COAL KILLS

An Assessment of Death and Disease caused by India's Dirtiest Energy Source

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Conservation ACTION TRUST

Founded in 2005, the Conservation Action Trust is a non-profit organization dedicated to the protection of the environment through advocacy and action.

5 Sahakar Building, LBS Road, Ghatkopar (West) Mumbai 400 086
T: (91-22) 2512 2422 / 20

www.cat.org.in

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Founded in 2007, Urban Emissions (India) program has four objectives (a) promote the sharing of knowledge base on air pollution analysis (b) analysis based on science (c) advocacy and awareness raising on air quality management and (d) building partnerships among local, national, and international stakeholders.

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#60, Wellington Street, Richmond Town, Bengaluru 560 025.
T: (080) 4282 1010. F: (080) 4115 4862.

www.greenpeaceindia.org

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Written by:
Debi Goenka, CAT <debi@cat.org.in> and Sarath Guttikunda, Urban Emissions
Edited by: Ashish Fernandes, Greenpeace <ashish.fernandes@greenpeace.org>
Design By: Mauli (M) 7738100010 <maulisaburi@gmail.com>
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EXECUTIVE SUMMARY

Globally, it is well established that emissions from coal-fired power are responsible for significant levels of illness and premature death. Whilst comprehensive studies of health impacts caused by particulate air pollution attributable to coal power plants have been carried out in the USA and parts of Europe, such data is hard to come by in India. To address this deficiency, Conservation Action Trust commissioned Urban Emissions to conduct the analysis for this study. Urban Emissions developed estimates of health impacts using a well-established and extensively peer-reviewed methodology based on concentration-response functions established from epidemiological studies. The technical study is appended, starting page 11.

The data in this study is derived from a database of coal-fired power plants compiled by Urban Emissions for the operational period of 2011-12 and takes into account a total of 111 coal-fired power plants representing a generation capacity of 121GW. The pollution impact generated by this fleet of coal plants is summarized below:

Estimated annual health impacts and health costs due to PM pollution from coal-fired power plants in India, 2011-12

Effect	Health impacts	Health costs (crores of Rupees) [a]	Health costs (million USD) [b]
Total premature mortality	80,000 to 115,000	16,000-23,000	3300-4600
Child mortality (under 5)	10,000	2100	420
Respiratory symptoms	625 million	6200	1200
Chronic bronchitis	170,000	900	170
Chest discomforts	8.4 million	170	35
Asthma attacks	20.9 million	2100	420
Emergency room visits	900,000	320	60
Restricted activity days	160 million	8000	1600

a – one crore = 10 million
b – using conversion rate of 1 USD = 50 Rupees

The results of this analysis show that coal is taking a heavy toll on human life across large parts of the country:

- **The study finds that in 2011-2012, emissions from Indian coal plants resulted in 80,000 to 115,000 premature deaths and more than 20 million asthma cases from exposure to total PM10 pollution.**

“POLLUTION FROM COAL PLANTS RESULTED IN 85,000-115,000 PREMATURE DEATHS IN 2011-2012.”

- **The study quantified additional health impacts such as hundreds of thousands of heart attacks, emergency room visits, hospital admissions, and lost workdays caused by coal-based emissions.**
- **The study estimates the monetary cost associated with these health impacts exceeds Rs.16,000 to 23,000 crores (USD $3.3 to 4.6 billion) per year.**

This burden is not distributed evenly across the population. Geographically, the largest impact is felt over the states of Delhi, Haryana, Maharashtra, Madhya Pradesh, Chhattisgarh, the Indo-Gangetic plain, and most of central India. Demographically, adverse impacts are especially severe for the elderly, children, and those with respiratory disease. In addition, the poor, minority groups, and people who live in areas downwind of multiple power plants are likely to be disproportionately exposed to the health risks and costs of fine particle pollution.

These impacts are likely to increase significantly in the future if Indian policymakers do not act. At approximately 210 GW, India has the fifth largest electricity generation sector in the world of which 66% comes from coal.[1] Current plans envision deepening this reliance with 76GW planned for the 12th Five Year Plan (2012-2017) and 93GW for the 13th Five Year Plan (2017-2022). The majority of planned capacity additions are coal-based and according to government projections, coal's share in the Indian electricity mix will remain largely constant. Very few require modern pollution control technologies that would significantly reduce health impacts.

Given the significant impacts associated with coal fired power plants it is important that the Indian public, and its policymakers, are well informed. This report is the first attempt to provide policymakers objective information on the morbidity and mortality caused by coal plants in India. The data represents a clarion call to action to avoid the deadly, and entirely avoidable, impact this pollution is having on India's population.

Bhagwat Saw, 69, in the emergency room at Life Line Hospital, Jharia. Bhagwat has been working as a coal loader for over 40 years and is suffering from pneumoconiosis.
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THE LINK BETWEEN POLLUTION FROM COAL-FIRED POWER PLANTS AND HUMAN HEALTH

The direct link between emissions (from transport, power plants, household cookstoves, industries, and fugitive dust), outdoor air pollution, and human health has been extensively documented.[2] Most notable of the health impacts resulting in premature deaths include chronic obstructive pulmonary disease, lower respiratory infections, cerebrovascular disease, ischemic heart disease, and cancers of trachea, bronchitis, and lung. Of all the pollutants, the public health concerns in India are focused on PM that contributes to a host of respiratory and cardiopulmonary ailments and increasing the risk of premature death. Epidemiological studies conducted in India (Delhi and Chennai) under the Public Health and Air Pollution in Asia (PAPA) programme also highlighted the linkages between outdoor air pollution and premature mortality, hospital admissions, and asthma cases.[3]

The morbidity and mortality burden is particularly costly for governments in terms of work days lost, lost productivity, and loss in terms of gross domestic product. Since most PM related deaths occur within a year or two of exposure, reducing PM pollution from sources like transport and power plants has almost immediate benefits for health and the national economy.

Fine particles are especially dangerous because, once inhaled, they can lodge deep in the human lung. Research indicates that short-term exposures to fine particle pollution are linked to cardiac effects, including increased risk of heart attack.[4] Long-term exposure to fine particle pollution has also been linked to an increased risk of death from lung cancer and cardiac and respiratory diseases. Cumulatively, this results in lower life-expectancy for residents of more polluted cities as against those residing in cleaner cities.[5]

“GIVEN COAL POWER EXPANSION PLANS, THE BURDEN OF DEATH AND DISEASE IS LIKELY TO INCREASE SIGNIFICANTLY IN COMING YEARS IF POLICY MAKERS DO NOT ACT.”

Anpara thermal power plant on the outskirts of Dibulganj, Uttar Pradesh.
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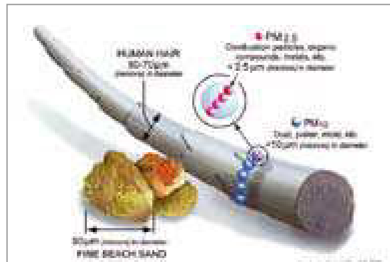
Adverse effects of fine particle pollution occur even at low ambient concentrations, suggesting there is no "safe" threshold.[6] (REF-9) Studies have also identified plausible biological mechanisms such as systemic inflammation, accelerated atherosclerosis, and altered cardiac function to explain the serious health impacts associated with exposure to fine particles.[7] Because most fine particle-related deaths are thought to occur within a year or two of exposure, reducing power plant pollution will have almost immediate benefits.[8]

Given the country's dependence on coal for electricity, and the absence of effective pollution controls, persistently elevated levels of fine particle pollution are common across large parts of the country, particularly in Central and Northern India.



WHAT ARE FINE PARTICLES?

Fine particles are a mixture of pollutants such as soot, acid droplets, heavy metals etc that originate primarily from combustion sources such as power plants, diesel trucks, buses, and cars. Fine particles are referred to as "PM2.5" or particulate matter smaller than 2.5 microns (2.5 millionths of a meter in diameter – less than one-thirtieth the width of a human hair). Fine particles are either soot emitted directly from these combustion sources or formed in the atmosphere from sulphur dioxide (SO2) or nitrogen oxide (NOx) emissions. The smallest fine combustion particles are of the gravest concern because they are so tiny that they can be inhaled deeply, evading the human lung's defences and be absorbed into the blood stream and transported to vital organs.

Power plants in Singrauli region.
© Greenpeace / Sudhanshu Malhotra

METHODOLOGY

To analyze adverse health impacts from current levels of power plant emissions in India, we estimated emission data and applied methodologies which have been extensively peer-reviewed. An estimate of emissions based on plant and fuel characteristics was necessary as India has no continuous and open emission monitoring data available at the plant level, making enforcement of what standards do exist nearly non-existent.

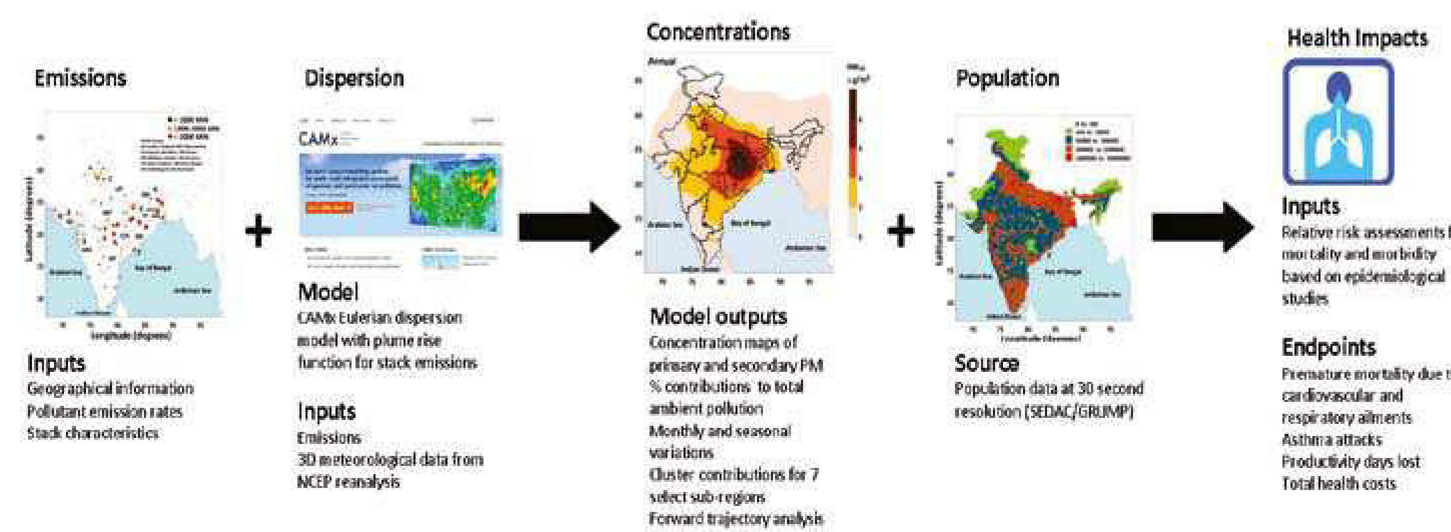
For each plant, the CEA database includes annual coal consumption rate, total emissions, number of stacks per plant, and stack parameters like location in longitude and latitude, suitable for atmospheric dispersion modelling. The total emission rates are calculated based on the boiler size, coal consumption rates, and control equipment efficiencies, which is collected from thermal power plant performance reports published by CEA.

The dispersion modelling was conducted utilising the ENVIRON - Comprehensive Air Quality Model with Extensions (CAMx) version 5.40 and meteorological data (3D wind, temperature, pressure, relative humidity, and precipitation fields) from the National Center for Environmental Prediction (NCEP Reanalysis) to estimate incremental changes in the ambient pollutant concentrations due to the presence of coal-fired power plants in the region.

We estimate the health impacts based on concentration-response functions, based on methodology applied for similar studies such as for the GBD assessments for 2010[9] and 2000[10]; for health impacts of urban air pollution in the cities of Santiago, Mexico city, and Sao Paulo[11]; and for benefits of better environmental regulations in controlling pollution from coal fired power plants in India.[12]

We also estimate morbidity in terms of asthma cases, chronic bronchitis, hospital admissions, and work days lost. The concentration-response functions for morbidity are extracted from Abbey et al.[13] and Croitoru et al.[14] The health impacts are calculated for the base year 2010, by overlaying the gridding population with the modeled PM_{10} 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 value of statistical life is established from surveys based on "willing to pay" by individuals for benefits associated with the health impacts. This methodology has been applied in a number of countries and cities.[15] The health costs based on value of statistical life is an uncertain estimate that has a range depending on methods. Using a conservative value of 2,000,000 Rupees (40,000 USD) per life



lost, the premature mortality estimates from this study would result in a health cost of 16,000 to 23,000 crores Rupees (USD 3.2 to 4.6 billion) annually.

