Atmospheric Environment 92 (2014) 449–460

Contents lists available at ScienceDirect

Atmospheric Environment

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

Atmospheric emissions and pollution from the coal-fired thermal power plants in India

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HIGHLIGHTS

- Review of emission factors and emissions analysis for coal-fired power plants.
- Review of environmental regulations for air pollution from coal-fired power plants.
- Particulate pollution analysis via CAMx dispersion model.
- Health impacts of particulate pollution from coal-fired power plants.

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form
26 April 2014
Accepted 29 April 2014
Available online 2 May 2014

Keywords:
Environmental regulations
Particulates
Sulfates
Flue gas desulfurization
CAMx
Health impacts

ABSTRACT

In India, of the 210 GW electricity generation capacity, 66% is derived from coal, with planned additions of 76 GW and 93 GW during the 12th and the 13th five year plans, respectively. Atmospheric emissions from the coal-fired power plants are responsible for a large burden on human health. In 2010–11, 111 plants with an installed capacity of 121 GW, consumed 503 million tons of coal, and generated an estimated 580 ktons of particulates with diameter less than 2.5 μm ($PM_{2.5}$), 2100 ktons of sulfur dioxides, 2000 ktons of nitrogen oxides, 1100 ktons of carbon monoxide, 100 ktons of volatile organic compounds, and 665 million tons of carbon dioxide. These emissions resulted in an estimated 80,000 to 115,000 premature deaths and 20.0 million asthma cases from exposure to $PM_{2.5}$ pollution, which cost the public and the government an estimated INR 16,000 to 23,000 crores (USD 3.2 to 4.6 billion). The emissions were estimated for the individual plants and the atmospheric modeling was conducted using CAMx chemical transport model, coupled with plume rise functions and hourly meteorology. The analysis shows that aggressive pollution control regulations such as mandating flue gas desulfurization, introduction and tightening of emission standards for all criteria pollutants, and updating procedures for environment impact assessments, are imperative for regional clean air and to reduce health impacts. For example, a mandate for installation of flue gas desulfurization systems for the operational 111 plants could reduce the $PM_{2.5}$ concentrations by 30–40% by eliminating the formation of the secondary sulfates and nitrates.

1. Introduction

India, at 210 GW, has the 5th largest electricity generation sector in the world (with captive power plants generating 31 GW more), with targets of additional 76 GW in the 12th five year plan (2012–2017) and another 93 GW in the 13th five year plan (Prayas, 2011, 2013). Thermal power plants account for 66% of generation, hydro for 19% and others (including nuclear energy) for 15%. In India, coal is the primary fuel of choice and accounts for 50–55% of the power generation and will only get larger in the coming years (Chikkatur et al., 2011; WISE, 2012; Prayas, 2013).

In India, the supply of electricity lags behind the demand. According to the Central Electricity Authority (CEA), in 2010–11, of the 122 GW peak demand, only 110 GW was supplied – which amounted to a shortfall of 10% (CEA, 2012). A third of the population that lives in rural India does not have access to electricity. Even those with access in urban India have to endure frequent power

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http://dx.doi.org/10.1016/j.atmosenv.2014.04.057
1352-2310/

cuts and load shedding, which results in use of in-situ diesel generator sets (Guttikunda and Jawahar, 2012; Guttikunda and Calori, 2013).

Coal-fired power generation comes with significant costs to environment and human health. The water runoff from coal washeries carries pollution loads of heavy metals that contaminate ground water, rivers, and lakes – thus affecting aquatic flora and fauna (Finkelman, 2007). Fly-ash residue and pollutants contaminate soil and are especially harmful to agricultural activities. Most importantly for human health, combustion of coal releases emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs), and various trace metals like mercury, into the air through stacks that can disperse this pollution over large areas. The 2010 global burden of disease (GBD) study listed the outdoor air pollution (PM and ozone pollution) among the top 10 health risks in India, with as estimated 695,000 annual premature deaths from respiratory illnesses, compromised immune systems, and cardiovascular conditions (IHME, 2013). The known sources of outdoor air pollution in India include emissions from power plants, manufacturing industries, vehicle exhaust, cooking and heating in the households, generator sets, nature dust, on-road dust resuspension, garbage burning, and seasonal agricultural burning.

Previously, the studies on power plants in India focused on coal usage trends, resource management, greenhouse gas emissions, and innovation in use of renewable energy (Chikkatur and Sagar, 2009; Chikkatur et al., 2011; Prayas, 2011; Chaudhary et al., 2012; Ghose, 2012; WISE, 2012; Prayas, 2013) and total emissions inventories for base year 2005 or older (Streets et al., 2003; Reddy et al., 2005; Ohara et al., 2007; GAINS, 2012). Of the estimated annual anthropogenic emissions in India, the thermal power plants account for ~15% for $PM_{2.5}$, ~30% for NO_x, and ~50% of SO_2 (GAINS, 2012). Studies based on satellite measurements (Lu and Streets, 2012; Prasad et al., 2012) looked at the influence of power plant emissions on the column NO_x concentrations, including the influences of other sources, but there is limited bottom-up analysis on dispersion of emissions from the coal-fired power plants.

Given the plans to greatly expand the contribution of coal to the Indian power sector (Chikkatur et al., 2011; WISE, 2012; Prayas, 2013), it is vital that decision makers understand the hidden costs of air pollution from power plants. In this paper, we present an updated list of operational coal-fired power plants in India, their generation capacities, coal consumption rates, and evaluation of the health impacts of their pollution via dispersion modeling. We also discuss the current environmental regulations for power plants in India or their lack of.

2. Data and methods

2.1. Coal-fired power plants in India

The installed power generation capacity in India grew at an average annual rate of 8% in the 1970s and at 10% since the 1980s (WISE, 2012; Prayas, 2013). The characteristics of operational coal-fired power plants in India are presented in Table 1 and the location of these plants is presented in Fig. 1. The database of plants documented by CEA was further updated with information from websites and annual reports of the state electricity boards and private electricity generation companies (CEA, 2011; CEA, 2012). The database includes geographical location in latitude and longitude, number of boiler units and size of all known power plants operated by both public and private entities.

Power plants are clustered at pit heads of coal mines in Central India, in northern Andhra Pradesh, western Maharashtra, northern Chhattisgarh, West Bengal, Bihar, Jharkhand, and Orissa. Some large power plants are located on the coast, for the availability of cooling water from the sea and ease of importing coal. While the coastal winds are beneficial in some cases, the impacts are still at large for cities in the vicinity. For example, Chennai (Tamilnadu) and Ahmedabad (Gujarat), each host two coal-fired power plants of more than 1000 MW electricity generation and located closer to the city premises. Chennai, being a coastal city, records a smaller fraction of the power plant emissions in their ambient measurements, compared to Ahmedabad, which is in-land (Guttikunda and Jawahar, 2012). In Delhi, up to 8% of the ambient PM pollution can be attributed to the coal-fired power plants of 2000 MW, operated within 60 km from the city center (Guttikunda and Goel, 2013). Similar shares are expected for the cities of Mumbai, Ahmedabad, Kolkata, and some medium to smaller size cities like Nagpur, Raipur, Ranchi, Kota, Bhatinda, Raichur, with power plants in the vicinity of 100 km.

