



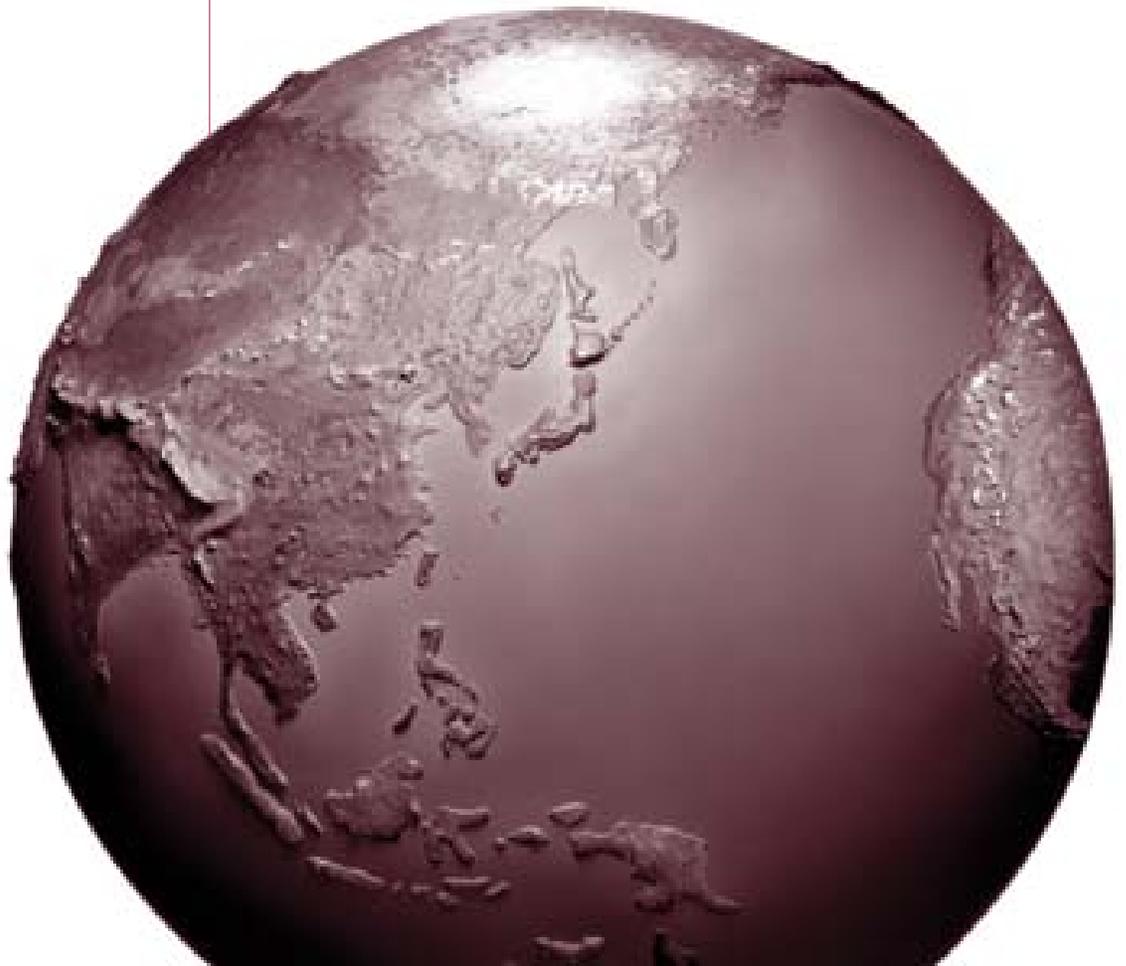
## SPECIAL REPORT 21

HEALTH  
EFFECTS  
INSTITUTE

January 2018

# Burden of Disease Attributable to Major Air Pollution Sources in India

GBD MAPS Working Group





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GBD MAPS Working Group

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Special Report 21  
Health Effects Institute  
Boston, Massachusetts