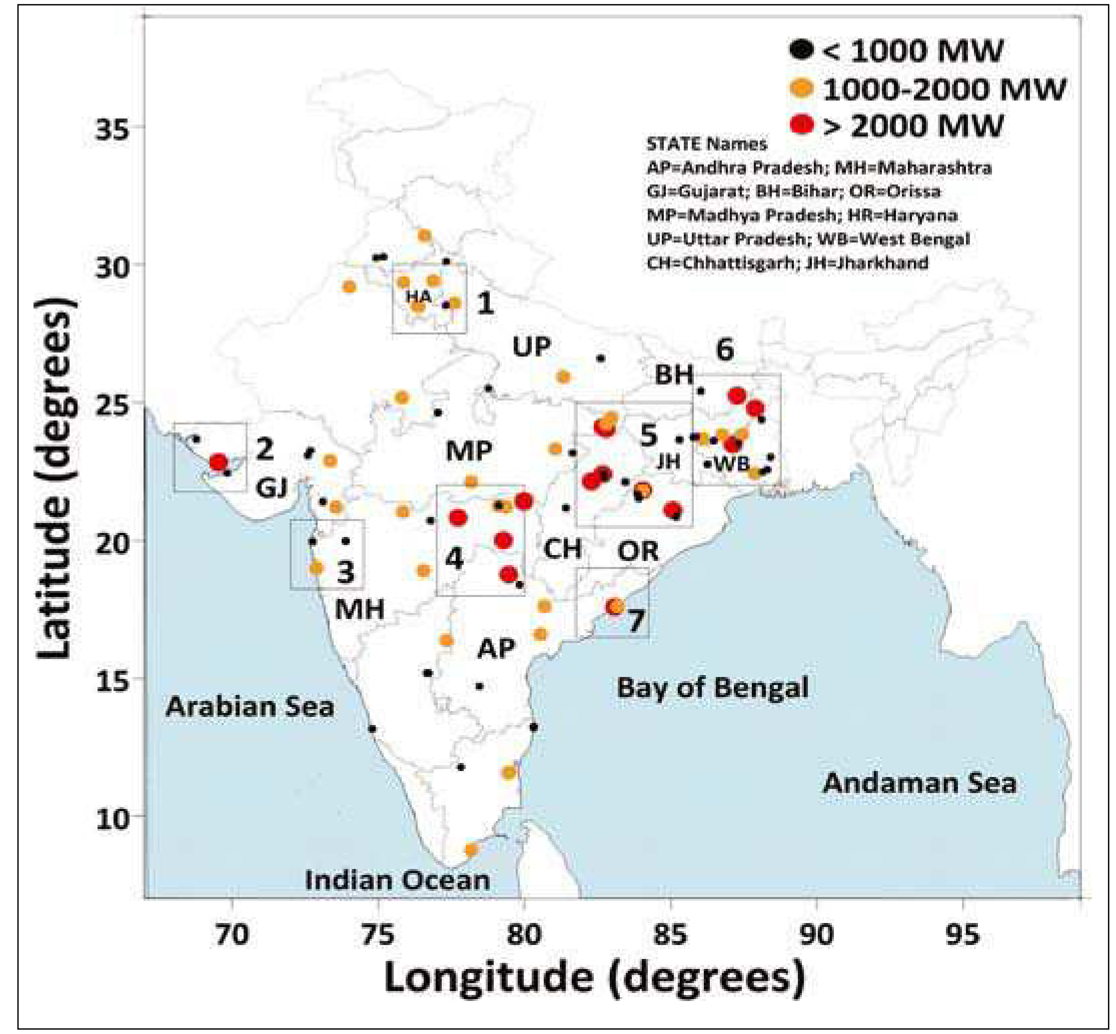
In table below, we also present the estimated range of premature deaths for the population exposed in the sub-regions. The regions 1 (Delhi-Haryana-UP) and 6 (WB-JH-BH) are the densest, with average population density above 1000 per sq. km, with peaks of more than 10,000 per sq. km. in the cities of Delhi (capital of India) and Kolkata (capital of WB). These regions also experience highest risk of exposure. These seven sub-regions account for 40% of the total premature deaths estimated for India.

Installed capacity, modeled daily average PM_{10} concentrations, health impacts of emissions from coal fired power plants for 7 regions at finer resolution in India in 2011-12

No.	Cluster (size in degrees)	Regional features	No. of plants (those more than 1000MW)	Installed capacity (MW)	Modeled PM_{10} [a] - median (95th percentile) µg/m³	Estimated premature mortality within the region [b]
1	Delhi – Haryana	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° x 2.5°)	Two super-critical power plants are commissioned 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° x 2.5°)	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° x 4.0°)	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° x 4.5°)	This the densest cluster region of the seven covering 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° x 4.0°)	This is the second densest cluster region covering clusters in 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° x 2.5°)	Another coastal cluster including the port city of Vishakhapatnam	2 (2)	3000	0.8 (1.8)	1100-1500

a - the PM_{10} concentrations are modeled grid averages – grid resolution is 0.1°, equivalent of 10km
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 – **Figure10**)

Figure 2 shows how these health risks and costs are distributed geographically. Those areas with the highest concentration of coal plants bear a disproportionate share of the aggregate burden of adverse impacts. Similarly, metropolitan areas with large populations near coal-fired power plants feel their impacts most acutely. In larger metropolitan areas, many hundreds of lives are shortened each year at current levels of power plant pollution.



CONCLUSION: THE NEED FOR ACTION

The shocking figures of sickness, premature mortality (and the resulting financial costs) attributable to coal-fired power plants in India demonstrates the need to implement long overdue pollution control regulations. These include mandating flue gas desulphurization and introduction/tightening of emission standards for pollutants such as SO2 and NOx. India's emission standards for power plants lag far behind those of China, Australia, the EU and the USA

Equally if not more important is the need to update the procedures for environment impact assessments for existing and newer plants to take into account the human health toll from coal emissions. Also necessary are measures to ensure that these norms and standards are actually adhered to, with deterrents for non-compliance.

The unacceptably high annual burden of death and disease from coal in India points to the need for significantly stronger measures to control coal-related pollution. Without a national commitment to bring emission

“INDIA’S EMISSIONS STANDARDS LAG BEHIND CHINA, THE US, EU AND AUSTRALIA. HUNDREDS OF THOUSANDS OF LIVES AND CRORES OF RUPEES COULD BE SAVED WITH CLEANER FUELS, STRICTER EMISSIONS STANDARDS AND EMISSION CONTROL TECHNOLOGIES.”

standards on par with other world leaders, deploy the most advanced pollution control technologies, implement cost-effective efficiency improvements, and increase the use of inherently cleaner sources of electricity, the Business As Usual Scenario will ensure that hundreds of thousands of lives will continue to be lost due to emissions from coal power plants. Any attempts to weaken even the current environmental regulations will add to this unfolding human tragedy.

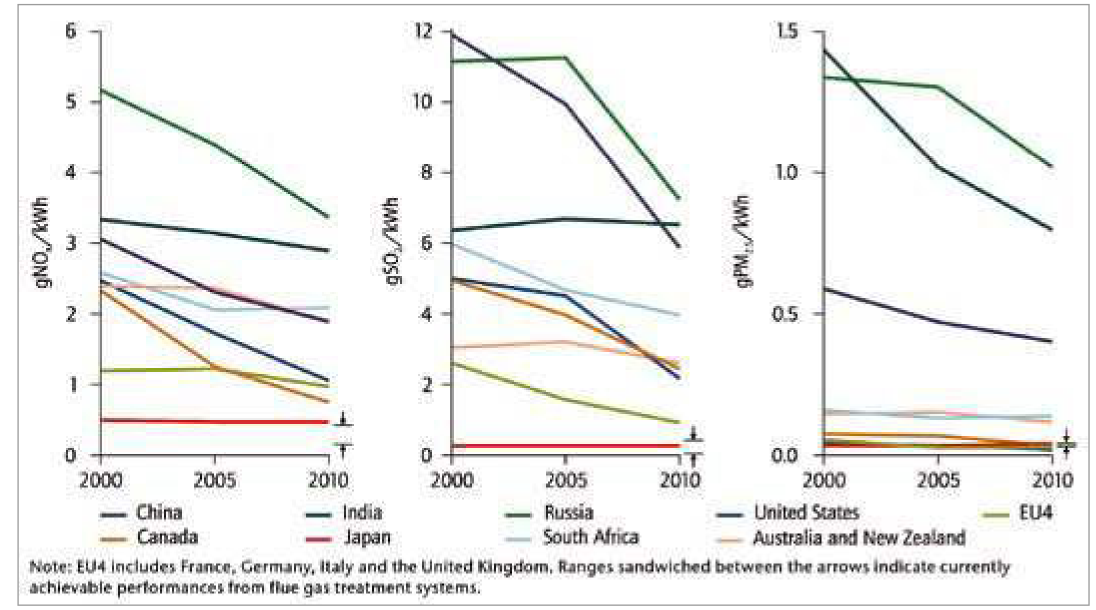
Hundreds of thousands of lives could be saved, and millions of asthma attacks, heart attacks, hospitalizations, lost workdays and associated costs to society could be avoided, with the use of cleaner fuels, stricter emission standards and the installation and use of the technologies required to achieve substantial reductions in these pollutants. These technologies are both widely available and very effective.

Cleaning up our nation’s power sector by strengthening and finalizing stringent emission standards, as well as by reducing mercury and other toxics would provide a host of benefits – prominent among them the longevity of crores of Indians – and would help propel the nation to a healthier and more sustainable energy future.

Summary of emission standards for coal-fired power plants

Country	PM	SO_2	NO_2	Mercury
India [a]	350mg/Nm³ for <210MW 150mg/Nm³ for >210MW	None	None	None
China [b]	30mg/Nm³ (proposed all) 20mg/Nm³ for key regions 50mg/Nm³ for key regions	100mg/Nm³ for new 200mg/Nm³ for old	100mg/Nm³	None
Australia [c]	100mg/Nm³ for 1997-2005 50mg/Nm³ after 2005 standards	None	800mg/Nm³ for 1997-2005 500mg/Nm³ after 2005	In discussion based on USA
European Union [c]	Pre-2003 100mg/Nm³ for <500MW 50mg/Nm³ for >500MW Post 2003 50mg/Nm³ for <100MW 30mg/Nm³ for >100MW	Pre-2003 Scaled for <500MW 400mg/Nm³ for >500MW Post 2003 850mg/Nm³ for <100MW 200mg/Nm³ for >100MW	Pre-2003 600mg/Nm³ for <500MW 500mg/Nm³ for >500MW Post 2003 400mg/Nm³ for <100MW 200mg/Nm³ for >100MW	In discussion
USA [c,d]	37 mg/Nm³ for new 6 mg/Nm³ for old	245 mg/Nm³ for new 50 mg/Nm³ for old	61 mg/Nm³ for new 42 mg/Nm³ for old	
USA [c,e]	6.4 gm/GJ	640 gm/MWh 720 gm/MWh for old	450 gm/MWh for new 0.01 gm/MWh for IGCC	0.08 gm/MWh for lignite

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/Nm³ based on assumed plant efficiency;
e – in official units; for mercury this is based on 12 month rolling average



Source: IEA 2012. Technology Roadmap, High Efficiency, Low Emissions Coal Fired Power Generation.