Table 1
Summary of annual coal consumption at the power plants in India in 2010–11.

State	Number of plants	MW	Coal million tons	kg coal/kWh 2006–07	% Installed units <210 MW
Andhra Pradesh	8	10,523	47.4	0.72	65%
Bihar	3	2870	10.2	0.94	77%
Chhattisgarh	8	9480	44.5	0.72	39%
Delhi	2	840	4.8	0.77	100%
Gujarat	11	14,710	55.9	0.65	69%
Haryana	5	5860	23.9	0.70	35%
Jharkhand	6	4548	12.0	0.75	86%
Karnataka	5	3680	14.6	0.69	64%
Madhya Pradesh	4	6703	33.1	0.79	79%
Maharashtra	13	17,560	71.5	0.73	51%
Orissa	8	8943	40.7	0.73	76%
Punjab	3	2620	13.2	0.66	82%
Rajasthan	4	3490	13.2	0.67	44%
Tamilnadu	8	6210	25.8	0.72	95%
Uttar Pradesh	11	11,997	56.0	0.80	86%
West Bengal	12	10,695	36.1	0.69	75%
Total	**111**	**120,727**	**503**	**0.73 ± 0.10**	**70%**

2.2. Coal characteristics

Indian coal (Gondwana coal) has high ash content (35–45%) and low calorific value (averaging 3820 kcal/kg in 2003–04 and 3603 kcal/kg in 2010–11). The sulfur content in Indian coals is less than those observed in the United States (1.0–1.8%) and Chinese coals (0.5–1.0%). The sulfur content in the Indian coal has a consumption-weighted average of 0.6% (Reddy and Venkataraman, 2002).

The high ash content and low calorific value affects the thermal power plant's operational efficiency and increases emissions per kWh generated. As a comparison, power plants in India use about 0.72 ± 0.10 kg of coal to generate 1 kWh, while a power plant in the USA of the same technology would consume 0.45 kg of coal per kWh (Chikkatur, 2008). The estimated annual coal consumption rates by state are listed in Table 1. The average thermal efficiency of the coal-fired power plants in India between 2004 and 2011 remained 32–33% (CEA, 2012) while this is peaking above 35% for the power plants in China (Seligsohn et al., 2009).

The high silica and alumina content in Indian coal ash is another problem, as it increases ash resistivity and reduces the collection efficiency at the electrostatic precipitators (ESPs). To address this issue, the government has mandated the use of coal whose ash content has been reduced to at least 34% in power plants in urban, ecologically sensitive, and other critically polluted areas. The

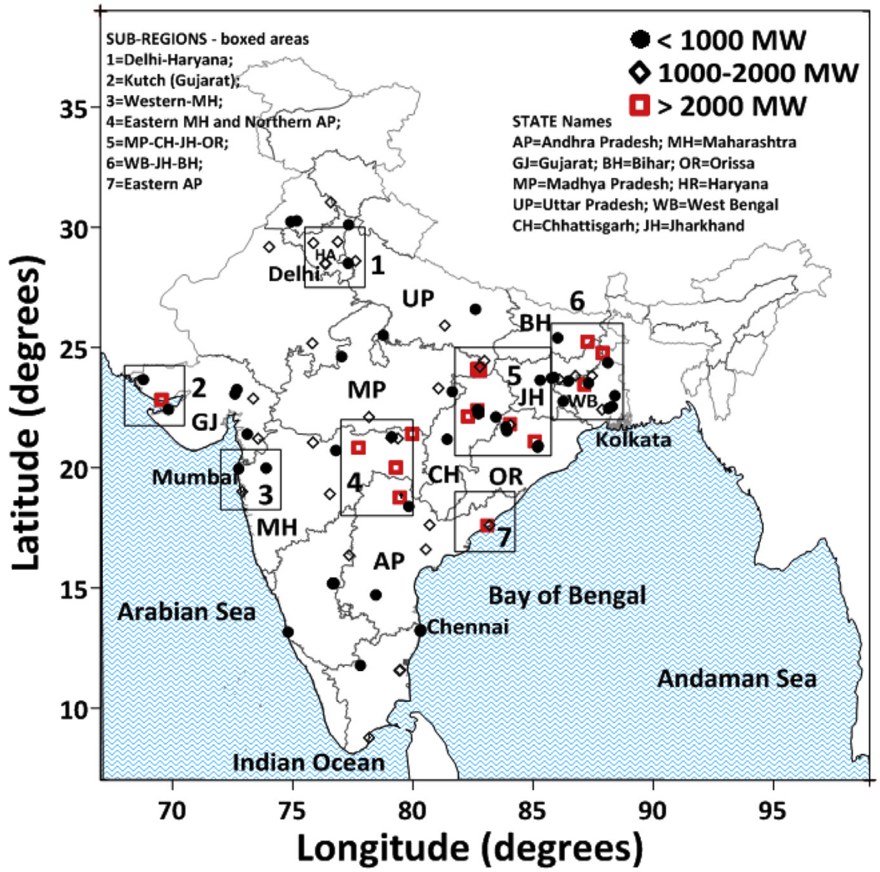

Fig. 1. Geographical location of the operational coal-based public and private power plants in India in 2012.

compliance with this mandate has been uncertain due to lack of access to the continuous monitoring data from the stacks.

Coal obtained from opencast mines has greater ash content – much of India's coal is mined using open caste methods and is likely to continue as such. In 2005, about 110 MT of coal ash was generated in India from more than 70 thermal power plants. Estimates for 2012 put this at 170 MT per annum (Bhangare et al., 2011).

2.3. Chemical transport dispersion model

Atmospheric dispersion modeling was conducted to study the impact of the emissions from the coal-fired power plants on the ambient PM concentrations and their health impacts. The modeling schematics are presented in the Supplementary Material. We utilized the ENVIRON – Comprehensive Air Quality Model with Extensions (CAMx), an Eulerian photochemical dispersion model, suitable for integrated assessments of gaseous and particulate air pollution over many scales ranging from sub-urban to continental. The model formulation, advection and scavenging schematics, chemical solvers, and gas-to-aerosol conversion mechanisms, are detailed in the model manual (http://www.camx.com). The model utilizes full gas phase SAPRC chemical mechanism (Carter et al., 2000) (217 reactions and 114 species) with two mode coarse/fine PM fractions including gas to aerosol conversions, for SO_2 to sulfates, NO_x to nitrates, and VOCs to secondary organic aerosols (SOA). The removal processes include dry deposition schemes using an updated approach with 26 landuse patterns and wet deposition due to predominant meteorological conditions. The most important advantage of CAMx is the use of 3D meteorology and independently controled plume rise and emission release point for each power plant, according to the stability profile at the plants location (Turner et al., 1986).