*Trusted Science • Cleaner Air • Better Health*

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# ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- Identifies the highest-priority areas for health effects research;
- Competitively funds and oversees research projects;
- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI typically receives balanced funding from the U.S. Environmental Protection Agency and the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or research programs; the William and Flora Hewlett Foundation and the Oak Foundation contributed the primary support for GBD MAPS. HEI has funded more than 330 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in more than 260 comprehensive reports published by HEI, as well as in more than 1,000 articles in the peer-reviewed literature.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. For this report, a GBD MAPS International Steering Committee was appointed to provide high-level advice to and oversight of the GBD MAPS Working Group. In addition, the draft final report was reviewed by independent external peer reviewers from India and other countries, who were selected by HEI for their expertise. A draft final version of this report was also reviewed by experts on the GBD MAPS Steering Committee.

All project results are widely disseminated through HEI's website ([www.healtheffects.org](http://www.healtheffects.org)), printed reports, newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.



# CONTRIBUTORS

## GBD MAPS WORKING GROUP

**Michael Brauer (cochair)** *University of British Columbia, Vancouver, British Columbia, Canada*

**Aaron Cohen (cochair)** *Health Effects Institute, Boston, Massachusetts, U.S.A.*

**Wang Shuxiao** *Tsinghua University, Beijing, China*

**Zhang Qiang** *Tsinghua University, Beijing, China*

**Ma Qiao** *Tsinghua University, Beijing, China*

**Zhou Maigeng** *Chinese Center for Disease Control and Prevention, Beijing, China*

**Yin Peng** *Chinese Center for Disease Control and Prevention, Beijing, China*

**Kalpana Balakrishnan** *Sri Ramachandra Medical College & Research Institute, Chennai, India*

**Chandra Venkataraman** *Indian Institute of Technology, Bombay, India*

**Pankaj Sadavarte** *Indian Institute of Technology, Bombay, India*

**Sarath Guttikunda** *Indian Institute of Technology, Bombay, India/Urban Emissions*

**Alok Jhaldiyal** *Indian Institute of Technology, Bombay, India*

**Wang Yuxuan** *University of Texas–Houston, U.S.A./ Tsinghua University, China*

**Kan Haidong** *Fudan University, Shanghai, China*

**Randall Martin** *Dalhousie University, Halifax, Nova Scotia, Canada*

**Aaron van Donkelaar** *Dalhousie University, Halifax, Nova Scotia, Canada*

**Richard Burnett** *Health Canada, Ottawa, Ontario, Canada*

**Mohammad Forouzanfar** *Institute for Health Metrics and Evaluation, University of Washington–Seattle, U.S.A.*

**Joseph Frostad** *Institute for Health Metrics and Evaluation, University of Washington–Seattle, U.S.A.*

## GBD MAPS INTERNATIONAL STEERING COMMITTEE

**Dan Greenbaum** *Health Effects Institute, Boston, Massachusetts, U.S.A.*

**Bob O’Keefe** *Health Effects Institute, Boston, Massachusetts, U.S.A.*

**Terry Keating** *U. S. Environmental Protection Agency*

**Hao Jiming** *Tsinghua University, Beijing, China*

**Yang Gonghuan** *Peking Union Medical College, Beijing, China*

**Christopher Murray** *Institute for Health Metrics and Evaluation, University of Washington–Seattle, U.S.A.*

**Majid Ezzati** *Imperial College, London, United Kingdom*

**K. Srinath Reddy** *Public Health Foundation of India, Delhi, India*

**Michal Krzyzanowski** *Kings College, London, United Kingdom*

**Greg Carmichael** *World Meteorological Organization/ University of Iowa–Iowa City, U.S.A.*

## PEER REVIEWERS

**Noelle Selin** *Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.*

**Pallavi Pant** *University of Massachusetts–Amherst, U.S.A.*

**Anup Bandivadekar** *International Council on Clean Transportation, San Francisco, California, U.S.A.*

**Bhargav Krishna** *Public Health Foundation of India, Haryana, India*

**Kunal Sharma** *Shakti Foundation, New Delhi, India*

## HEI PROJECT STAFF

**Katherine Walker** *Principal Scientist*

**Allison P. Patton** *Staff Scientist*

**Kathryn Liziewski** *Research Assistant*

**Devashri Salvi** *Research Intern*

**Hilary Selby Polk** *Managing Editor*

**Mary Brennan** *Consulting Editor*

**Fred Howe** *Consulting Proofreader*

**Ruth Shaw** *Consulting Compositor*



Map of India. Copyright © 2017 www.mapsofindia.com (adapted).