End Notes:

[1] http://cea.nic.in/reports/yearly/energy_generation_11_12.pdf

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KEY MESSAGES

- 66% of India's power generation is coal-fired. The vast majority of capacity additions planned are also coal-based - the 12th five year plan (2012-2017) specifies a total addition of 76GW and the 13th five year plan (2017-2022) is for 93GW.
- In 2011-12, particulate emissions from coal-fired power plants, resulted in an estimated 80,000 to 115,000 premature deaths and more than 20 million asthma cases, which cost the public and the government an estimated 16,000 to 23,000 crores Rupees (USD 3.2 to 4.6 billion). The largest impact of these emissions is felt over the states of Delhi, Haryana, Maharashtra, Madhya Pradesh, Chhattisgarh, Indo-Gangetic plain, and most of central-east India
- Besides the emissions from the stack, fugitive dust from coal-handling units and ash ponds (after the disposal from the plants) is of concern, particularly given the expected increase in coal-fired power plants
- The forward trajectory analysis, using 3-dimensional meteorology, of emissions released at the stacks show that the impacts can be observed farther than 50-100km from the source region, increasing not only ambient concentrations at these receptor points, but also the morbidity and mortality risk. Additional impacts include deposition of heavy metals and sulphur oxides on agriculture through dry and wet deposition. The environmental impact assessments necessary for commissioning power plants should include long-range transport to account for these impacts.
- The secondary contributions from sulphur dioxide and nitrogen oxides emissions to the total fine particulate matter (with aerodynamic size less than 2.5 micron) varies from 30-60% over Madhya Pradesh, Chhattisgarh, and most of central-eastern India. This is primarily due to lack of flue gas desulfurization units for most power plants. A mandate to implement this for all new and existing power plants will immediately result in lower ambient particulate pollution, with related health benefits. An added important benefit will be a reduction in the deposition of these substances over rich agricultural lands.
- To date, pollution standards exist for ambient air quality only and not for individual power plants, which compromises monitoring and enforcement efforts. Only after standards are set and regulations mandated at the plant level can we proceed to the next steps of monitoring and enforcing policy, so as to have reduce negative environment and health impacts due to coal fired power plants.
- For particulate matter emissions, the emission standards in India lag behind those implemented in China, Australia, the United States and the European Union. For other key pollutants like sulphur dioxide, nitrogen oxides and mercury, there are no prescribed emission standards in India.
- There is also no open and continuous emission monitoring data available at the plant level. This renders nearly non-existent the enforcement of what standards do exist.
- The way forward is (a) to revise the emission standards for coal power plants for particulates and introduce new emission standards for other pollutants (b) introduce continuous monitoring at the plant stacks, such that the data is in the public domain in real time and (c) enforce the standards with improved impact assessment methods with human health as the primary indicator

COAL BASED THERMAL POWER PLANTS IN INDIA – AN ASSESSMENT OF ATMOSPHERIC EMISSIONS, PARTICULATE POLLUTION, AND HEALTH IMPACTS

Sarath K. Guttikunda [a],* and Puja Jawahar [a]

[a] UrbanEmissions.Info, New Delhi, India

*Corresponding author; E-mail – sguttikunda@urbanemissions.info

ABSTRACT

Access to electricity is a basic requirement to support a growing economy. Currently coal accounts for 41% of the world's electricity generation. At approximately 210 GW, India is the 5th largest generator of electricity in the world and will increase in the future. Currently, 66% of this power generation capacity is derived from coal with the vast majority of capacity additions planned - the 12th five year plan (2012-2017) includes an addition of 76GW and the 13th five year plan (2017-2022) includes 93GW. Emissions from coal-fired power are responsible for a large mortality and morbidity burden on human health and this paper assesses the health burden of emissions from India's coal fired power plants. In 2011-12, 111 coal-fired power plants with a total generation capacity of 121GW, consumed 503 million tons of coal, and generated an estimated 580 ktons of particulates with diameter less than 2.5 µm, 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 annually. These emissions resulted in 80,000 to 115,000 premature deaths and more than 20.0 million asthma cases from exposure to total PM10 pollution in 2011-2012, which cost the public and the government an estimated 16,000 to 23,000 crores of Rupees (USD 3.2 to 4.6 billion). The largest impact of the coal-fired power plant emissions is felt over the states of Delhi, Haryana, Maharashtra, Madhya Pradesh, Chhattisgarh, Indo-Gangetic plain, and most of central-east India. The dispersion modeling of emissions was conducted using CAMx Eulerian model coupled with plume rise functions for the point sources and meteorological data from the NCEP reanalysis dataset. 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 the procedures for environment impact assessments for existing and newer plants, are imperative to reduce health impacts.

KEYWORDS: Dispersion modeling; emissions inventory; CAMx; plume rise equation; mortality; environmental regulations

1.0 POWER GENERATION IN INDIA

Access to electricity is necessary to support developing economies. Currently coal accounts for 41% of the world's electricity generation **(IEA, 2012)**. At approximately 210 GW, India has the 5th largest electricity generation sector in the world (captive power plants generate about 31 GW more) with targets of 76GW of addition in the 12th five year plan (2012-2017) and 93GW for the 13th five year plan **(Prayas, 2011; Prayas, 2013)**. Thermal power plants account for 66% of generation, hydro for 19% and the remaining 15% from other sources including natural gas and nuclear energy. Coal became the fuel of choice because of its availability, especially during the oil crisis of the 1970's when indigenous coal was a relatively cheap source of energy. The government nationalized coal mines between 1970's and set up coal-based power plants close to major mines to reduce the costs of transporting coal to power plants. Coal accounts for 50-55% of the power generation in India and for various reasons discussed below – is only going to get larger in the coming years **(Chikkatur et al., 2011; WISE, 2012; Prayas, 2013)**.

In India, the supply of electricity lags behind the demand from a growing population and economy. Despite that, India is the 4th largest consumer of electricity in the world. According to the Central Electricity Authority (CEA), in 2010-11, of the 122 GW demand for electricity, only 110 GW was supplied – which amounted to a shortfall of 10%. 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 deal with frequent power cuts and load shedding **(CEA, 2012)**.

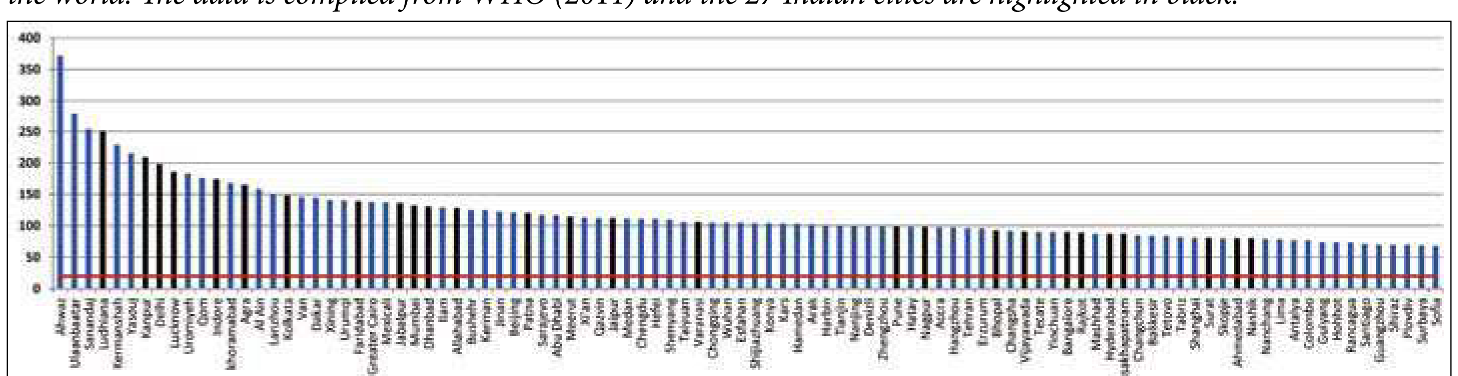
Coal-fired power comes with significant costs to environment and human health. The water runoff from coal washeries carries pollution loads of heavy metals that contaminate ground water, rivers, and lakes - thus affecting aquatic flora and fauna **(Finkelman, 2007)**. Fly-ash residue and pollutants settle on soil contaminating areas 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. Chronic and acute exposure to these pollutants has health impacts that include respiratory illnesses, compromised immune systems, cardiovascular conditions, and premature death **(HEI, 2004 and 2010)**.

The global burden of disease (GBD) for 1990-2010 quantified the trends of more than 200 causes of deaths and listed outdoor air pollution among the top 10 causes of deaths for India **(Lancet, 2012)**. For India, total premature mortality due to outdoor particulate matter (PM) pollution is estimated at 627,000. This GBD assessment utilized a combination of ground measurements (where available) from the cities and substituted the remaining urban and rural area with data retrieved from satellite measurements for PM2.5 pollution (Van Donkelaar et al., 2010). $PM_{2.5}$ refers to particulate matter less than 2.5µm in aerodynamic diameter. The World Health Organization (WHO) studied publicly available air quality data from 1100 cities and listed 27 cities in India among the top 100 cities with the worst air quality in the world (WHO, 2011). The ambient PM_{10} measurements available between 2008 and 2010 for the top 100 cities with the worst air quality are presented in **Figure 1**; with Ludhiana, Kanpur, Delhi, and Lucknow listed in the top 10 cities. PM_{10} refers to particulate matter less than 10µm in aerodynamic diameter.

A number of emissions modeling studies have been conducted and published for the transport sector, with improvements in understanding the vehicle registrations numbers, vehicle movement on the road, on-road emission factors for ambient pollutants, total emissions, and exposure assessments **(Baidya and Borken-Kleefeld, 2009; Ramachandra and Shwetmala, 2009; Schipper et al., 2009; CPCB, 2010; Arora et al., 2011; Apte et al., 2011; Yan et al., 2011; Grieshop et al., 2012; Sahu et al., 2012; Wagner et al., 2012)**, but only a few studies have been conducted and published for the power sector in similar detail. Existing studies focus on the coal usage trends, resource management, greenhouse gases, and innovation in use of renewable energy **(Chikkatur and Sagar, 2009; Chikkatur et al., 2011; Prayas, 2011; Chaurdary et al., 2012; IEA, 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, 2010). 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 pollution dispersion of emissions from the power plants.

Given the plans to greatly expand the contribution of coal to the Indian power sector, it is vital that decision makers understand the hidden costs of air pollution from coal fired power plants. Technology exists that may not eliminate the pollution in entirety, but will reduce emissions so as to minimize the health impacts. In this paper, we present an updated list of coal-based power plants operational in 2011-12, their generation capacities, coal consumption, and evaluation of the impacts of PM, SO_2, and NO_x, emissions on ambient pollution via dispersion modeling. We also discuss the current environmental regulation for various pollutants and their implication on health impacts.

***Figure 1:** Ambient PM10 measurements between 2008 and 2010 for the top 100 cities with the worst air quality in the world. The data is compiled from WHO (2011) and the 27 Indian cities are highlighted in black.*



2.0 ATMOSPHERIC EMISSIONS

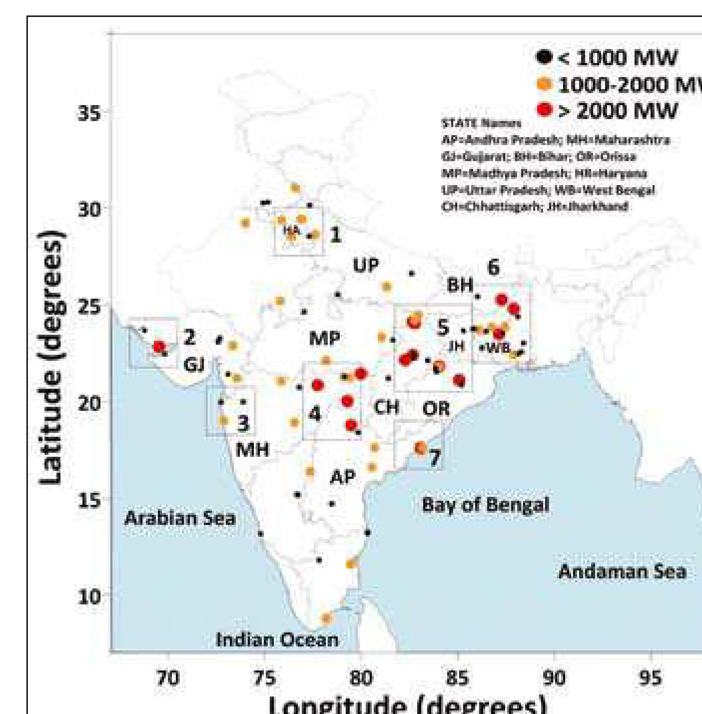
2.1 Coal based power plants in India

The public sector operates most of the existing coal-fired power plants in India. The public sector entity - National Thermal Power Corporation (NTPC) was established in 1975 to accelerate the installation of pithead coal power plants and to supply to regional grids - installed capacity of coal power grew at an average annual rate of 8% in the 1970s and at 10% in the 1980s. **(Chikkatur and Sagar, 2009; CEA, 2011; CEA, 2012; WISE, 2012; Prayas, 2013).**

We used the list of thermal power plants documented by CEA (http://www.cea.nic.in) as a starting point for building our database of operational coal-fired power plants in the country **(CEA, 2011; CEA, 2012)**. We updated this database for 2011-12 representing a total generation capacity of 121GW. We also include in the database, geographical location in latitude and longitude, number of boiler units and size of all known power plants operated by both public and private entities. The power plant characteristics by state are presented in **Table 1**. This data was gathered from websites and annual reports of the state electricity boards for public and private sectors. The public sector entities include - National Thermal Power Corporation; Indraprastha Power Generation Company; Haryana Power Generation Corporation; Punjab State Power Corporation; Rajasthan Rajya Vidyut Utpadan Nigam; Uttar Pradesh Rajya Vidyut Utpadan Nigam; Gujarat State Electricity Corporation; Madhya Pradesh Power Generation Company; Chhattisgarh State Power Generation Company; Maharashtra State Electricity Board; Andhra Pradesh Power Generation Corporation; Karnataka Power Corporation; Tamil Nadu Electricity Board; The West Bengal Power Development Corporation; Orissa Power Generation Corporation; and Calcutta Electric Supply Corporation. The private sector entities include – Jindal Power; CPL India; Azure India; Adani Power; Reliance Power; and Tata Power.