There are other atmospheric dispersion models, equally capable of carrying out this modeling exercise. The CAMx model was selected for its modular nature in characterizing and treating the plumes from point sources. Recent CAMx applications for similar modeling exercises include Huang et al. (2010) – an urban scale study to quantify the contributions of various sources to PM_{10} pollution in Beijing, China; Sun et al. (2012) – a regional study to simulate the changes in ozone concentrations due to new NO_x emission regulations in the power plants in Eastern USA; Emery et al. (2012) – a study on sources of background ozone concentrations over the USA and its policy implications; Wu et al. (2013) – a regional study evaluating the control policies for the sources of $PM_{2.5}$ in the Pearl River Delta region.

For the modeling domain, the meteorological data (3D wind, temperature, pressure, relative humidity, and precipitation fields) is derived from the National Center for Environmental Prediction (NCEP) (NCEP, 2012) global reanalysis database for the base year 2010–11 and processed through WRF 3.5 meteorological model at 1 h temporal resolution. An example animation for the wind speeds and wind directions at the surface level, mixing layer height, and precipitation fields, for one month are presented in the Supplementary Material. The initial conditions for the dispersion model were extracted from the MOZART global chemical transport model, for which an interface is available with the CAMx model. To further localize the initial conditions, the model was looped over each month for 10 days before starting the model calculations for the study analysis. The boundary conditions are also extracted from the MOZART global chemical transport model. After initializing the model, the emissions from only the power plants were utilized in order to isolate the impacts of these emissions on the ambient concentrations.

The study 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 23 layers, with the lowest layer designated at 50 m and six layers within 1 km to advance vertical advection closer to the ground level.

2.4. Health impacts

In India, the morbidity and mortality burden of outdoor air pollution, is particularly costly in terms of work days lost, lost productivity, and loss in terms of gross domestic product, approximately USD 23.4 billion and 1.7% of national GDP in 2009 (World-Bank, 2012). Since, most of the pollution related deaths occur within a year or two of exposure, reducing PM pollution from sources like transport and power plants has immediate benefits for health and national economy. The direct link between outdoor air pollution and human health has been extensively documented under the 2010 GBD study (IHME, 2013). Epidemiological studies conducted in India have consistently demonstrated higher rates of respiratory and cardiovascular diseases in populations exposed to PM, NO_x, and ozone pollution (Chhabra et al., 2001; Pande et al., 2002; Gupta et al., 2007; Wong et al., 2008; CBHI, 2010; Siddique et al., 2010; Balakrishnan et al., 2013).

The total health risk for mortality is quantified using the relative risk functions for various endpoints defined as

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

$$RR_i = \exp(\beta * \delta C_i) \quad (2)$$

The total health risk for morbidity is quantified using the following equation for various endpoints

$$\delta E = \sum_{i=1}^{\#grids} \beta * \delta C_i * \delta POP_i \quad (3)$$

where

δE = number of estimated health effects (various end points for mortality and morbidity).
IR = incidence rate of the mortality and morbidity endpoints. A total death incidence rate for India is set at 7.1 per 1000 inhabitants.
δPOP = the population exposed to the incremental concentration δC in grid i; defined as the vulnerable population in each grid. The gridded population is estimated using GRUMP (2010) for the model resolution of 0.25°. The total population of 1.2 billion is adjusted to Census-India (2012) by state totals, with the urban centers accounting for 30% of the total.
RR = relative risk for mortality and morbidity end points.
β = the concentration–response function; which is defined as the change in number cases per unit change in concentrations per capita. For all-cause mortality in this study, the function is defined as 3.9% change in the mortality rate per 4 μg/m^3 of change in the $PM_{2.5}$ concentrations (Hart et al., 2011). The uncertainties involved in the risk assessments are detailed in IHME (2013) for long term integrated exposures. The morbidity effects are calculated as cases of asthma attacks, chronic bronchitis, hospital admissions, and work days lost, for which the concentration–response functions are extracted from Abbey et al. (1995) and World-Bank (2012).
δC = the change in concentrations from the ambient standards in grid i; an output from the CAMx dispersion model as the annual average $PM_{2.5}$ concentration due to the coal-fired power plant emissions.

This methodology of relative risk and concentration–response function was applied for similar studies – IHME (2013) and Ostro (2004) for GBD assessments for 2010 and 2000 respectively; Bell et al. (2006) for health impacts of urban air pollution in the cities of Santiago, Mexico city, and Sao Paulo; GAINS (2012) for Asia and Europe regional studies evaluating the impacts in terms of life years lost due to baseline air pollution or benefits in life years saved due to future controls; Yim and Barrett (2012) for premature deaths in the United Kingdom caused by long-range transport of combustion emissions from the European Union; Cropper et al. (2012) for benefits of better environmental regulations in controlling pollution from coal fired power plants in India; Guttikunda and Jawahar (2012) for health impacts of urban air pollution in 2 large, 2 medium, and 2 small cities in India; Guttikunda and Goel (2013) for a megacity Delhi and its surrounding satellite cities.

3. Results and discussion

3.1. Atmospheric emissions

For 2010–11, the total estimated annual emissions are 580 ktons for $PM_{2.5}$, 1200 ktons for PM_{10}, 2100 ktons of SO_2, 2000 ktons of NO_x, 1100 ktons of CO, 100 ktons of VOCs and 665 million tons of carbon dioxide (CO_2). The total estimated emissions by state are presented in Table 2. The total emission rates are calculated based on the boiler size, coal consumption rates, and control equipment efficiencies, which is collected from thermal power plant performance reports (CEA, 2011; CEA, 2012). For the emissions input to the dispersion model, the annual emissions were further segregated by month, based on the coal-consumption data by month from the power plants. The diurnal cycle of the emissions was kept constant by month.

3.1.1. Emission factors

We summarized the regional emission factors for the coal based power plants in Table 3 in both tons/PJ and tons/h. The latter is for comparisons with any data available from the online monitoring. Previously published studies are regional estimates either for all of India and for all the power plants in Asia, and most are estimated for the base year 2000–05 and prior. A serious lack of monitoring data availability from the stacks, results in uncertainty estimates of emission factors. The overall uncertainty in the total emission estimates is ±20%, stemming from the variations in the information at the plant level on in-use coal characteristics, coal consumption rates, efficiencies in control operations, and emission factors.

