30.3	1,010–1,090	1,440–1,470	1,580–1,600	1,920–1,950	2,140–2,210
Rajasthan	73.3	3,520–3,590	4,340–4,400	4,860–5,010	5,800–6,160	6,510–7,000
Sikkim	0.7	20–20	30–30	30–30	40–40	50–50
Tamilnadu	69.2	3,860–3,900	5,080–5,290	6,110–6,570	7,650–8,540	9,020–10,320
Tripura	4.8	150–150	200–210	240–260	320–360	370–420
Uttar Pradesh	206.3	13,310–13,830	16,470–17,800	18,740–20,720	22,870–26,140	26,000–30,240
Uttarakhand	11.0	270–320	360–390	410–440	510–540	590–610
West Bengal	93.4	10,130–12,180	12,360–15,370	14,470–18,540	18,060–24,140	20,440–27,870

the largest contributors to sulfur (and other pollutant) emissions are coal-fired TPPs (Guttikunda and Jawahar, 2014) and the diesel-based heavy-duty vehicles (including trucks and buses) (Guttikunda and Mohan, 2014)—and both largely operate outside the city limits. In cities, interventions such as introduction of Bharat-4 diesel (equivalent of Euro-4, with 50 ppm sulfur) and relocation or refurbishing of industries consuming coal and diesel with better efficiency norms have led to sulfur pollution compliance. This is however changing since the use of diesel powered generators for electricity backup is increasing in Indian cities. Using the OMI satellite data, Lu *et al.* (2013) reported that the annual average SO_2 concentrations near the coal-fired TPP regions increased by 60% between 2005 and 2012. Similar observations are reported based on satellite measurements of column nitrogen dioxide (NO_2) concentrations (Lu and Streets, 2012; Prasad *et al.*, 2012).

Application of FGD Systems in India

Table 1 presents the new stack emission standards for coal-fired TPPs (MoEFCC, 2015). While the new PM emission standard in India is comparable to other countries, there is a conspicuous lack of operations to control SO_2 and NO_x emissions. The secondary sulfate aerosols are a large part of the $PM_{2.5}$ concentrations (Guttikunda and Jawahar, 2014) which can be avoided by mandating some form of control for SO_2 emissions (Chikkatur *et al.*, 2011). In India, only three coal-fired TPPs in Maharashtra and one in Karnataka operate FGD systems. According to MoEFCC, installation of FGD is in process at NTPC Bongaigaon (Assam), NTPC Vindhyachal Stage V (Uttar Pradesh), and Adani Power Mundra Phase III (Gujarat) (PIB, 2012).

The Trombay thermal power plant (TTPP) (near Mumbai) uses sea water's natural alkalinity to scrub SO_2 from the flue gas. After neutralization, the sea water passes through the cooling water and heat exchanger, and the effluent is discharged back into the sea. The removal efficiency is estimated at 85–90%. Because of the use of sea water for scrubbing (and no additional sorbent), the designing and operations are performed at the lowest cost. A disadvantage, however, is that the pollution is discharged into the sea, which in the long run, could lead to other contamination.

The Dahanu thermal power plant (DTPP) started its commercial operation in 1996. However, only after an order from Bombay High Court dated 12 May 1999 were they required to install an FGD system for environmental safety and protection and for the well-being of the people of Dahanu. This 2 × 250 MW plant also uses 80% local coal from the Korba mining areas (in Chhattisgarh) and remaining 20% imported from Indonesia and South Africa. DTPP also utilizes sea water for scrubbing and cooling in its FGD plant.

The 2 × 600 MW Udupi thermal power plant (UTPP) (near Mangalore) started its commercial operations in 2010, is also a coastal power plant, and operates limestone injection and gypsum production system to control SO_2 emissions. This FGD technology is a zero-discharge system utilizing all wastewater in the system, thus reducing the need for fresh water and eliminating waste disposal costs.

According to Prayas (2011) only 7 plants, or just 3.2% of the total coal-fired TPP capacity that has been granted environmental clearance, have provision for installing and operating an FGD (Table 7). With no mandatory requirements, in all the remaining future power plants, only a space provision is mentioned in the environmental clearance process, in case an FGD is to be installed in the future. MoEFCC (2015) issued December 2017 as the deadline for implementation of FGD at all operational TPPs. However, this is now delayed by at least 4 years.