Figure 2 is a map of the coal fired power plants in India. 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. A few 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, in Chennai (Tamilnadu) and Ahmedabad (Gujarat), each host two coal based power plants of more than 1000MW electricity generation and both of them are 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 based power plants of 2000MW generation capacity **(Guttikunda and Goel, 2013)**. In 2010, the Ministry of Environment and Forests (MoEF) published the results of a source apportionment study for six cities in India (Bangalore, Chennai, Delhi, Kanpur, Mumbai, and Pune), with information on the contributions of local transport, domestic, industrial, and power sectors to the ambient pollution **(CPCB, 2010)**. For cities like Delhi, Chennai, Mumbai, Ahmedabad, Kolkata, and some medium to smaller size cities like Nagpur, Raipur, Ranchi, Kota, Bhatinda, Raichur, with power plants in the vicinity of 100km, do measure significant (5-30%) ambient contributions from these point sources.

***Figure 2:** Geographical location of the operational coal-based public and private power plants in India in 2012*



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 lesser than those observed in the United States (1.0 to 1.8%) and Chinese coals (0.5 to 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 one 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, which reduces the collection efficiency of electrostatic precipitators. 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 compliance with this mandate has been uncertain due to lack of continuous monitoring.

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 (**MoC, 2006**). Another disincentive to use good quality coal is inadequacy of grading systems for differential pricing (**Chikkatur, 2008**). In 2005, about 110MT 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**). In India, approximately 13% of the fly ash byproduct is used for brick manufacturing and other construction activities.

2.3 Total Emissions and Regulations

In India, even though 55% of the installed capacity is based on coal, there is a conspicuous lack of regulations for power plant stack emissions. China, the United States, the European Union (EU) and Australia have stronger regulations for a variety of pollutants that affect human health (**Table 2**). There is also no continuous and open emission monitoring data available at the plant level. The latter makes enforcement of what standards do exist, nearly non-existent.

Table 1: Summary of annual coal consumption at the power plants in India in 2011-12

STATE	Number of plants	MW	Coal million tons	kg coal/kwh 2006-07	% installed units <210MW
Andhra Pradesh	8	10,523	47.4	0.72	65%
Bihar	3	2,870	10.2	0.94	77%
Chhattisgarh	8	9,480	44.5	0.72	39%
Delhi	2	840	4.8	0.77	100%
Gujarat	11	14,710	55.9	0.65	69%
Haryana	5	5,860	23.9	0.70	35%
Jharkhand	6	4,548	12.0	0.75	86%
Karnataka	5	3,680	14.6	0.69	64%
Madhya Pradesh	4	6,703	33.1	0.79	79%
Maharashtra	13	17,560	71.5	0.73	51%
Orissa	8	8,943	40.7	0.73	76%
Punjab	3	2,620	13.2	0.66	82%
Rajasthan	4	3,490	13.2	0.67	44%
Tamilnadu	8	6,210	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%**

Table 2: Summary of emission standards for coal-fired power plants

Country	PM	SO_2	NO_2	Mercury
India [a]	350mg/Nm³ for <210MW 150mg/Nm³ for >210MW	None	None	None
China [b]	30mg/Nm³ (proposed all) 20mg/Nm³ for key regions 50mg/Nm³ for key regions	100mg/Nm³ for new 200mg/Nm³ for old	100mg/Nm³	None
Australia [c]	100mg/Nm³ for 1997-2005 50mg/Nm³ after 2005 standards	None	800mg/Nm³ for 1997-2005 500mg/Nm³ after 2005	In discussion based on USA
European Union [c]	Pre-2003 100mg/Nm³ for <500MW 50mg/Nm³ for >500MW Post 2003 50mg/Nm³ for <100MW 30mg/Nm³ for >100MW	Pre-2003 Scaled for <500MW 400mg/Nm³ for >500MW Post 2003 850mg/Nm³ for <100MW 200mg/Nm³ for >100MW	Pre-2003 600mg/Nm³ for <500MW 500mg/Nm³ for >500MW Post 2003 400mg/Nm³ for <100MW 200mg/Nm³ for >100MW	In discussion
USA [c, d]	37 mg/Nm³ for new 6 mg/Nm³ for old	245 mg/Nm³ for new 50 mg/Nm³ for old	61 mg/Nm³ for new 42 mg/Nm³ for old	
USA [c, e]	6.4 gm/GJ	640 gm/MWh 720 gm/MWh for old	450 gm/MWh for new 0.01 gm/MWh for IGCC	0.08 gm/MWh for lignite

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/Nm³ based on assumed plant efficiency;
e – in official units; for mercury this is based on 12 month rolling average

For 2011-12, we estimated the annual emissions at 580 ktons for $PM_{2.5}$, 1200 ktons for PM_{10}, 2100 ktons of SO_2, 2000 ktons of NOx, 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 3.** For each plant in the state, the database includes annual coal consumption rate, total emissions, number of stacks per plant, and stack parameters like location in longitude and latitude, suitable for atmospheric dispersion modeling. 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 published by CEA.

All the stack emissions at the power plants are monitored and regulated as concentrations only and not in terms of total emissions per plant. For example, for PM, the plants with generation capacity more than 210MW, the concentration limit in the flue gas is 150 mg/Nm³ and for the plants with generation capacity of less than 210MW, the limit is 300 mg/Nm³. These limits are much higher than the currently practiced limits in Australia, China, USA, and EU. The limit for the smaller plants can be reverted to 150 mg/Nm³, 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 210MW 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 210MW and these units tend to have the worst net efficiency and plant load factor. The newer plants are mostly 500MW or higher with the best net efficiency of more than 33% (**CEA, 2012**). Hence, efficiency improvement of existing older power plants and tightening of emission standards for all sizes should become a critical component for reducing the coal consumption and atmospheric emissions. Differential emission regulations also tend to result in use of control equipment with low efficiency and higher emissions.

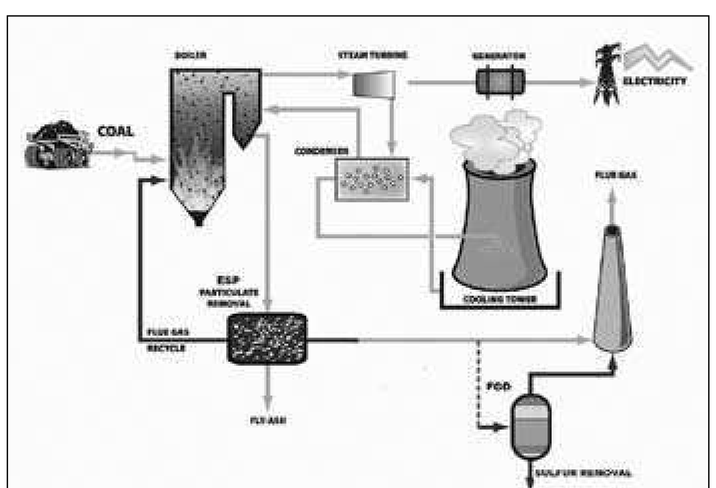
Particulate matter (PM) is the only pollutant for which any pollution controls are widely used in India. A schematic of a coal-fired power plant is presented

Table 3: *Total annual emissions (rounded) from coal based power plants in India in 2011-12*

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	9,500	62.8
Bihar	15,500	31,000	43,000	39,500	22,500	2,500	13.5
Chhattisgarh	39,000	84,000	187,000	172,500	97,500	9,000	58.9
Delhi	7,500	14,500	20,500	20,000	11,000	1,000	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	5,000	31.7
Jharkhand	15,500	31,500	50,500	48,500	26,500	2,500	15.9
Karnataka	17,500	36,000	61,500	58,500	32,000	3,000	19.4
Madhya Pradesh	49,500	100,000	139,500	130,500	73,000	7,000	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	8,500	53.9
Punjab	16,500	34,000	56,000	53,000	29,000	3,000	17.5
Rajasthan	14,500	30,000	55,500	52,000	29,000	3,000	17.5
Tamilnadu	36,500	74,000	108,500	104,500	56,500	5,500	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	7,500	47.8
Total	**580,000**	**1,200,000**	**2,100,000**	**2,000,000**	**1,100,000**	**100,000**	**665.4**

in **Figure 3** 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 (ESP and cyclone bag filters) for removal of entrained ash. Electrostatic precipitators (ESPs) are installed in all coal-fired power plants. 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 (10µm or less). **Lu et al. (2010)**

Figure 3: *Simplified schematics of coal-fired power plant operations*



measured fractions of 50-60% $PM_{2.5}$ and 90-95% PM_{10} in the total filterable PM in the flue gas at a 660MW 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 ESP 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 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. It is assumed that the remaining ash is dispersed from the stacks. In 2003, an amendment notification from MoEF mandated 25% bottom ash in all brick kilns within 100km radius of any coal based thermal power plant and all building construction within 100km for any coal based thermal power plant to use 100% ash based bricks, blocks, and tiles. To date percentage of ash utilized in the construction industry is low.

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 SO2 in the flue gas through industrial processes **(Figure 3)**. Presence of FGD at the plants 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 500MW to build a stack of 275m; those between 210MW and 500MW to build a stack of 220m; and those with less than 210MW to build a stack based on the estimated SO2 emissions using a thumb rule of height = $14*(Q)^{0.3}$ where Q is the estimated SO_2 emissions rate in kg/hr. The stack heights for old and new power plants ranged between 150m and 275m.

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

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 this inventory and our study is in the database of plants, which we 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, 2010)**. 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 performance evaluation of the thermal power plants, the emissions for total suspended PM in mg/Nm3 **(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 based power plants in and surrounding Delhi metropolitan area, 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 110kons/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.

We summarized the regional emission factors for the coal based power plants in **Table 4** in both tons/PJ and tons/hr. The latter is for comparisons with any data available from the online monitoring. Previously published studies are regional estimates either for all of India as one and in general for the power plants in Asia, and most are estimated for the base year 2000-05 and prior. A serious lack of availability of the data from the continuous monitoring at the power plants, for all pollutants, results in these high ranges of estimates and uncertainty in

Table 4: Regional emission factors database

Resource	Base year	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC
This study [a, 1]	2011-12	49-68	90-138	174-192	177-189	100	9
Streets et al. (2003) [1]	2000			400-762	219-562		
GAINS (2010) (base) [b, 1]	2000-05	53-261	18-374	69-1380	100-270		1-15
GAINS (2010) (controlled) [c, 1]	2000-05	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]	2011-12	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]	2004-05		0.7-1.1	4.0-5.0	1.2-1.8		

1 – units: tons/PJ
2 – units: tons/hr
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 emission factors. The overall uncertainty in the total emission estimates is ±30%, 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.

3.0 ATMOSPHERIC DISPERSION

3.1 Study Domain

For the dispersion modeling and health impacts analysis of emissions from coal based power plants, we selected the study domain ranging from 7° to 39° in latitudes and 37° to 99° in longitudes at 0.25° horizontal resolution. The vertical resolution of the model extends to 12km stretched over 23 layers with the lowest layer designated at 50m and six layers with 1km to advance vertical advection closer to the ground level. The geography of the study domain is presented in **Figure 2,** along with the location of the power plants and their generation capacity.