# SUMMARY FOR POLICY MAKERS

## Burden of Disease Attributable to Major Air Pollution Sources in India

### THE AIR POLLUTION CHALLENGE

India has some of the highest levels of outdoor air pollution in the world. The most comprehensive air pollution estimates available from both

satellite and Indian ground-level measurements of fine particulate matter (PM<sub>2.5</sub>\*) indicate that 99.9% of the Indian population is estimated to live in areas where the World Health Organization (WHO) Air Quality Guideline of 10 µg/m<sup>3</sup> for

### What This Study Adds

- **This report provides the first comprehensive assessment of the current and predicted burdens of disease attributable to major sources of air pollution in India.**
- **In 2015, particulate matter (PM) air pollution from several major sources was responsible for approximately 1.1 million deaths, or 10.6% of the total number of deaths in India.** Combustion sources are among the leading contributors:
  - **Residential biomass burning is the largest individual contributor to the burden of disease in India.** Residential biomass burning was responsible for 267,700 deaths, or nearly 25% of the deaths attributable to PM<sub>2.5</sub>, making it the most important single anthropogenic source related to mortality in 2015. These burden estimates do not include the considerable additional burden from indoor exposure to biomass burning.
  - **Coal combustion and open burning also contribute substantially to disease burden.** Coal combustion, roughly evenly split between industrial sources and thermal power plants, was responsible for 169,300 deaths (15.5%) in 2015. The open burning of agricultural residue was responsible for 66,200 (6.1%) PM<sub>2.5</sub>-attributable deaths.
  - **Transport, distributed diesel, and brick production are also important contributors to PM<sub>2.5</sub>-attributable disease burden.** In 2015, transportation contributed 23,100 deaths, distributed diesel contributed 20,400 deaths, and brick production contributed 24,100 deaths.
- **If no action is taken, population exposures to PM<sub>2.5</sub> are likely to increase by more than 40% by 2050.** Three different energy efficiency and air pollution control pathways (scenarios) were evaluated. In the reference scenario (REF), in which little additional action is taken, exposures increase from 74 µg/m<sup>3</sup> in 2015 to 106 µg/m<sup>3</sup> in 2050. Exposure levels are kept close to 2015 levels under an ambitious S2 scenario. Only under the most active reductions envisioned in the aspirational S3 scenario are exposures projected to be reduced in a major way — by nearly 35% from 2015 to 2050, reaching about 48 µg/m<sup>3</sup>.
- **If no action is taken, the future burden of disease from all sources will grow substantially by 2050.** The burden of disease is expected to grow in the future, as the population ages and grows and leaves more people susceptible to air pollution, despite the projected exposure decreases in the S2 and S3 scenarios. Compared with nearly 1.1 million deaths in 2015, deaths attributable to ambient PM<sub>2.5</sub> are projected to rise to 3.6 million with no action.
- **Aggressive action could avoid nearly 1.2 million deaths; all major sectors will need to achieve reductions in air pollution to reduce disease burden.** The Indian government has begun taking actions to improve air quality. This analysis demonstrates that aggressive actions under the S3 scenario could avoid nearly 1.2 million deaths in 2050 compared with the REF scenario. That will be especially true for actions to reduce exposure from *residential biomass combustion, coal burning, and dusts related to human activities.*

This document was made possible, in part, through support provided by the William and Flora Hewlett Foundation and the Oak Foundation. The contents of this document have not been reviewed by these or other institutions, including those that support the Health Effects Institute; therefore, it may not reflect the

views or policies of these parties, and no endorsement by them should be inferred.