SO_2 Emission Control Systems

The sulfur emission control systems (Table 8) could range from in-furnace control via limestone injection or wet scrubbing of flue gas to capturing SO_2 in the flue gas through industrial processes.

- The limestone injection is an in-furnace process, where crushed coal and limestone are passed together into the boiler as a fluidized mixture with hot air. The sulfur from combustion gases then combines with limestone to form a solid compound rather than being released as SO_2 in the flue gas. This is a low capital cost, low feed rate, and low operating cost technology, with co-benefits of mercury control and capture, during the coal burning process. This technology achieves emission reduction rates of 50–60%, making it an attractive option. These technologies require a high sorbent-to-sulfur ratio to achieve sufficient reduction rates and consequently also produce large amounts of waste material (solids other than ash from the boilers), the disposal of which faces increasing difficulties.
- Wet FGD is the most commonly used process with

Table 7. List of future coal-fired thermal power plants in India mandated with sulfur removal equipment.

Power plant	District (State)	Maximum sulfur content in coal (%)	Sulfur control system
2 × 800 MW	Nagpur (Maharashtra)	0.8	one unit will be installed with wet limestone FGD, and the other will operate depending on ambient SO_2 concentration
Expansion of 1050 MW to 2 × 600 MW	North Kannada (Karnataka)	0.8	Wet limestone scrubbing on the flue gas
2 × 660 MW	Nagapattinam (Tamilnadu)	0.6	FGD using sea water scrubbing
540 MW	Nellore (Andhra Pradesh)	1.3	Circulating fluidized bed combustion technology with lime injection
2 × 60 MW	Cuttack (Orissa)	0.4	Circulating fluidized bed combustion technology with lime injection
2 × 60 MW	Chandrapur (Maharashtra)	-	Circulating fluidized bed combustion technology with lime injection
1 × 8 MW Captive Power Plant at Patapura	Durgapur (Rajasthan)	-	Atmospheric fluidized bed combustion technology with lime injection

Source: Prayas (2011).

Table 8. SO_2 emission control options for coal-fired TPPs (Source: GAINS, 2012).

	Removal efficiency	Investment costs (1000 ECU/MW)	Operational Costs (% year^{-1})
Retrofitting of existing power plants			
Limestone injection	50–60%	30	4%
Wet FGD	90%	69	4%
Regenerative FGD	98%	165	4%
New power plants			
Limestone injection	50–60%	22	4%
Wet FGD	95%	49	4%
Regenerative FGD	98%	119	4%

typical sulfur removal rates of 90% at moderate costs. This method includes application of wet limestone scrubbing or a spray dryer process on the flue gas, after the combustion, to form gypsum as a by-product. A wet FGD flue gas treatment system is usually located after removal of PM via an electrostatic precipitator (ESP) and the cleaned gas is discharged to the stack for further dispersion. Gypsum can be used for producing building material.

- The high efficiency regenerative desulfurization process is relatively expensive compared to the other two processes and produces SO_2 rich gas (~97%) which can be used as raw input in chemical industry to produce sulfuric acid or even elementary sulfur. Caustic soda (sodium hydroxide) is used as sorbent, which is regenerated to keep the sorbent losses to the minimum. Typical sulfur removal rate of more than 98% is possible, along with tons of commercial by-products.

Need for Mandating FGD at India's TPPs

The only justification towards not mandating the FGD systems in India is the availability of the low sulfur fuel (compared to sulfur content of coal from other countries). This scenario will change as soon as more coal is imported from countries like Indonesia, South Africa, and Australia to meet the demand. While the sulfur content is low in the coal, more tonnage of coal consumed means more tonnage of sulfur emitted at the same clusters. This was also evident from the analysis of satellite observations, suggesting an increase of 60% in the regional sulfur concentrations, especially in and around the TPP clusters, between 2005 and 2012 (Lu *et al.*, 2013).