3.2 Dispersion Model

We utilized the ENVIRON - Comprehensive Air Quality Model with Extensions (CAMx) version 5.40, an Eulerian photochemical dispersion model, suitable for integrated assessments of gaseous and particulate air pollution over many scales ranging from sub-urban to continental. This model unifies all the necessary technical features of a "state-of-the-science" air quality model into a single open-source system that is computationally efficient, easy to use, and publicly available (http://www.camx.com). The model utilizes full gas phase SAPRC chemical mechanism (**Carter, 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 of **Zhang et al. (2001; 2003)** with 26 landuse patterns and wet deposition due to predominant meteorological conditions. 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.

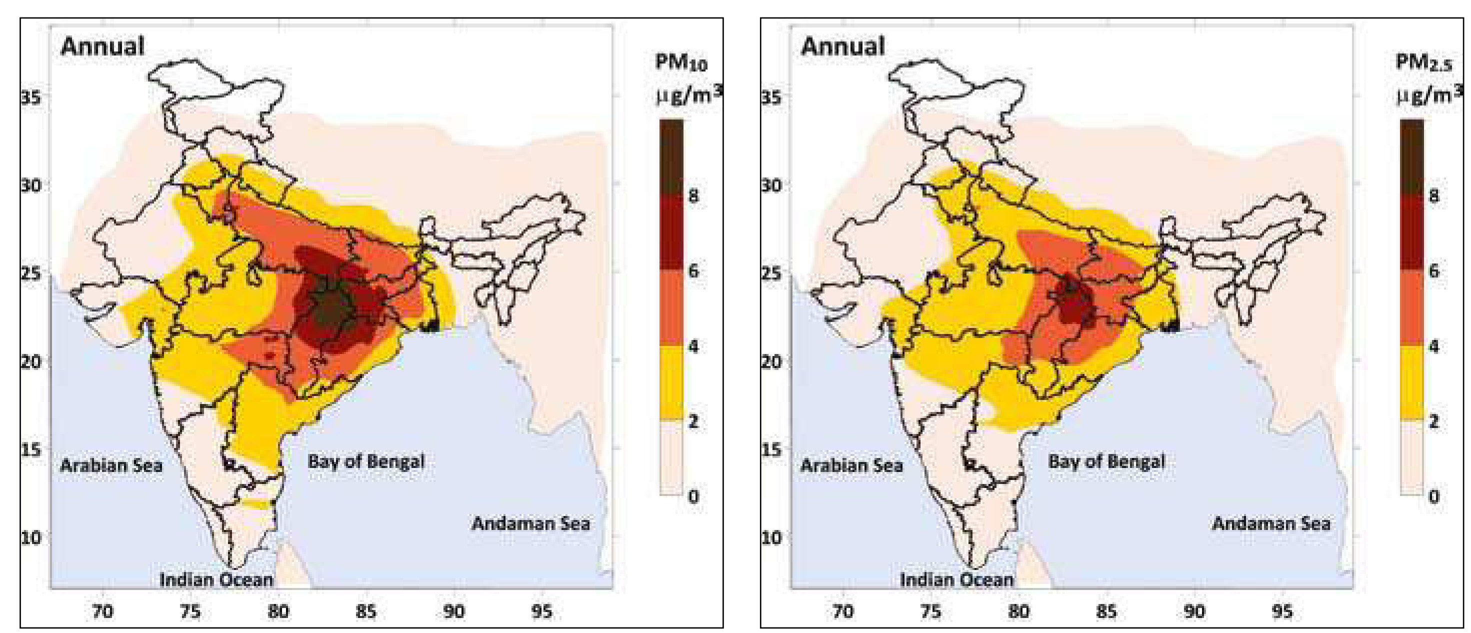
For the modeling domain, the meteorological data (3D wind, temperature, pressure, relative humidity, and precipitation fields) is derived from the National Center for Environmental Prediction **(NCEP, 2012)** global reanalysis database for the base year 2010 and processed through the RAMS meteorological model (version 6.0) at 1 hour temporal resolution. The initial conditions are generated by looping the simulations over each month for 10 days and the boundary conditions are kept to the minimum to minimize any influence on the ground level concentrations – this was assigned to ease the analysis of the incremental changes in the ground level concentrations due to power plant emissions.

The most important advantage of CAMx is the use of 3D meteorology and independently control plume rise and emission release point for each power plant, according to the stability profile at the plants location **(Turner et al., 1986)**. The exit velocity of the flue gas at the stack height provides the necessary momentum to disperse vertically, which is quickly reduced by entrainment as the plume acquires horizontal momentum from the wind. This causes the plume to bend and disperse horizontally. The difference between the temperature of the flue gas and the surrounding atmosphere results in the buoyancy of the plume, which further increasing the vertical release point. The emissions for each stack are released in the vertical layer corresponding to stack height + plume rise due to momentum and buoyancy. We did not include emissions from the other sectors and considered the results of this exercise as the incremental change in the ambient concentrations due to the presence of these coal based power plants in the region.

3.3 Particulate Pollution

The atmospheric dispersion simulation are 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_{10} and $PM_{2.5}$ concentrations due to emissions from coal based power plants only are presented in **Figure 4.** These totals include both the primary PM and secondary PM – from chemical conversion of SO_2 and NO_x emissions to sulfates and nitrates, respectively. The coarse/fine bins are modeled independently with varying dry and wet deposition schematics, predefined in the CAMx model. For PM_{10}, the sum includes coarse, fine, sulfate, and nitrate concentrations and for $PM_{2.5}$ the sum includes only fine, sulfate, and nitrate concentrations. The national ambient annual average standard for PM_{10} is 60µg/m3 and the WHO guideline is 20µg/m3. The national ambient annual average standard for $PM_{2.5}$ is 40µg/m^3 and the WHO guideline is 10µg/m3. While the absolute values in **Figure 4** may seem small, this should be considered as incremental pollution which

Figure 4: Modeled annual average PM_{10} and $PM_{2.5}$ ambient concentrations due to the emissions from coal-fired thermal power plants in India



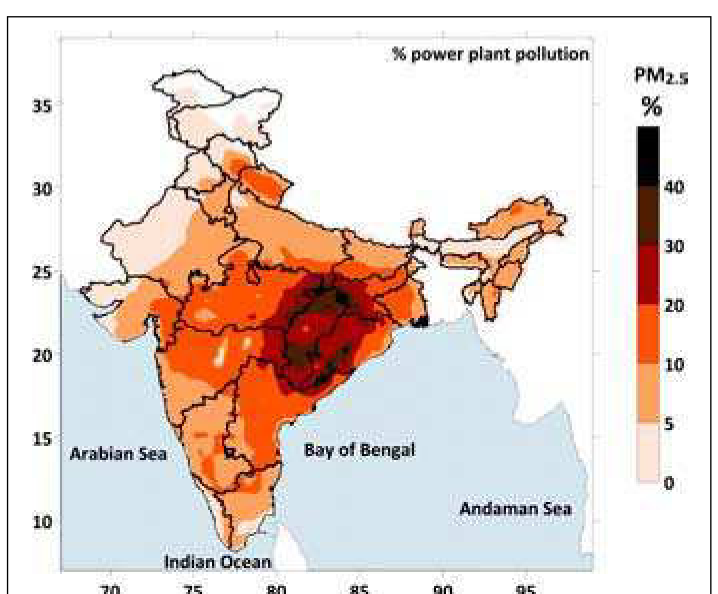
the population in the region is exposed to, besides the pollution from transport, domestic, and other industrial activities, on an annual basis.

The $PM_{2.5}$ concentrations were overlaid on the annual average concentrations retrieved from 2001-06 satellite observations **(van Donkelaar et al., 2010)** to estimate the percentage contribution of power plant emissions to the ambient concentrations in India **(Figure 5)**. The data from the satellite observations has large uncertainty, since the retrieval methodology could not be corroborated with a large enough $PM_{2.5}$ monitoring data sample, and tend miss the urban peaks in the southern India. However, this provides an immediate baseline for the comparison, to identify hotspots, and to estimate contributions. The largest impact of the coal-based power plant emissions is felt over most of the central-east India including states of Maharashtra, Madhya Pradesh, Chhattisgarh, and Orissa, with the highest and the largest coal based power plants. Similar observations are reported based on satellite measurements of column NO2 concentrations **(Lu and Streets, 2012; Prasad et al., 2012)**.

3.4 Secondary Chemical Contributions

The CAMx modeling system includes full gas phase chemistry, with gas and aerosol chemical conversions to support particulate pollution assessment. The SAPRC chemical mechanism utilized in this model was extended to study the secondary contribution – which is significant in case of the coal-fired power plants in India with no FGD systems in place. Most of the SO_2

Figure 5: *Percent contribution of power plant emissions to ambient $PM_{2.5}$ concentrations (based on satellite measurements -* ***van Donkelaar et al., 2010****) in India*



emissions from the plants, once airborne, are expected to further interact with the hydroxyl radicals to form sulfates **(Carter, 2000)**, which in the aerosol chemistry module are treated to form aerosol components. The formation of 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_{10} from the coal fired power plants in presented in **Figure 6.** The maps are presented by season, DJF for winter, MAM for spring, JJA for summer, and SON 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 NOx gases and their conversion rate to sulfates and nitrates.

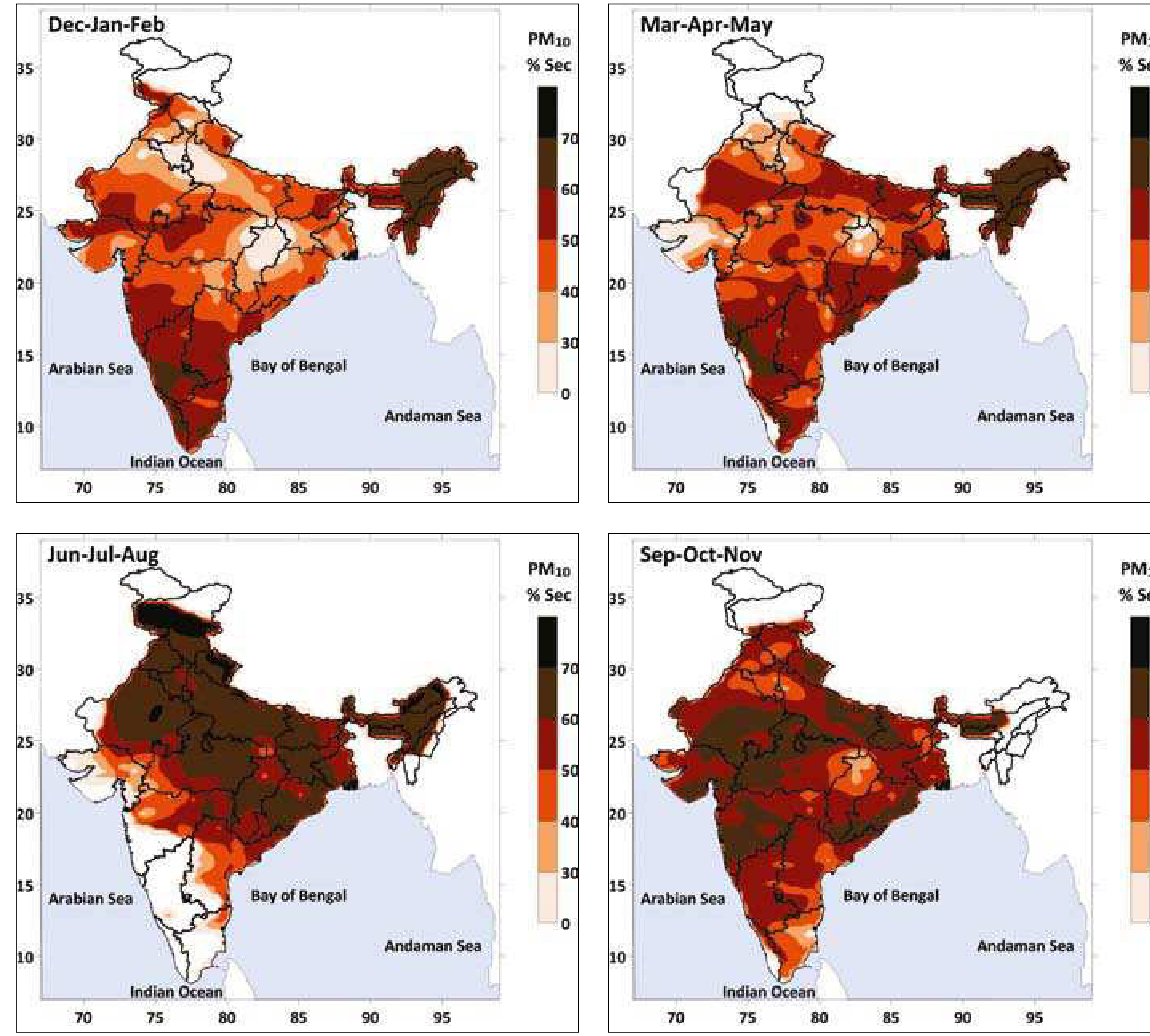
3.5 Meteorological Influences

Generally, the wind speeds at 200m or above is 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 wind speeds and direction have a large variation in the subcontinent between the monsoonal and non-monsoonal months. This variation affects the dry and wet deposition and final ambient concentrations for all pollutants. In **Figure 7**, we present the monthly average concentrations due to emissions from the coal fired power plants. 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. There is much uncertainty in the monsoons and weather patterns that could not only influence the pollution patterns, but there is also growing evidence that the pollution from transport and industrial processes can affect the monsoonal patterns **(Corrigan et al., 2006; Lau et al., 2009)**.