3.1.2. Emission regulations

Comparative emission rates as gm/kWh for NO_2, SO_2, and $PM_{2.5}$ is presented in IEA (2012) for France, Germany, Italy, United Kingdom, China, India, Russia, the United States, Canada, Japan, South Africa, and Australia (Supplementary Material). Under the current emission regulations, the emissions rates are the highest in Russia and India. China, the United States, the European Union (EU) and Australia have stronger regulations (Table 4). Even with 55% of the installed coal-based generation capacity, there is a conspicuous lack of regulations for SO_2, NO_x, and Mercury emissions. There is also no continuous and open emission monitoring data available at

Table 2
Total annual emissions (rounded) from coal based power plants in India in 2010–11.

State	$PM_{2.5}$ tons	PM_{10} tons	SO_2 tons	NO_x tons	CO tons	VOC tons	CO_2 million tons
Andhra Pradesh	51,500	107,500	199,500	187,500	104,000	9500	62.8
Bihar	15,500	31,000	43,000	39,500	22,500	2500	13.5
Chhattisgarh	39,000	84,000	187,000	172,500	97,500	9000	58.9
Delhi	7500	14,500	20,500	20,000	11,000	1000	6.4
Gujarat	53,000	111,000	214,000	220,000	122,500	11,500	74.0
Haryana	23,500	50,000	100,500	93,500	52,500	5000	31.7
Jharkhand	15,500	31,500	50,500	48,500	26,500	2500	15.9
Karnataka	17,500	36,000	61,500	58,500	32,000	3000	19.4
Madhya Pradesh	49,500	100,000	139,500	130,500	73,000	7000	43.9
Maharashtra	80,500	167,000	300,500	278,500	156,500	14,500	94.6
Orissa	40,000	85,000	171,000	159,500	89,500	8500	53.9
Punjab	16,500	34,000	56,000	53,000	29,000	3000	17.5
Rajasthan	14,500	30,000	55,500	52,000	29,000	3000	17.5
Tamilnadu	36,500	74,000	108,500	104,500	56,500	5500	34.2
Uttar Pradesh	83,500	168,500	235,500	225,000	122,500	11,500	74.1
West Bengal	40,000	83,500	152,000	143,000	79,000	7500	47.8
Total	**580,000**	**1,200,000**	**2,100,000**	**2,000,000**	**1,100,000**	**100,000**	**665.4**

the plant level, which makes enforcement of what standards do exist, nearly non-existent.

3.1.3. Particulate emissions

The total PM emissions from the power plant stacks are regulated as concentrations and vary with boiler size. For example, for the plants with generation capacity more than 210 MW, the PM concentration limit is 150 mg/Nm^3 and for the plants with generation capacity less than 210 MW, the limit is 350 mg/Nm^3. These limits are much weaker compared to those practiced limits in Australia, China, USA, and EU. The limit for the smaller plants is 150 mg/Nm^3, if they are located in an urban, ecologically sensitive, and other critically polluted areas – which is at the discretion of MoEF. A breakup in the emissions regulation at 210 MW also led to installation of smaller boilers at most of the power plants (Table 1). Approximately 70% of the operational units in the country are of the size less than or equal to 210 MW and these units tend to have the worst net efficiency and plant load factor. The newer plants are mostly 500 MW or higher with the best net efficiency of more than 33% (CEA, 2012).

Differential emission regulations also tend to result in use of control equipment with low efficiency and higher emissions. For example, the Kolghat power plant in West Bengal state has 6 units of 210 MW and the Raichur power plant in Karnataka state has 7 units of 210 MW, each with a total generation capacity of more than 1000 MW, are allowed to adhere to the lower emission standard, only because the individual boiler size is less than or equal to 210 MW.

PM is the only pollutant for which any pollution controls are widely applied. A schematic of a coal-fired power plant is presented in Fig. 2 that shows flue gas from the boilers at high temperature and velocity passing through heat exchangers to recycle the residual energy. This then enters the particulate control equipment (ESPs and cyclone bag filters) for removal of entrained ash. ESPs are installed in all coal-fired power plants in India. As removal efficiencies at ESPs are higher for coarse particles, most of the PM dispersing from the top of the stack is in the size range of respirable PM (10 μm or less). Lu et al. (2010) measured fractions of 50–60% $PM_{2.5}$ and 90–95% PM_{10} in the total filterable PM in the flue gas at a 660 MW power plant. The PM in the flue gas also contains high concentrations of heavy metals such as arsenic, lead, cadmium, mercury, copper, and zinc, which not only contributes to potential health hazard than the bottom ash (Finkelman, 2007), but also increases the resistivity and reduces the ESPs collection efficiency to as low as 98%. Reddy et al. (2005) measured the chemical composition of the bottom ash, fly ash, and flue gas from a coal fired power plant in the western India and estimated 1–7% of zinc, 2–7% of copper, 5–8% of manganese, 7–10% of cobalt, 12–18% of

Table 3
Regional emission factors database.

Resource	Base year	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC
This study[c,a]	2010–11	49–68	90–138	174–192	177–189	100	9
Streets et al. (2003)[a]	2000			400–762	219–562		
GAINS (2012) (base)[d,a]	2000–05	53–261	18–374	69–1380	100–270		1–15
GAINS (2012) (controlled)[e,a]	2000–05	13–27	19–43	27–69	20–54		1–15
Ohara et al. (2007)[f,a]	2000			504	267	154	
Garg et al. (2006)[g,a]	2000		251	367	205	56	
Lu and Streets (2012)[h,a]	1996–2006				177–410		
This study[i,b]	2010–11	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)[j,b]	2004–05		0.7–1.1	4.0–5.0	1.2–1.8		

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

Table 4
Summary of emission standards for coal-fired power plants.

Country	PM	SO_2	NO_2	Mercury
India[a]	350 mg/Nm^3 for <210 MW 150 mg/Nm^3 for >210 MW	None	None	None
China[b]	30 mg/Nm^3 (proposed all) 20 mg/Nm^3 for key regions	100 mg/Nm^3 for new 200 mg/Nm^3 for old 50 mg/Nm^3 for key regions	100 mg/Nm^3	None
Australia[c]	100 mg/Nm^3 for 1997–2005 50 mg/Nm^3 after 2005	None	800 mg/Nm^3 for 1997–2005 500 mg/Nm^3 after 2005	In discussion based on USA standards
European Union[c]	Pre-2003 100 mg/Nm^3 for <500 MW 50 mg/Nm^3 for >500 MW Post 2003 50 mg/Nm^3 for <100 MW 30 mg/Nm^3 for >100 MW	Pre-2003 Scaled for <500 MW 400 mg/Nm^3 for >500 MW Post 2003 850 mg/Nm^3 for <100 MW 200 mg/Nm^3 for >100 MW	Pre-2003 600 mg/Nm^3 for <500 MW 500 mg/Nm^3 for >500 MW Post 2003 400 mg/Nm^3 for <100 MW 200 mg/Nm^3 for >100 MW	In discussion
USA[c,d]	37 mg/Nm^3 for old 6 mg/Nm^3 for new	245 mg/Nm^3 for old 50 mg/Nm^3 for new	61 mg/Nm^3 for old 42 mg/Nm^3 for new	
USA[c,e]	6.4 gm/GJ	640 gm/MWh	720 gm/MWh for old 450 gm/MWh for new	0.08 gm/MWh for lignite 0.01 gm/MWh for IGCC