An immediate benefit of installing and operating FGD systems is for the human health. The share of secondary sulfates contributing to the ambient $PM_{2.5}$ ranges from 30–40% and can be as high as 60% for the denser clusters (Guttikunda and Jawahar, 2014). By controlling sulfur emissions either during the combustion, which can achieve up to 60% removal, or post-combustion, which can achieve up to 98% removal, the overall health impacts can be reduced accordingly. For example, for 2011–2012, the health impacts calculated for the modeled $PM_{2.5}$ pollution from the coal-fired TPPs ranged between 80,000 and 115,000 per year. With application of FGD systems for all these TPPs, this could have been reduced by at least 26,000 (for 60% removal efficiency) or 38,000 (for 95% removal efficiency). Even with a conservative value of INR 2,000,000 (approximately USD 40,000) per life lost, based on the average life insurance policies issued in India, the estimated benefits could have ranged from INR 5,100 to 7,600 crores (approximately USD 0.9 to 1.3 billion).

For the planned coal expansion, these benefits at least double. A summary of the anticipated health benefits with FGDs operational at all the TPPs is summarized in Table 9. By mandating some form of FGD system operational at all the plants, the benefits of lives saved alone could range from INR 12,200 to 20,300 crores (approximately USD 2.0 to 3.4 billion) in 2030. Assuming the systems are operational in 2017, as required when the new emission standards were passed (MoEFCC, 2015), cumulative benefits through 2030 will be an estimated USD 23.8 to 39.2 billion, enough to justify the costs of implementing and operating an FGD at every existing coal-fired TPP. This does not include the morbidity costs of hospital visits or hospitalization in case of asthma attacks, bronchitis, or other cardio-vascular ailments, which could at least double these estimated health benefits.

The co-benefits of an FGD system extend to other pollutants. For example, during wet FGD process, total PM is also trapped in the sorbents, resulting in further removal of the PM emissions in the flue gas. Given the volume of the coal consumed and the ash content, even a fraction of improvement in the PM removal efficiency will result in large benefits for ambient PM concentrations and health impacts. This is included in the calculations discussed above. For the operational and the proposed coal-fired TPPs, the benefits of operating an FGD are open for interpretation and only require a stricter timeline on implementation of FGDs for overall improvements in air quality and health.

CONCLUSIONS

Supporting the 3rd largest economy in the world, the supply of power in India can scarcely keep up with the demand. Across the country, households and industry suffer from regular power cuts, with more than 400 million still lacking access. The need to expand power generation capacity and deliver more electricity to India's growing population and economy is urgent.

The current pipeline of projects will result in establishing a new generation capacity of 300 GW through 2030; some of these facilities are expected to perform better than the TPPs operational in 2014 and 2015. While the sulfur content of Indian coal is lower than that observed in other countries,

Table 9. Anticipated health impacts of emissions from planned coal-fired TPPs and likely number of lives saved by operating a FGD units in India.

	Premature mortality under no FGD	Lives saved under 60%- and 95%-FGD efficiency	Monetary benefits under FGD (INR crores)
Year 2017	112,500–126,000	39,000–63,000	7,800–12,600
Year 2020	132,500–153,500	45,000–74,000	9,000–14,800
Year 2025	164,000–197,500	54,500–90,500	10,900–18,100
Year 2030	186,500–229,500	61,000–101,500	12,200–20,300

with an increase in the overall coal consumption (at least tripling through 2030), these emissions will be large enough to significantly affect the ambient $PM_{2.5}$ concentrations and the resulting health impacts. The technology to control SO_2 emissions, is widely available, and the only barrier to implementing these solutions at all coal-fired TPPs is the lack of a timeline mandating that the TPPs operate FGD systems.

In India, the mixture of emissions is complex, and the sources of these emissions are many. The coexistence of high concentrations of primary and secondary gaseous and aerosol pollutants results in numerous heterogeneous reactions. These reactions change the oxidizing capacity of the atmosphere, and the chemical compositions and optical properties of PM, resulting in accelerated haze formation and other air pollution impacts. Thus, it is imperative that the chemical mechanisms leading up to these effects are studied and controlled, even if it means controlling one pollutant and one source at a time. In this paper, the dispersion modeling results and health benefits analysis of controlling SO_2 and PM emissions are presented since these two pollutants have proven direct linkages to human health and their fractional contributions to the ambient $PM_{2.5}$ concentrations are higher than those of other pollutants. This study will be extended to include the impacts of TPP emissions on the overall regional photochemistry, involving the full chemical mechanisms of the NO_x-VOC-O_3 cycle.