3.6 Sub-regional Pollution

The concentration maps presented in **Figure 4** and **Figure 7** are from CAMx model simulations at a spatial resolution of 0.25°, which tend to average the local influences over each of the grid boxes. In order to better understand these local influences, we conducted

Figure 6: *Percentage contribution of secondary (sulfates and nitrates) aerosols to average PM_{10} concentrations 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*



CAMx dispersion model simulations for 4 inland regions and 3 coastal regions **(Figure 2)** at 0.1° spatial resolution. A summary of these regions is presented in **Table 5**. The modeled daily average concentration maps are presented in **Figure 8** for the inland regions and **Figure 9** for the coastal regions.

The movement of the elevated emissions is illustrated using meteorology of two days for three months in **Figure 10** 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 300m height every hour and tracking its movement through the next 48 hours. The lines represent only the movement of the puffs in the horizontal direction and do not include any information on the vertical mixing or the pollutant concentrations. The release height of 300m is assumed, considering the large power plants in these clusters are mandated to have stacks of minimum 275m and allowing 25m for additional minimum plume rise.

The Korba cluster (State: Chhattisgarh) has a combined generation capacity of 4380MW between four power plants located within a 10km radius. The Jhajjar cluster (State:Haryana) has a combined generation capacity of 2700MW between two power

Figure 7: Monthly average PM10 concentrations due to the emissions from coal fired thermal power plants in India

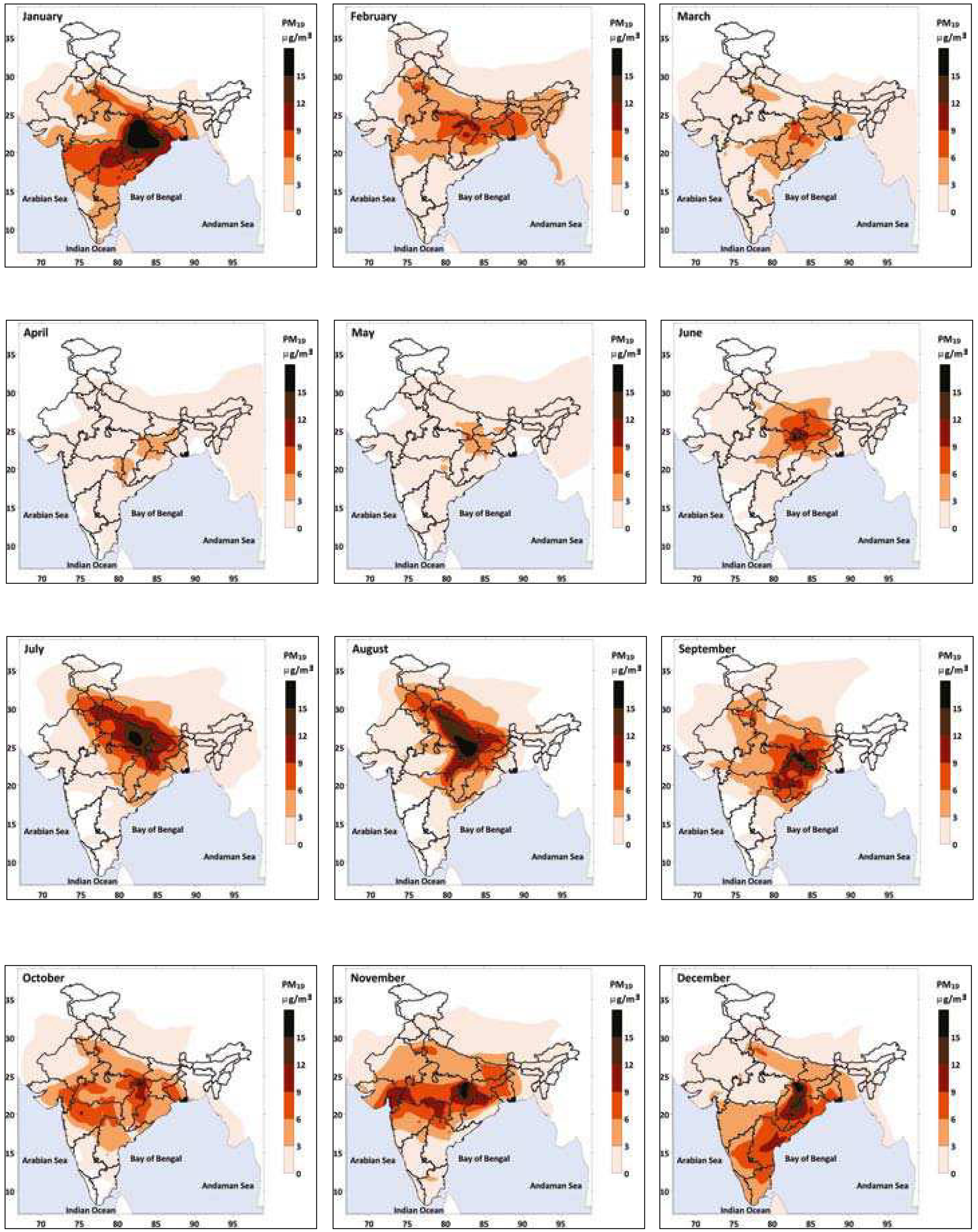
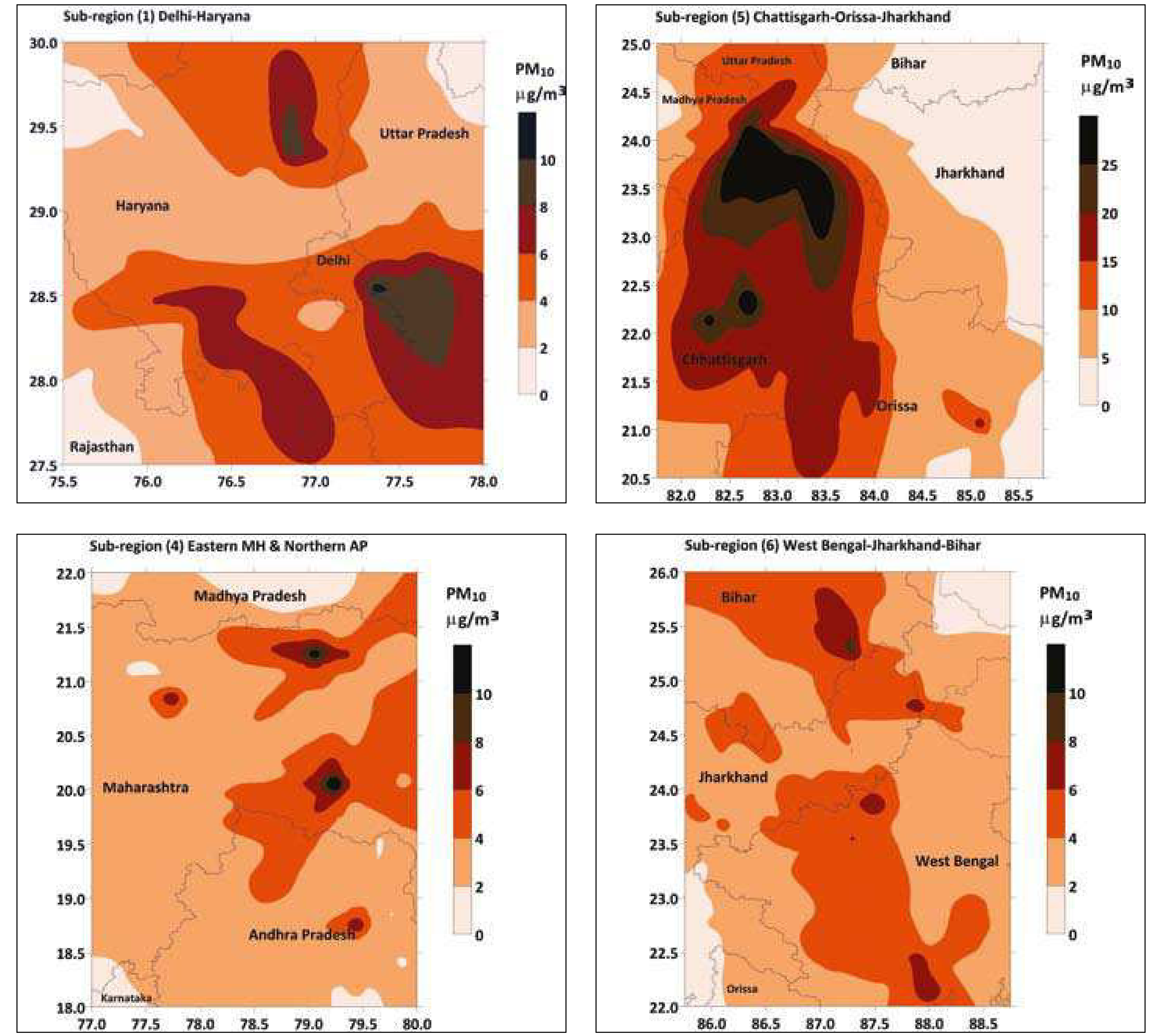


Figure 8: Daily average PM_{10} concentrations due to the emissions from coal-fired thermal power plants in-land of India



plants within the radius of 10km, with an additional power plant with 1000MW under construction.

The Mundra cluster (State: Gujarat) has a combined generation capacity of 9620 MW between two private sector power plants located within 5km radius. The Mumbai cluster (State: Maharashtra) has one coal based power plant in Trombay and multiple gas powered plants. While the impact of the emissions is felt within 200km of the power plants, under windy conditions the influence can be tracked to distances as far as 400km from the source region. Major cities in the Korba region are Ranchi, Jamshedpur, Rourkela, Jabalpur, Nagpur, and Raipur (capital of Chhattisgarh). Major cities in the Mundra region are Jamnagar (major industrial port), Rajkot, and Ahmedabad (300km away, with two power plants of 1000MW in the city). The city of Delhi is 70km from the Jhajjar cluster. 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 we want to illustrate through these forward trajectories is that the emissions from these high stacks affects the regions and people far away from the source region, even if the pollution levels are diluted, compared to the original emission rates, and this should be accounted for in the environmental and health assessments.