[a] From Central Pollution Control Board (India) (http://cpcb.nic.in/Industry_Specific_Standards.php). Last accessed Feb 17th, 2013. Besides PM, only national ambient standards exist.
[b] From standards information in Chinese (http://www.zhb.gov.cn/gkml/hbb/qt/201109/t20110921_217526.htm). Last accessed Feb 17th, 2013. Prior to 2011, the standards were based on commissioning year (before 1996, 1997 to 2004, and after 2004).
[c] Power stations emissions handbook (http://www.ccsd.biz/PSE_Handbook). Last accessed Feb 17th, 2013.
[d] Emission rates are translated to mg/Nm^3 based on assumed plant efficiency.
[e] In official units; for mercury this is based on 12 month rolling average.

cadmium, 60–70% of selenium, 70–80% of mercury, and traces of arsenic, iron, lead, and chromium contained in the coal was emitted in the flue gas. Similar levels of entrainment were reported in an estimate of total trace metal emissions from coal fired power plants in China (Chen et al., 2013).

Besides flue gas PM emissions, fugitive dust from coal-handling plants and ash ponds (after the disposal from the plants) is a problem. According to CEA, after the combustion and application of control equipment, ash collection at the power plants ranged 70–80% of the total ash in the coal (CEA, 2011; CEA, 2012). It is assumed that the remaining ash is dispersed from the stacks. In 2003, an amendment notification from MoEF mandated 25% of bottom ash in all brick kilns within 100 km radius of any coal based thermal power plant and all building construction within 100 km for any coal-fired thermal power plant to use 100% ash based bricks, blocks, and tiles. To date, percentage of ash utilized in the construction industry is low – approximately 13% used for brick manufacturing and other construction activities.

3.1.4. Gaseous emissions

There are no legally mandated emission standards for SO_2. Only a handful of coal-fired power plants operate flue gas desulfurization (FGD) units and among those to be commissioned through 2020, only 7 power plants are listed to have FGD (Prayas, 2011). The FGD systems could range from in furnace control via limestone injection, wet scrubbing of flue gas, to capturing SO_2 in the flue gas through industrial processes (Fig. 2). Presence of a FGD system further improves removal of PM.

In India, for SO_2, only the stack heights are mandated assuming that the emissions will be dispersed to farther distances and thus diluting the ambient concentrations. For example, MoEF requires all power plants with generation capacity more than 500 MW to

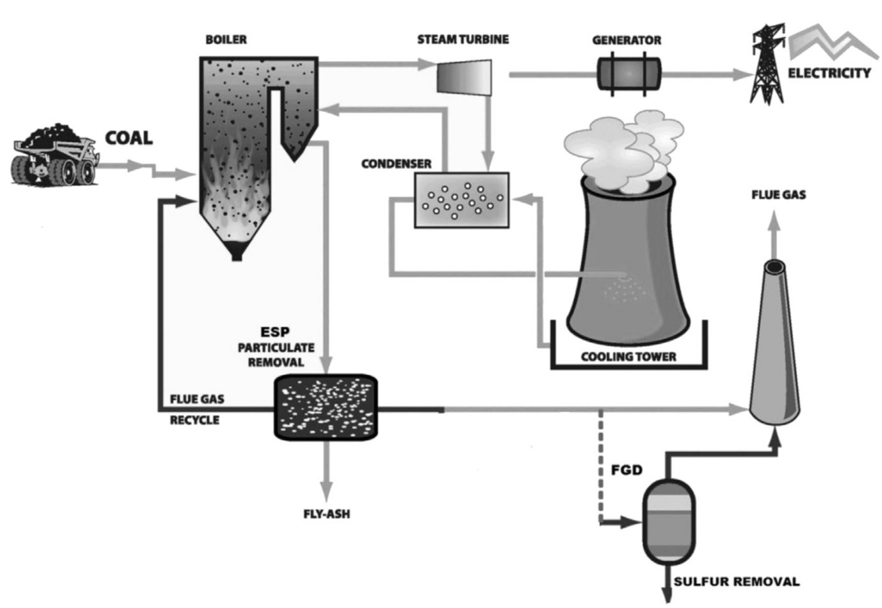

Fig. 2. Simplified schematics of coal-fired power plant operations.

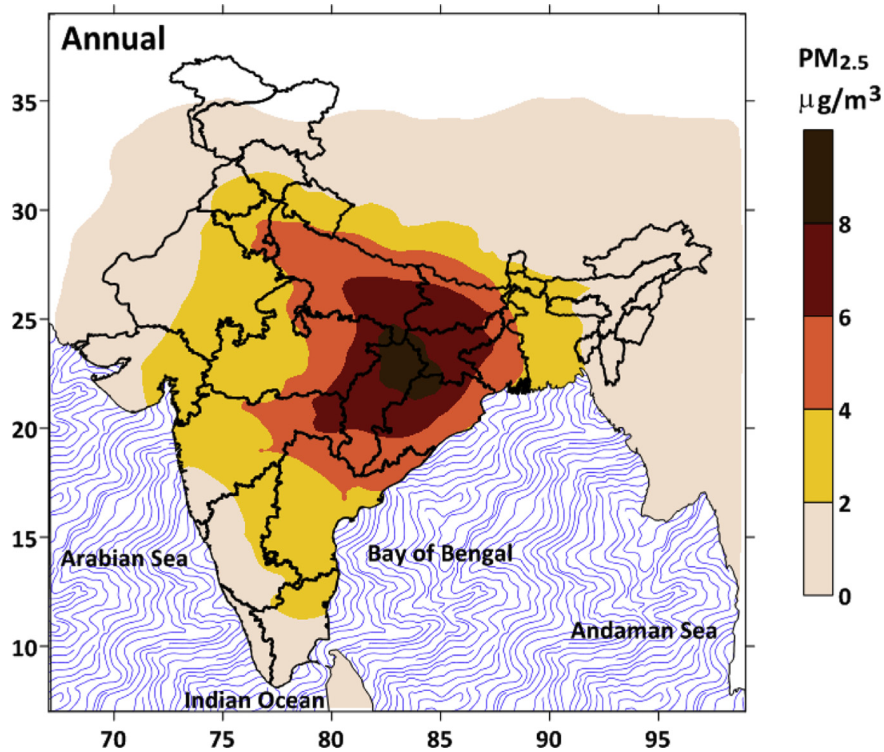

Fig. 3. Modeled annual average ambient $PM_{2.5}$ concentrations due to the emissions from coal-fired thermal power plants in India.

build a stack of 275 m; those between 210 MW and 500 MW to build a stack of 220 m; and those with less than 210 MW to build a stack based on the estimated SO_2 emissions using a thumb rule of height $= 14^*(Q)^{0.3}$ where Q is the estimated SO_2 emissions rate in kg/h. The stack heights for old power plants ranged between 150 m and 220 m.