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REFERENCES

Burnett, R.T., Pope III, C.A., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B. and Brauer, M. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* 122: 397–403.

CEA (2013). *All India electricity statistics - General review 2012*, Central Electrical Authority, Ministry of Power, the Government of India, New Delhi, India.

CEA (2017). *All India electricity statistics - General review 2016*, Central Electrical Authority, Ministry of Power, the Government of India, New Delhi, India.

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

Chen, L., Sun, Y., Wu, X., Zhang, Y., Zheng, C., Gao, X. and Cen, K. (2014). Unit-based emission inventory and uncertainty assessment of coal-fired power plants. *Atmos. Environ.* 99: 527–535.

Chikkatur, A.P., Chaudhary, A. and Sagar, A.D. (2011). Coal power impacts, technology, and policy: Connecting the dots. *Annu. Rev. Environ. Resour.* 36: 101–138.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., III, Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L. and Forouzanfar, M.H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 389: 1907–1918.

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

CPCB (2018). *Guidelines for continuous emission monitoring systems (Revision 1)*, Central Pollution Control Board, Government of India, New Delhi, India.

Cropper, M., Gamkhar, S., Malik, K., Limonov, A. and Partridge, I. (2012). *The health effects of coal electricity generation in India*. Discussion paper, Resources for the Future, Washington DC, U.S.A.

Dodla, V.B.R., Gubbala, C.S. and Desamsetti, S. (2017). Atmospheric dispersion of $PM_{2.5}$ precursor gases from two major thermal power plants in Andhra Pradesh, India. *Aerosol Air Qual. Res.* 17: 381–393.

GAINS (2015). *Greenhouse gas and air pollution interactions and synergies - South Asia program*. International Institute of Applied Systems Analysis, Laxenburg, Austria.

Garg, A., Shukla, P.R. and Kapshe, M. (2006). The sectoral trends of multigas emissions inventory of India. *Atmos. Environ.* 40: 4608–4620.

GBD (2017). *The global burden of disease 2010: Generating evidence and guiding policy*, Institute for Health Metrics and Evaluation, Seattle, USA.

GBD-MAPS (2018). *Burden of disease attributable to major air pollution sources in India*, Health Effects Institute, Boston, USA.

GRUMP (2015). *Gridded population of the world and* *global rural and urban mapping project*, Center for International Earth Science Information Network (CIESIN) of the Earth Institute, Columbia University, New York, U. S. A.

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

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

Guttikunda, S.K., Goel, R. and Pant, P. (2014). Nature of air pollution, emission sources, and management in the Indian cities. *Atmos. Environ.* 95: 501–510.

Kansal, A., Khare, M. and Sharma, C.S. (2009). Health benefits valuation of regulatory intervention for air pollution control in thermal power plants in Delhi, India. *J. Environ. Plann. Manage.* 52: 881–899.

Landscan (2013). *Gridded global population database*. Developed by the Department of Energy's Oak Ridge National Laboratory, Distributed by East View Information Services, U.S.A.

Lu, Z. and Streets, D.G. (2012). Increase in NO_x emissions from Indian thermal power plants during 1996-2010: Unit-based inventories and multisatellite observations. *Environ. Sci. Technol.* 46: 7463–7470.

Lu, Z., Streets, D.G., de Foy, B. and Krotkov, N.A. (2013). Ozone monitoring instrument observations of interannual increases in SO_2 emissions from Indian coal-fired power plants during 2005-2012. *Environ. Sci. Technol.* 47: 13993–14000.

McKinsey (2008). *Powering India's the road to 2017*, McKinsey and Co., U.S.A.

MoEFCC (2010). *Environmental impact assessment guidelines for thermal power plants*, Ministry of Environment, Forests, and Climate Change, The Government of India, New Delhi, India.