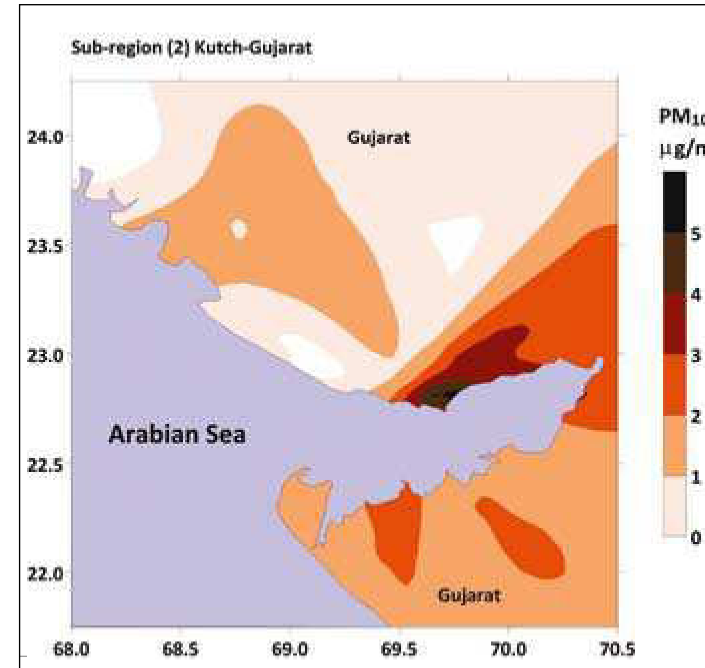
***Table 5**: Installed capacity, modeled daily average PM_{10} concentrations, health impacts of emissions from coal fired power plants for 7 regions at finer resolution in India in 2011-12*

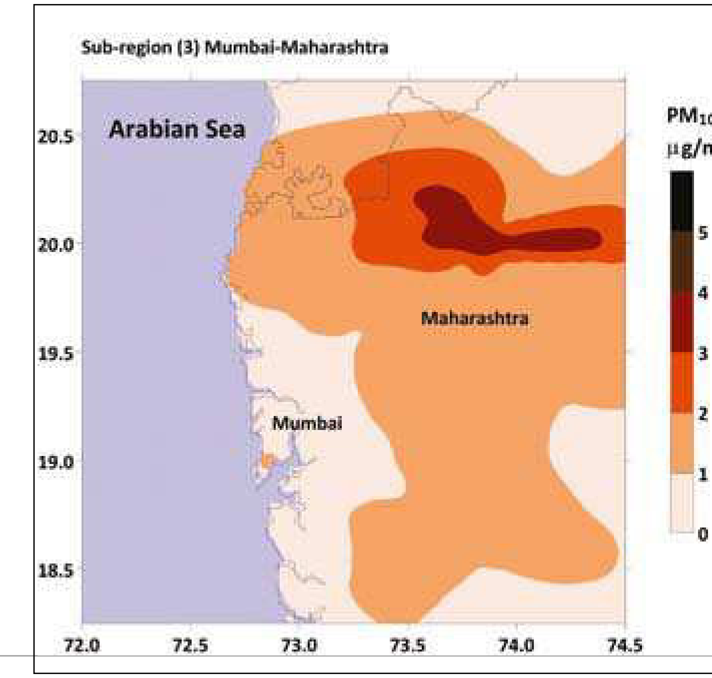
No.	Cluster (size in degrees)	Regional features	No. of plants (those more than 1000MW)	Installed capacity (MW)	Modeled PM_{10} [a] - median (95th percentile) µg/m³	Estimated premature mortality within the region [b]
1	Delhi – Haryana	Delhi is the national capital, listed among the top 10 cities with 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° x 2.5°)	Two super-critical power plants are commissioned 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° x 2.5°)	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° x 4.0°)	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° x 4.5°)	This the densest cluster region of the seven covering 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° x 4.0°)	This is the second densest cluster region covering clusters in 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° x 2.5°)	Another coastal cluster including the port city of Vishakhapatnam	2 (2)	3000	0.8 (1.8)	1100-1500

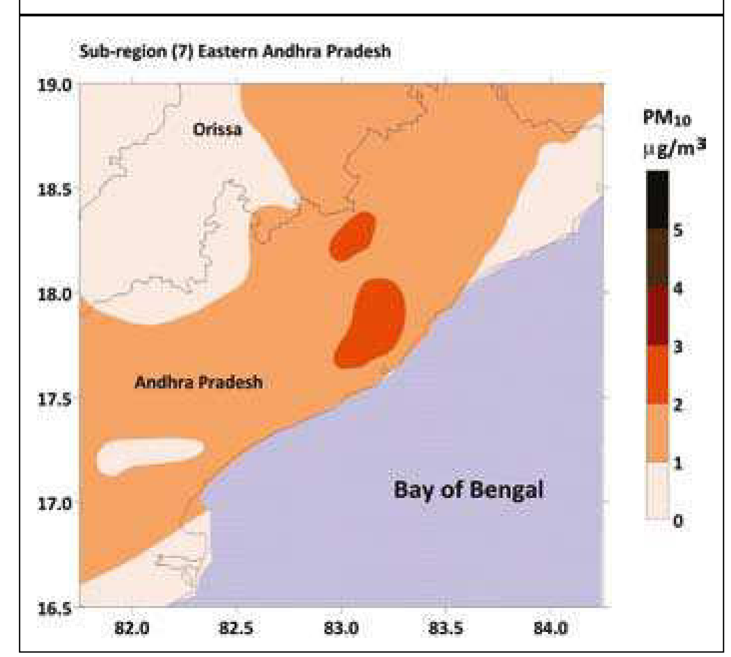
a - the PM_{10} concentrations are modeled grid averages – grid resolution is 0.1°, equivalent of 10km Median and 95[th] percentile value is based on averages for all the grids in the select sub-regional domain
b – this is the estimate for the exposed population in the select geographical sub-region, but the influence of the power plant emissions reaches farther (illustrated in the forward trajectories – **Figure10**)

The PM pollution from the coal-fired power plants in Central India (sub-region 5) covering states of Madhya Pradesh, Jharkhand, Orissa, and Chhattisgarh, is the highest due to the density of the power plants in the region and higher installed generation capacity because of its proximity to the coal mines. The sub-region 1, Delhi-Haryana, region with the highest population density with more than 21.5 million inhabitants in Delhi and its satellite cities, also experiences substantial PM pollution from coal fired power plants. The range of modeled PM pollution is also presented in **Table 5**. The coastal regions in **Figure 9** experience the least of the PM pollution due to strong land-sea breezes, with much of the pollution dispersed over the seas. While the air pollution from these coastal power plants is diluted over the seas for some months, they are equally threatening from water and soil pollution from the coal washeries and ash dumps. To date the inland power plants are still the majority in the country and a serious threat to human health and other environmental concerns.

***Figure 9:** Daily average PM_{10} concentrations due to the emissions from coal-fired thermal power plants in the coastal regions of India*







4.0 HEALTH IMPACTS

The direct link between emissions (from transport, power plants, household cookstoves, industries, and fugitive dust), outdoor air pollution, and human health has been extensively documented (**Brunekreef, 1997; Pope, et al., 2002; HEI, 2004; Laden et al., 2006; Schwartz et al., 2008; Pope et al., 2009; USEPA, 2009; HEI, 2010, Atkinson et al., 2011; Lancet, 2012**). Most notable of the health impacts resulting in premature deaths include chronic obstructive pulmonary disease, lower respiratory infections, cerebrovascular disease, ischemic heart disease, and cancers of trachea, bronchitis, and lung. Of all the pollutants, the public health concerns in India are focused on PM that contributes to a host of respiratory and cardiopulmonary ailments and increasing the risk of premature death. Epidemiological studies conducted in India (Delhi and Chennai) under the public health and air pollution in Asia (PAPA) program also highlighted the linkages between outdoor air pollution and premature mortality, hospital admissions, and asthma cases (**Wong et al., 2008; Balakrishnan et al., 2011**).

The morbidity and mortality burden is particularly costly for governments in terms of work days lost, lost productivity, and loss in terms of gross domestic product. Since, the most PM related deaths occur within a year or two of exposure, reducing PM pollution from sources like transport and power plant has almost immediate benefits for health and national economy.

4.1 Evaluation Method and Inputs

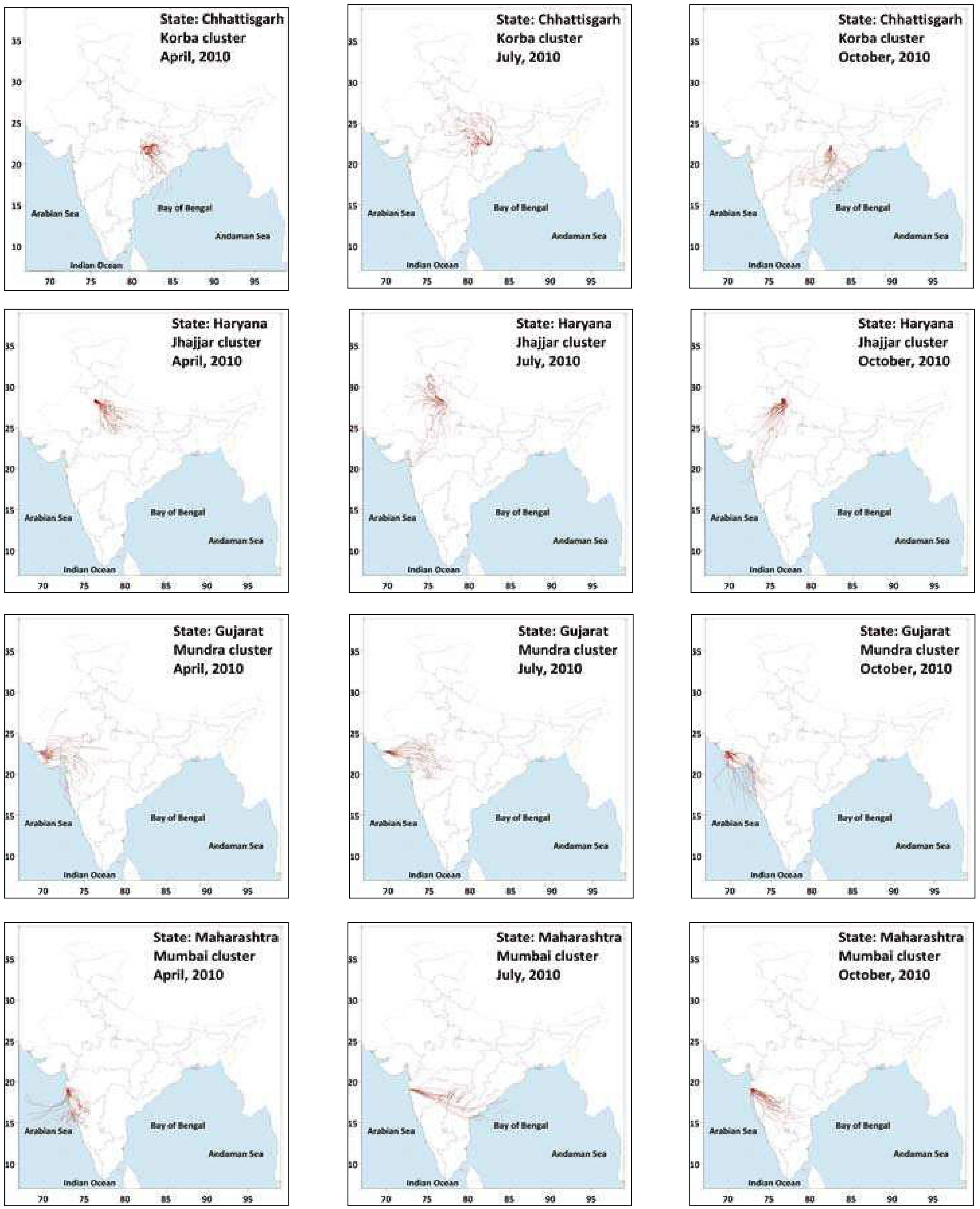
The health impacts of mortality and morbidity are based on concentration-response functions established from epidemiological studies. We estimate the health impacts, using the following equation

$$\delta E = \beta^{*}\, \delta C^{*}\, \delta P$$

where,

δE = number of estimated health effects (various end points for mortality and morbidity)

Figure 10: 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



β = the concentration-response function; which is defined as the change in number cases per unit change in concentrations per capita.