Despite an estimated 30% of the total NO_x emissions in India originating from power generation (Garg et al., 2006; GAINS, 2012), there are no regulations to control these emissions. Some of the new installations and extensions are equipped with low-NO_x burners, with little details on their operational performance (Chikkatur et al., 2011).

3.1.5. Previous estimates

Few studies have reported emission rates and total emissions from the power plants in India. One national emissions inventory for the coal and gas based power plants is maintained by the GAINS program at the International Institute for Applied Systems Analysis (IIASA, Austria), which for the base year 2005, estimated total emissions of 490 ktons for $PM_{2.5}$, 1900 ktons for SO_2, 1300 ktons for NO_x, 43 ktons of VOCs. A major difference between GAINS and this study is in the database of plants, which is updated for the new installations and extensions for the existing plants, and assumed control efficiencies. A database of coal characteristics, control efficiencies, and emission rates is available online (GAINS, 2012). Another global emissions inventory by specific sectors is EDGAR with estimates for base year 2008 (http://edgar.jrc.ec.europa.eu). Average emission factors for PM, SO_2, NO_x, CO, and BC for all combustion sectors for base year 2000 are presented in Streets et al. (2003).

The CEA also reports, as part of the power plants performance evaluation, the emissions for total suspended PM in mg/Nm^3 (CEA, 2012). Since, these are not continuous measurements and mostly observed at select times during the year, it was difficult to either confirm or reject the estimates based on them. Kansal et al. (2009) studied the emissions from six coal and gas fired power plants in and around Delhi, based on the reported measurements, which tend to underestimate the contribution of power plant emissions to the region (Guttikunda and Goel, 2013). Similarly, based on intermittent measurements Cropper et al. (2012) estimated average emissions of 110 ktons/year for $PM_{2.5}$ from 92 coal fired power plants.

For NO_x, Prasad et al. (2012) studied the influence of thermal power plants on tropospheric NO_2 column measurements from the ozone monitoring instrument (OMI) onboard aura satellite (http://aura.gsfc.nasa.gov) and also studied the algorithm to deduce ground level concentrations, which could reflect the power plant emissions. This study particularly highlights the cluster regions over the states of Delhi, Haryana, Indo-Gangetic plains, and most of central India with the highest concentrations possibly originating from the power plants. Lu and Streets (2012) also studied the satellite data and further estimated the emissions based on boiler size and coal consumed for the period between 1996 and 2010, which overlays the changes in satellite observations to the newer installations and extensions commissioned during this period. They estimated a 70% increase in the column NO_x concentrations during this period, with the power plants contributing a total estimated 2300 ktons NO_x emissions for 2010.

3.2. Atmospheric dispersion

3.2.1. Ambient pollution

The atmospheric dispersion simulation was carried out for 11 days per month from 10th to 21st of each month and averaged to obtain monthly, seasonal, and annual concentrations. The modeled annual average $PM_{2.5}$ concentrations due to emissions from coal based power plants only are presented in Fig. 3. The modeled monthly average concentration maps and animations of modeled daily average concentrations are presented in the Supplementary Material. The largest impact is felt over most of the central-east India including states of Maharashtra, Madhya Pradesh, Chhattisgarh, and Orissa, with the largest 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).

For $PM_{2.5}$ concentrations in Fig. 3 includes fine PM, sulfate, and nitrate concentrations (from chemical conversion of SO_2 and NO_x emissions, using the predefined chemical mechanisms in CAMx). The concentrations are an incremental pollution from the coal-fired power plants only, which is considered in addition to the pollution from transport, domestic, and other industrial activities, on an annual basis. The population weighted concentration due to the coal-fired power plant emissions only is 3.6 $\mu g/m^3$. The national ambient annual average standard for $PM_{2.5}$ is 40 $\mu g/m^3$ and the WHO guideline is 10 $\mu g/m^3$.

The PM pollution in Central India, covering the states of Madhya Pradesh, Jharkhand, Orissa, and Chhattisgarh, is the highest due to the density of the power plants in the region and high installed generation capacity, due their proximity to the coal mines. The Delhi-Haryana region with the highest population density with more than 21.5 million inhabitants in Delhi and its satellite cities is exposed to higher PM pollution from coal-fired power plants. The range of modeled PM pollution in 7 sub-regions is presented in Table 5. The coastal regions experience the least of the PM pollution due to strong land-sea breezes, with much of the pollution dispersed over the seas. To date the inland power plants are still the majority in the country and a serious threat to human health and other environmental concerns.

- The Korba cluster (State: Chhattisgarh (CH)) has a combined generation capacity of 4380 MW between four power plants located within a 10 km radius. Major cities in the Korba region are Ranchi, Jamshedpur, Rourkela, Jabalpur, Nagpur, and Raipur (capital of Chhattisgarh).
- The Jhajjar cluster (State: Haryana) has a combined generation capacity of 2700 MW between two power plants within the radius of 10 km, with an additional power plant with 1000 MW under construction. The city of Delhi is 70 km from the Jhajjar cluster.
- The Mundra cluster (State: Gujarat (GJ)) has a combined generation capacity of 9620 MW between two private sector power plants located within 5 km radius. Major cities in the Mundra region are Jamnagar (major industrial port), Rajkot, and Ahmedabad (300 km away, with two local power plants of 1000 MW).
- The Mumbai cluster (State: Maharashtra (MH)) has one coal based power plant in Trombay and multiple gas powered plants.

While the impact of the emissions is felt within 200 km of the power plants, under windy conditions the influence can be tracked to distances as far as 400 km from the source region. The animated forward trajectories over one day for the coal-fired power plants in Korba, Jhajjar, Mumbai, and Mundra clusters, for three months (April, July, and October), is presented in the Supplementary Material. The forward trajectories illustrate that the emissions from these high stacks affects the regions and people far away from the source region and this should be accounted for in the environmental impact assessments of the coal-fired power plants, which under the current regulations is limited to only 50 km radius, from the power plant stacks (MoEF, 2010).

3.2.2. Seasonal variations

Generally, the wind speeds at 200 m or above are much faster than those observed at the ground level. The release of the emissions at the stack height plus any uplift due to the flue gas velocity and temperature, dictates the movement of the emissions and its vertical diffusion towards the ground. The forward trajectories presented in the Supplementary Material for the select clusters, further demonstrates the fast movement of the power plant plumes

Table 5
Installed capacity, modeled daily average $PM_{2.5}$ concentrations, health impacts of emissions from coal fired power plants for 7 regions at finer resolution in India in 2010–11.