MoEFCC (2015). *Environment standards for thermal power plants along with the corrigendum*, S.O.3305(E), Ministry of Environment, Forests, and Climate Change, The Government of India, New Delhi, India.

MoEFCC (2018). *Reports at environmental impact assessment division*, Ministry of Environment, Forests, and Climate Change, The Government of India, New Delhi, India.

NCEP (2016). *National centers for environmental prediction*, National Oceanic and Atmospheric Administration, Maryland, U. S. A.

Ni, Z.Z., Luo, K., Gao, Y., Gao, X., Fan, J.R. and Cen, K.F. (2018). Potential air quality improvements from ultralow emissions at coal-fired power plants in China. *Aerosol Air Qual. Res.* 18: 1944–1951.

NPP (2018). *National power portal*, Ministry of Power, the Government of India, New Delhi, India.

Ohara, T., Akimoto, H., Kurokawa, J.I., Horii, N., Yamaji, K., Yan, X. and Hayasaka, T. (2007). An asian emission inventory of anthropogenic emission sources for the period 1980–2020. *Atmos. Chem. Phys.* 7: 4419–4444.

Pande, J.N., Bhatta, N., Biswas, D., Pandey, R.M., Ahluwalia, G., Siddaramaiah, N.H. and Khilnani, G.C. (2002). Outdoor air pollution and emergency room visits at a hospital in Delhi. *Indian J. Chest Dis. Allied Sci.* 44: 13–19.

PIB (2012). *Use of FGD technology in power plants.* In Press Information Bureau, Release ID - 84323, The Government of India, New Delhi, India.

PIB (2013). *Health hazards from emission in coal-fired power plants.* In Press Information Bureau, Release ID - 98090, The Government of India, New Delhi, India.

Pope III, C.A., Cropper, M., Coggins, J. and Cohen, A. (2015). Health benefits of air pollution abatement policy: Role of the shape of the concentration-response function. *J. Air Waste Manage. Assoc.* 65: 516–522.

Prasad, A., Singh, R. and Kafatos, M. (2012). Influence of coal-based thermal power plants on the spatial-temporal variability of tropospheric NO_2 column over India. *Environ. Monit. Assess.* 184: 1891–1907.

Prayas (2011). *Thermal power plants on the anvil: Implications and need for rationalisation*. Prayas Energy Group, Pune, India.

Prayas (2013). *Black and dirty - The Real challenges facing India's coal sector*. Prayas Energy Group, Pune, India.

Sadavarte, P. and Venkataraman, C. (2014). Trends in multi-pollutant emissions from a technology-linked inventory for India: I. Industry and transport sectors. *Atmos. Environ.* 99: 353–364.

Sarkar, M., Venkataraman, C., Guttikunda, S. and Sadavarte, P. (2016). Indian emissions of technology-linked NMVOCs with chemical speciation: An evaluation of the SAPRC99 mechanism with WRF-CAMx simulations. *Atmos. Environ.* 134: 70–83.

Streets, D., Bond, T., Carmichael, G., Fernandes, S., Fu, Q., He, D., Klimont, Z., Nelson, S., Tsai, N. and Wang, M.Q. (2003). An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J. Geophys. Res.* 108: 8809.

Venkataraman, C., Brauer, M., Tibrewal, K., Sadavarte, P., Ma, Q., Cohen, A., Chaliyakunnel, S., Frostad, J., Klimont, Z., Martin, R.V., Millet, D.B., Philip, S., Walker, K. and Wang, S. (2018). Source influence on emission pathways and ambient $PM_{2.5}$ pollution over India (2015-2050). *Atmos. Chem. Phys.* 18: 8017–8039.

Wang, Y., Cheng, K., Tian, H.Z., Yi, P. and Xue, Z.G. (2016). Emission characteristics and control prospects of primary $PM_{2.5}$ from fossil fuel power plants in China. *Aerosol Air Qual. Res.* 16: 3290–3301.

WISE (2012). *Risks of coal based electricity generation in India*, World Institute of Sustainable Energy, Pune, India

World-Bank (2012). *An analysis of physical and monetary losses of environmental health and natural resources in India*. Policy Research Working Papers, WPS-6219, The World Bank, Washington DC, USA.

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