\*A list of abbreviations and other terms appears at the end of this volume.

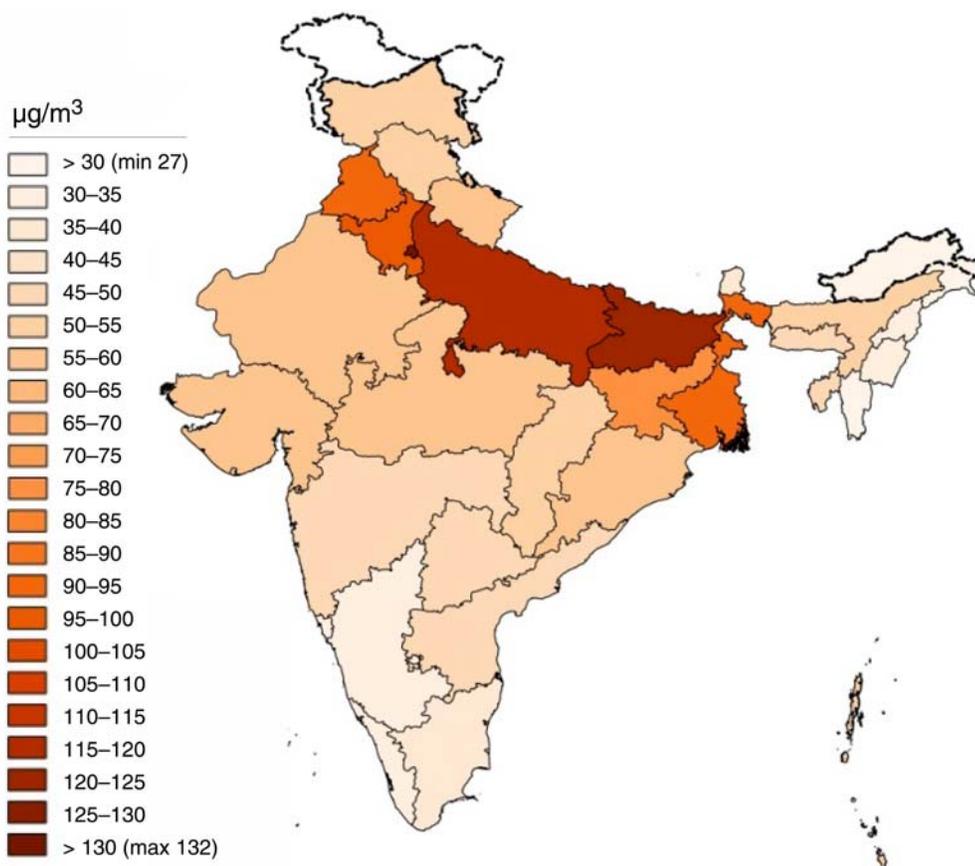
PM<sub>2.5</sub> was exceeded in 2015. Nearly 90% of people live in areas exceeding the WHO Interim Target-1 (35 µg/m<sup>3</sup>). Similarly, the population in most Indian states (21) and minor territories (6) was exposed to PM<sub>2.5</sub> levels above the Indian annual standard of 40 µg/m<sup>3</sup> in 2015. Summary Figure 1 shows that, although the air pollution levels experienced by the Indian population can vary substantially depending on where people live, these levels are unusually high compared with WHO guidelines and Indian standards.