No.	Cluster (size in degrees)	Regional features	No. of plants (those more than 1000 MW)	Installed capacity (MW)	Modeled $PM_{2.5}$[a] – median (95th percentile) $\mu g/m^3$	Estimated premature mortality within the region[b]
1	Delhi – Haryana (2.5° × 2.5°) (in-land)	Delhi is the national capital, listed among the top 10 cities with worst air quality in the world (WHO, 2011) and Haryana is an agricultural state	8 (5)	8080	3.9 (7.7)	6400–8800
2	Kutch (Gujarat) (2.5° × 2.5°) (coastal)	A coastal cluster, with two super-critical power plants in Mundra (Gujarat), both private, operated by Tata and Adani power groups	5 (2)	9900	1.0 (2.8)	100–120
3	Western-MH (2.5° × 2.5°) (coastal)	Including Mumbai, the most commercial and congested city in the country	3 (1)	2780	0.9 (2.3)	1700–2400
4	Eastern MH and Northern AP (3.0° × 4.0°) (in-land)	All plants are located closer to the coal belts of Chandarpur and Ghugus (Maharashtra – MH) and Singareni (Andhra Pradesh – AP)	10 (6)	14,800	3.2 (5.1)	1100–1500
5	MP–CH–JH-OR (4.0° × 4.5°) (in-land)	This cluster covers four states – Madhya Pradesh (MP), Jharkhand (JH), Chhattisgarh (CH) and Orissa (OR) and home to the largest coal fields of Jharia, Dhanbad, Korba, Singrauli, Karanpura, and Mahanadi	21 (10)	29,900	9.1 (23.1)	7900–11000
6	WB–JH–BH (3.0° × 4.0°) (in-land)	This cluster covers West Bengal (WB), JH, and Bihar (BH) sourcing mostly from Raniganj and Jharia coal belts	19 (7)	17,100	3.7 (5.6)	10700–14900
7	Eastern AP (2.5° × 2.5°) (coastal)	A coastal cluster including the port city of Vishakhapatnam	2 (2)	3000	0.8 (1.8)	1100–1500

[a] The $PM_{2.5}$ concentrations are modeled grid averages and is the concentration due to the emissions from the coal-fired power plants only, which is incremental to pollution from other sources in the region. For these sub-regional domains, the CAMx dispersion modeling was repeated @ grid resolution of 0.1°, equivalent of 10 km. Median and 95th percentile value is based on averages for all the grids in the select sub-regional domain.

[b] This is the estimate for the exposed population in the select geographical sub-region, but the influence of the power plant emissions reaches farther (illustrated in the forward trajectories – Supplementary Material).

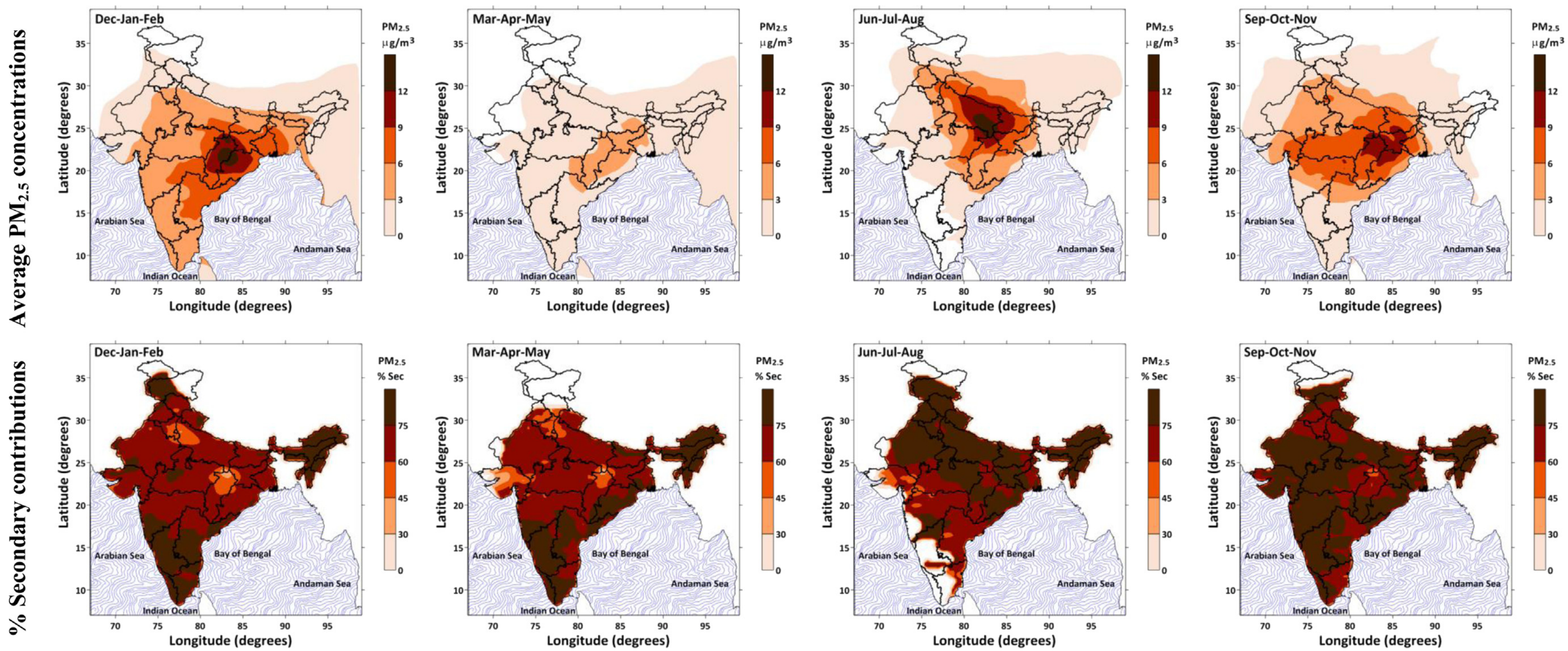

Fig. 4. Dispersion modeling results by season (Dec–Jan–Feb for winter; Mar–Apr–May for spring; Jun–Jul–Aug for summer; and Sep–Oct–Nov for fall) due to the emissions from coal fired thermal power plants in India (a) average $PM_{2.5}$ concentrations (b) percentage contribution of secondary (sulfates and nitrates) aerosols to average $PM_{2.5}$ concentrations by season.

in India. The meteorological conditions have a large variation in the subcontinent between the monsoonal and non-monsoonal months. This variation also affects the dry and wet deposition and the ambient concentrations of various pollutants. In Fig. 4, we present the seasonal average concentrations – Dec–Jan–Feb for winter, Mar–Apr–May for spring, Jun–Jul–Aug for summer, and Sep–Oct–Nov for fall season. The south-west monsoons from the Arabian Sea during the months of April to August tend to push and disperse the emissions upwards and north, while the north-east monsoons from the Bay of Bengal Sea during the months of October to November tend to push and disperse the emissions inland and south resulting in a wider spread of pollution. For the spring season, beginning of the south-west monsoon, strong winds and higher mixing heights were observed (Supplementary Material), which tend to lift the pollution higher into the troposphere, resulting in lower ground concentrations. In the later months, the cloud cover is higher, reducing the mixing heights, and increasing the ground level concentrations. There is much uncertainty in the monsoons and weather patterns that could not only influence the pollution patterns, but also there is growing evidence that the pollution from transport and industrial processes can affect the monsoonal patterns (Corrigan et al., 2006; Lau et al., 2009).