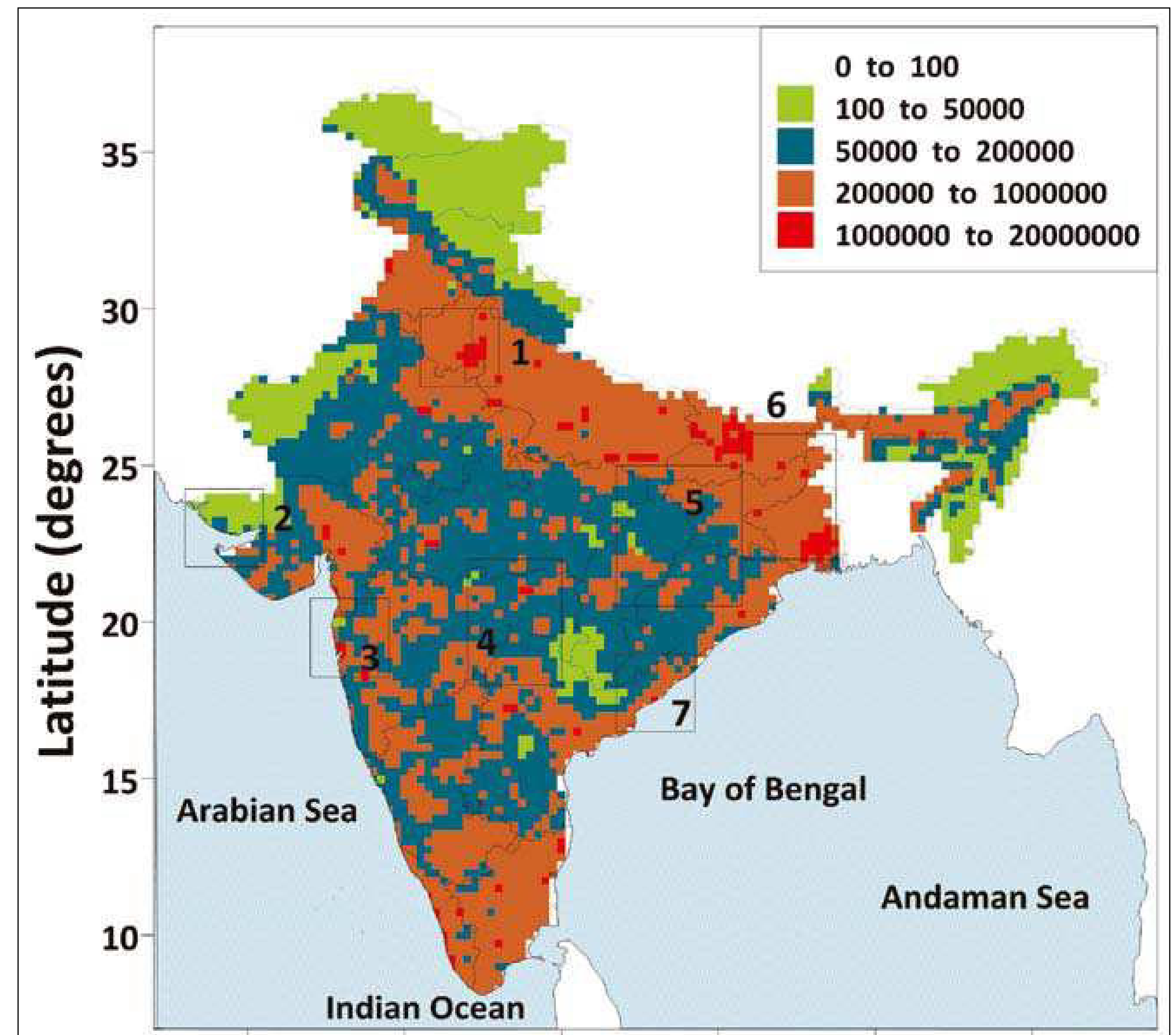
δC = the change in concentrations; in this paper, we consider this as the incremental change in the concentrations due to the emissions from all coal based power plants

δP = the population exposed to the incremental concentration δC ; defined as the vulnerable population in each grid

This methodology of relative risk and concentration-response function was applied for similar studies – **Lancet (2012)** and **Ostro (2004)** for GBD assessments for 2010 and 2000 respectively; **Bell et al. (2006)** for health impawcts of urban air pollution in the cities of Santiago, Mexico city, and Sao Paulo; **GAINS (2010)** 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 Barret (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 India; **Guttikunda and Goel (2013)** for a megacity Delhi and its surrounding satellite cities.

In case of mortality, **Pope et al., (2006)** and **Atkinson et al. (2011)** presents a meta-analysis of chronic and acute exposure studies conducted around

Figure 11: Gridded population at 0.25° spatial resolution based on Census-India (2012)



the world and the range of concentration-response function for PM pollution, including the results of **Wong et al. (2008)** and **Balakrishnan et al. (2011)** from PAPA program in Asia. **Atkinson et al. (2011)** reported change in all-cause daily mortality per 10 µg/m3 change in ambient PM_{10} concentrations for average and high estimates as 0.55% and 0.8% respectively. A combined analysis for the 4 cities under the PAPA program in Asia reported an average value of 0.45%. We also estimate morbidity in terms of asthma cases, chronic bronchitis, hospital admissions, and work days lost. The concentration-response functions for morbidity are extracted from **Abbey et al. (1995)** and **Croitoru et al. (2012)**.

The following assumptions are applied (a) that the concentration-response to changing air pollution is similar to all residents in India and (b) that the population baseline health status is similar to those observed at the national level **(CBHI, 2010). Krewski et al. (2009)** and **Jahn et al. (2012)** have explored in detail the differences between the linear (used in this study) and log-linear concentration-response functions, which are pertinent to high PM pollution levels observed in the Asian cities. We explored the use of both the linear and log-linear forms of the relative risks presented in these studies and finally, utilized the linear correlation since the analysis is focused on the incremental changes in concentrations due to the power plant emissions and the focus of the analysis is to estimate the burden of the emissions on the health impacts.

The global burden of disease study for 2010 reported an all-cause mortality of 210-320 per 1000 male adults and 140-220 per 1000 female adults for India **(Wang et al., 2012)**. This was adjusted the mortality rate due to lower and upper respiratory illnesses (including bronchitis and asthma) and cardio vascular diseases. Among the reported number of deaths, these account for 15% of the annual death rate in India **(DoES, 2010)**.

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 more 30% of the total. The gridded population data is presented in **Figure 11.**

4.2 Mortality and Morbidity Estimates

The health impacts are calculated for the base year 2010, by overlaying the gridding population with the modeled PM_{10} 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.** We believe that our estimations of the premature deaths and morbidity cases are conservative. We have not included in the analysis the impacts of the trace metals, such as mercury and impacts due to water and soil contamination, which could further aggravate the overall implications of power plants. The uncertainties involved in the risk assessments are detailed in **Atkinson et al. (2011)** for the time series and **Lancet (2012)** for long term integrated exposures.

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-UP) and 6 (WB-JH-BH) 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 WB). These regions also experience highest risk of exposure. For the total premature deaths estimated for India, these seven sub-regions account for 40% of them.

The value of statistical life is established from surveys based on "willing to pay" by individuals for benefits associated with the health impacts. This methodology was applied for assessing the impacts of current air pollution levels and for future "what-if" scenarios in a number of countries and cities, in spite of known uncertainties in the associated inputs, such as the relative risk functions for health impacts of air pollution, spatial resolution of pollution monitoring, and monetizing impacts based on surveys **(Bell et al., 2011; Chikkatur et al., 2011)**. Some example studies include **Alberini et al. (1997)** for Taiwan; **Kan et al., (2004)** for **Shanghai; Bell et al. (2006)** for Mexico City, Sao Paulo, and Santiago; **Wang and Mullahy (2006)** for Chongqing; **Hedley et al. (2008)** for Hong Kong; **Desaigues et al. (2011)** for 9 European countries; **Patankar and Trivedi (2011)** for Mumbai. The health costs based on value of statistical life is an uncertain estimate that has a range depending on methods. Using a conservative value of 2,000,000 Rupees (40,000 USD) per life lost, the premature mortality estimates from this study would result in a health cost of 16,000 to 23,000 crores Rupees (USD 3.2 to 4.6 billion) annually. The morbidity impacts and health costs are listed in **Table 6.**

Table 6: *Estimated annual health impacts and health costs due to PM pollution from the coal-fired power plants in India for 2011-12*

Effect	Health impacts	Health costs (crores of Rupees) [a]	Health costs (million USD) [b]
Total premature mortality	80,000 to 115,000	16,000-23,000	3300-4600
Child mortality (under 5)	10,000	2100	420
Respiratory symptoms	625 million	6200	1200
Chronic bronchitis	170,000	900	170
Chest discomforts	8.4 million	170	35
Asthma attacks	20.9 million	2100	420
Emergency room visits	900,000	320	60
Restricted activity days	160 million	8000	1600

a – one crore = 10 million
b – using conversion rate of 1 USD = 50 Rupees

5.0 SUMMARY AND DISCUSSION

Coal remains the main fossil fuel for power generation in India. Supplies of other fuel sources such as naphtha and natural gas are not stable and need to be imported, which led to lesser growth in this sector. The power sector in India is currently dealing with two competing priorities – (a) demand for power outstrips supply and as the economy grows, access to electricity is increasingly an economic and a political issue (b) power generation using coal is polluting (especially given the low quality coal used in India) and hazards associated with the air pollution are a serious concern. This means, the government has a low incentive to take action on a power plant violating environmental norms, when struggling to meet the demand for electricity from the domestic and manufacturing sectors. To date, the pollution standards exist for ambient air quality only and not for individual power plants, which compromises the monitoring and enforcement efforts. Only after standards are set and regulations mandated at the plant level, can we proceed to the next steps of monitoring and enforcing policy, so as to have lesser environment and health impacts due to coal fired power plants.

Of all the operational units in the country, 70% are of the size less than or equal to 210MW and these units tend to have the worst net efficiency and plant load factor. We believe that a bifurcated environmental standard for PM emissions at the stack led to this **(Table 1)**. For example, the Kolghat power plant in West Bengal state has 6 units of 210MW and the Raichur power plant in Karnataka state has 7 units of 210MW, each with a total generation capacity of more than 1000MW, are allowed to adhere to the lower emission standard, only because the individual boiler size is less than or equal to 210MW. The efficiency improvement of existing older power plants and tightening of emission standards for all sizes should become a starting point for reducing the coal consumption and atmospheric emissions. Going forward, coal-fired power plants should be subject to tighter emission standards based on those found in emerging economies (like China) and developed economies (like EU, Australia, and USA).

Unlike pollution from the transport or domestic sector, pollution from power plants stacks is a point source. This means that there are a finite and known number of units from where pollution is released and thus can be controlled. Moreover, with a majority of the power plants run by the public sector, mandating technologies that reduce pollution would seem to represent a simple solution. However, power plant regulation has thus far lagged far behind other emerging economies and power plants by themselves have no incentive to improve pollution control. Combined with a strong demand for reliable electricity and lack of supply it is doubtful that pollution will be controlled absent strong regulation and enforcement.

The stack emissions being point sources, are limited in number, and can be monitored relatively easily as compared to non-point sources (such as vehicles, garbage burning, domestic burning, and fugitive dust). Some of the larger power plants are now equipped with continuous monitoring of the criteria pollutant concentrations. However, this information is not available in the public domain, either for analysis or for scrutiny of the emission loads. This adds to the uncertainty of the estimates, for analyzing the impacts of the emissions, understanding the contribution loads, and for planning. Besides, strengthening of emission standards, new policies are required for information dissemination.

From the power plants, we estimate 30-40% of the PM pollution is secondary in nature, with the most coming from chemical conversion of SO2 emissions. Since a majority of the power plants in the country do not operate a dedicated FGD system, most of the SO2 from coal combustion is emitted and ends up in respirable PM fraction, resulting in more health impacts. In the environmental impact assessment studies, required before the commissioning of a power plant, a provision for a FGD for all power plants is discussed for the future years, but not yet mandated. The combined benefits of a FGD in conjunction with the already operational ESPs at most of the power plants 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.

Air pollution is a complex mixture of pollutants with sources ranging from fossil fuel burning in transportation, power generation, industries, and domestic sectors to natural sources such as dust storms and forest fires. In this study, our objective was to isolate the health impacts of the emissions due to coal-fired power plants. We calculate the health impacts for total PM_{10} which includes contributions from primary PM and those from reactions of SO_2, NO_x, and VOCs in the SAPRC chemical mechanism, via CAMx Eulerian dispersion model. We estimated a premature mortality rate of 80,000 to 115,000 due to the ambient particulate pollution from the coal-fired power plants. We believe that this is an underestimation, and does not include the impacts of the water run-off and soil contamination due to the release of heavy metals like zinc, copper, manganese, cobalt, cadmium, selenium, mercury, arsenic, iron, lead, and chromium.

Ultimately, the government and citizen groups need to demand clean power, keeping in mind the health impacts of the emissions from power plants in India. An environmental outlook study concluded that a least-cost policy mix to reduce air pollution in the developing economies of Brazil, China, India, and South Africa is made up of 50% end of pipe measures and 50% of shifting to cleaner energy sources **(OECD, 2012)**. In the future – while the share of power generation from coal is projected to decline **(IEA, 2012)** – the amount of power generated from coal will remain high at least through 2030, and unless we find a better way to manage the power plants, the environmental effects due to growing air and CO_2 emissions and the human health cost will be high.

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