Trends in outdoor air pollution levels are not promising. Air pollution estimates indicate that, in the last 25 years, average exposure for India increased from about 60 µg/m<sup>3</sup> in 1990 to 74 µg/m<sup>3</sup> in 2015 — a level more than double the WHO Interim Target-1 and more than seven times higher than the WHO Air Quality Guideline (see related map at

the State of Global Air website, [www.stateofglobalair.org/air](http://www.stateofglobalair.org/air)). The steepest increases have occurred in the last 10 years. The Indian government has begun to take action to improve air quality by addressing emissions from vehicles, thermal power plants, and household energy use, among other sources (see full report for details), but significant challenges remain.

### THE EVIDENCE ON AIR POLLUTION AND HUMAN HEALTH IN INDIA

Exposure to air pollution has serious consequences for human health. A recent authoritative report of the Steering Committee on Air Pollution and Health-Related Issues of the Indian Ministry of Health and Family Welfare reviewed



**Summary Figure 1. Population-weighted state-level mean PM<sub>2.5</sub> concentrations in 2015 across India.** These state-level means are created by aggregating up from the 11-by-11-km-grid population and ambient PM<sub>2.5</sub> concentration data developed for GBD 2015 (see text for details).

current evidence on the health effects of exposure to ambient and household air pollution and noted the “... long history and substantive volume of studies in India that have examined the health effects of ambient and household air pollution,” pointing out the “... comparability of available study results to the global pool of evidence ...” (MoHFW [Ministry of Health and Family Welfare] 2015). The report bases its assessment on the growing body of Indian studies on the adverse effects of air pollution whose results are consistent with studies conducted elsewhere in Asia and with systematic scientific reviews of the worldwide literature by national governments and international agencies.

This report focuses on PM<sub>2.5</sub> as the primary indicator of air pollution. A substantial body of evidence links PM<sub>2.5</sub> to many adverse health effects, including diminished lung function, acute and chronic respiratory symptoms (such as asthma and cough and wheeze), and increased risk of mortality from non-communicable diseases such as chronic obstructive pulmonary (lung) disease, heart disease, stroke, and lung cancer, and from lower-respiratory infections in children and adults.

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#### ESTIMATING THE HEALTH BURDEN ATTRIBUTABLE TO AIR POLLUTION: THE GBD PROJECT

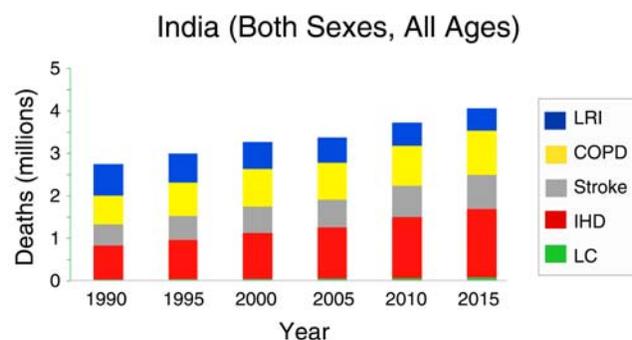
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Population exposure to air pollution places a substantial burden on public health and on society. The burden on public health is measured by the Global Burden of Diseases, Injuries, and Risk Factors project (GBD), which is the largest and most comprehensive effort to measure epidemiological levels and trends worldwide ([www.healthdata.org/gbd](http://www.healthdata.org/gbd)). The 2015 update of the GBD involved more than 1,800 collaborators (including 229 Indian experts) from more than 120 countries and 3 territories. GBD 2015 estimated the burden of disease attributable to 79 risk factors — that is, behavioral, environmental (including ambient and household air pollution), and diet-related metabolic factors that can affect health — in 195 countries and territories over a 25-year period (1990–2015) (GBD 2015 Risk Factor Collaborators 2016). These estimates are updated annually, with the 2016 results released in September 2017 and the India-specific 2016 results for all diseases and risk factors published in November 2017 (Dandona et al. 2017; Indian Council of Medical Research, Public Health Foundation of India, and Institute for Health Metrics and Evaluation 2017).