3.2.3. Secondary chemical contributions

The CAMx modeling system includes full gas phase SAPRC chemical mechanism, with gas and aerosol chemical conversions to support secondary particulate pollution assessment. With no FGD systems to control SO_2 emissions at most of the power plants, the secondary contributions are significant. SO_2, once airborne, further interacts with the hydroxyl radicals to form aerosol sulfates. The formation of aerosol nitrates is more complicated due to the involvement of the multiple nitrogen species and numerous chemical reactions with hydroxyl radicals and volatile organic compounds.

The percentage contribution of the secondary aerosols (sulfates and nitrates) to total $PM_{2.5}$ from the coal fired power plants in presented in Fig. 4. The maps are presented by season, Dec–Jan–Feb for winter, Mar–Apr–May for spring, Jun–Jul–Aug for summer, and Sep–Oct–Nov for fall season. The highest secondary contributions were estimated for the summer months. This is partly due to the higher photochemical activities and presence of oxidizing agents, which increase the oxidation of SO_2 and NO_x gases and their conversion rate to sulfates and nitrates.

From the coal-fired power plants, we estimate 30–40% of the PM pollution is secondary in nature, with the most coming from chemical conversion of gaseous SO_2 to aerosol sulfate. Since a majority of the power plants do not operate a dedicated FGD system, most of the SO_2 from coal combustion is emitted and ends up in respirable PM fraction, resulting in more health impacts. In the environmental impact assessment studies, which is required before commissioning any power plant, a provision for a FGD is discussed, but the power plants are not required to operate a FGD. The combined benefits of a FGD in conjunction with the already operational ESPs will have a significant effect on overall health impacts. We believe that FGD technology should become mandatory for all new power plants and a provision should be introduced to implement the same for the larger and older power plants to control SO_2 emissions and to reduce the overall $PM_{2.5}$ concentrations by at least 30–40%.

3.3. Mortality and morbidity estimates

The health impacts are calculated by overlaying the gridding population with the modeled $PM_{2.5}$ pollution from the coal fired power plants. Total premature mortality using for the range of mortality risks ranged between 80,000 and 115,000 per year. The estimated mortality and morbidity cases due to these emissions are summarized in Table 6. Using a conservative value of INR 2,000,000 (approximately USD 40,000) per life lost, based on the average life insurance policy's issued in India, the estimated premature deaths would result in a health cost of INR 16,000 to 23,000 crores (approximately USD 3.2 to 4.6 billion) annually.

In Table 5, we also present the estimated range of premature deaths for the population exposed in the sub-regions. The regions 1 (Delhi–Haryana–Uttar Pradesh) and 6 (West Bengal–Jharkhand–Bihar) are the densest, with average population density above 1000 per km^2, with peaks of more than 10,000 per km^2 in the cities of Delhi (capital of India) and Kolkata (capital of West Bengal). These regions also experience highest risk of exposure. These seven sub-regions account for 40% of the total premature deaths estimated for India.

4. Implications

Coal remains the main fossil fuel for power generation in India. In this study, we isolated the emissions from the coal-fired power plants and estimated a premature mortality rate of 80,000 to 115,000 due to their contribution to the ambient $PM_{2.5}$ concentrations. This number does not include the impacts of the water run-off and soil contamination due to the release of heavy metals. Combined with a strong demand for reliable electricity and consistent shortage in supply, it is doubtful that pollution will be controlled absent strong regulation for the operational 111 coal-fired power plants. There is a vast potential for controlling emissions from these plants and the resultant health impacts. The main conclusions from this analysis are the following

- To date, the pollution standards exist only for ambient air quality and not for individual power plants, which compromises the efforts to control any pollution. Only after standards are regulated at the plant level, can we proceed to the next steps of monitoring and enforcing, and reduce the impact of emissions from coal-fired power plants
- Going forward, coal-fired power plants should be subjected to tighter emission standards, similar to those found in emerging economies (like China) and developed economies (like EU, Australia, and USA). For example, a mandate for installation of FGD systems for the existing 111 coal-fired power plants could reduce the $PM_{2.5}$ concentrations by 30–40%, by eliminating the formation of secondary sulfates and nitrates, and some additional benefits to the primary particulates
- The efficiency improvement of existing older power plants, irrespective of the boiler size, should become a starting point for reducing overall coal consumption and associated atmospheric emissions
- Unlike pollution from the transport or domestic sector, pollution from stacks is a point source – meaning a finite and known

Table 6
Estimated 2010-11 health impacts due to emissions from the coal-fired power plants in India.

Effect	Health impacts
Total premature mortality	80,000 to 115,000
Child mortality (under 5)	10,000
Respiratory symptoms	625 million
Chronic bronchitis	170,000
Chest discomforts	8.4 million
Asthma attacks	20.9 million
Emergency room visits	900,000
Restricted activity days	160 million

number of units releasing emissions. Moreover, with a majority of the power plants operated by the public sector, mandating technologies that reduce pollution would seem to represent a simple solution.

- The stack emissions can be monitored relatively easily as compared to non-point sources (such as vehicles, garbage burning, domestic burning, and fugitive dust). While, the larger power plants are now equipped with continuous stack monitors, this information is not open to public, either for analysis or for scrutiny of the emission loads. This adds to the uncertainty of similar studies. Besides strengthening standards, newer policies are required for dissemination of information from the coal-fired power plants
- The environmental impact assessment procedures need to be revised, in order to include the health and environment damages due to long-range transport of pollution from the stacks, as high as 275 m, and travelling the distances of more than 300 km in less than 24 h. Currently, the procedure require assessment for an area of 50 km radius from the plants

In India, the amount of power generated from coal will remain high at least through 2030 (Prayas, 2011, 2013), and unless a better way is proposed to manage pollution from the coal-fired thermal power plants, the environmental effects and human health costs will be high.

Acknowledgments

This project was supported by a grant from the Conservation Action Trust (Mumbai, India). We thank Mr. Debi Goenka (Director) for his continued support in this research.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2014.04.057.

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