The GBD project measures public health burden in terms of the numbers of deaths and years of healthy life lost (DALYs, or disability-adjusted life-years). The burden of

disease attributable to air pollution is estimated from (1) integrated exposure–response relationships between air pollution exposure and the increased risk of mortality from specific diseases using the evidence from a large peer-reviewed international literature combined with (2) India-specific data on baseline population rates of each disease or cause of death and (3) India-specific exposures to air pollution.

In India, the GBD 2015 study found exposure to outdoor PM<sub>2.5</sub> to be the third leading risk factor contributing to mortality among the 79 behavioral, environmental, and metabolic factors that were analyzed; it was responsible for more than 1 million deaths in 2015, which represent nearly a quarter of the 4.2 million deaths attributable to outdoor air pollution worldwide. It also accounted for 29.6 million years of healthy life lost (i.e., DALYs). The number of deaths attributable to air pollution has been growing steadily in India over the past 25 years (Summary Figure 2). This trend is in part attributable to increases in ambient PM<sub>2.5</sub> levels, but also to a growing and aging population with increasing numbers of people with ailments that are affected by exposure to air pollution, such as cardiovascular disease. When this loss of life is translated into economic terms, the costs are considerable — more than US\$225 billion in lost labor income and US\$5.11 trillion in welfare losses (considered a more comprehensive measure of economic losses, beyond just lost income) worldwide in 2013 according to an analysis by the World Bank and the Institute for Health Metrics and Evaluation (2016). For India alone, the estimate for lost labor output was US\$55 billion and for welfare losses US\$505 billion.



**Summary Figure 2. Total deaths in India (1990–2015) from diseases for which exposure to PM<sub>2.5</sub> is a risk factor.** (LRI = lower-respiratory infection, COPD = chronic obstructive pulmonary disease, IHD = ischemic heart disease, and LC = lung cancer). Data from the Institute for Health Metrics and Evaluation’s GBD Compare website (<http://vizhub.healthdata.org/gbd-compare/>) [accessed 2 February 2017].

These estimates of burden do not include the additional effects that air pollution has on society via its impacts on climate and on the environment.

---

### ESTIMATING BURDEN OF DISEASE ATTRIBUTABLE TO MAJOR AIR POLLUTION SOURCES: GBD MAPS

---

Understanding the major sources of air pollution and their relative contributions to PM<sub>2.5</sub> exposure and, thereby, to disease is a critical next step toward implementing systematic and effective air quality management solutions and reducing exposures and health impacts. The Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project was designed to improve our understanding of these issues. Specifically, its objectives were

- To apply Indian emissions data to estimate ambient PM<sub>2.5</sub> concentrations and the associated disease burden (defined in terms of numbers of deaths) for the baseline year 2015 that were attributable to major air pollution sources in India, including residential burning of biomass, the burning of coal for industry and power generation, open burning of agricultural residues, transportation, brick kilns, and dust related to industrial and human activities, among others.
- To estimate future (years 2030 and 2050) ambient PM<sub>2.5</sub> concentrations and the disease burden attributable to major sources or sectors (hereafter referred to simply as “sources”) under three future scenarios. The three scenarios were designed to reflect population growth, development, energy policy, technology changes, and different strategies to address emissions from major sources.

GBD MAPS is a multiyear collaboration between the Health Effects Institute (HEI), the Institute for Health Metrics and Evaluation, the India Institute of Technology (IIT)–Bombay, Tsinghua University, the University of British Columbia, Sri Ramachandra Medical College and Research Institute, and other leading academic centers. (A list of GBD MAPS Working Group members can be found at the front of this volume.) GBD MAPS builds on its parent project, the Global Burden of Disease (GBD). The current GBD MAPS study relies on the 2015 update of the GBD data.

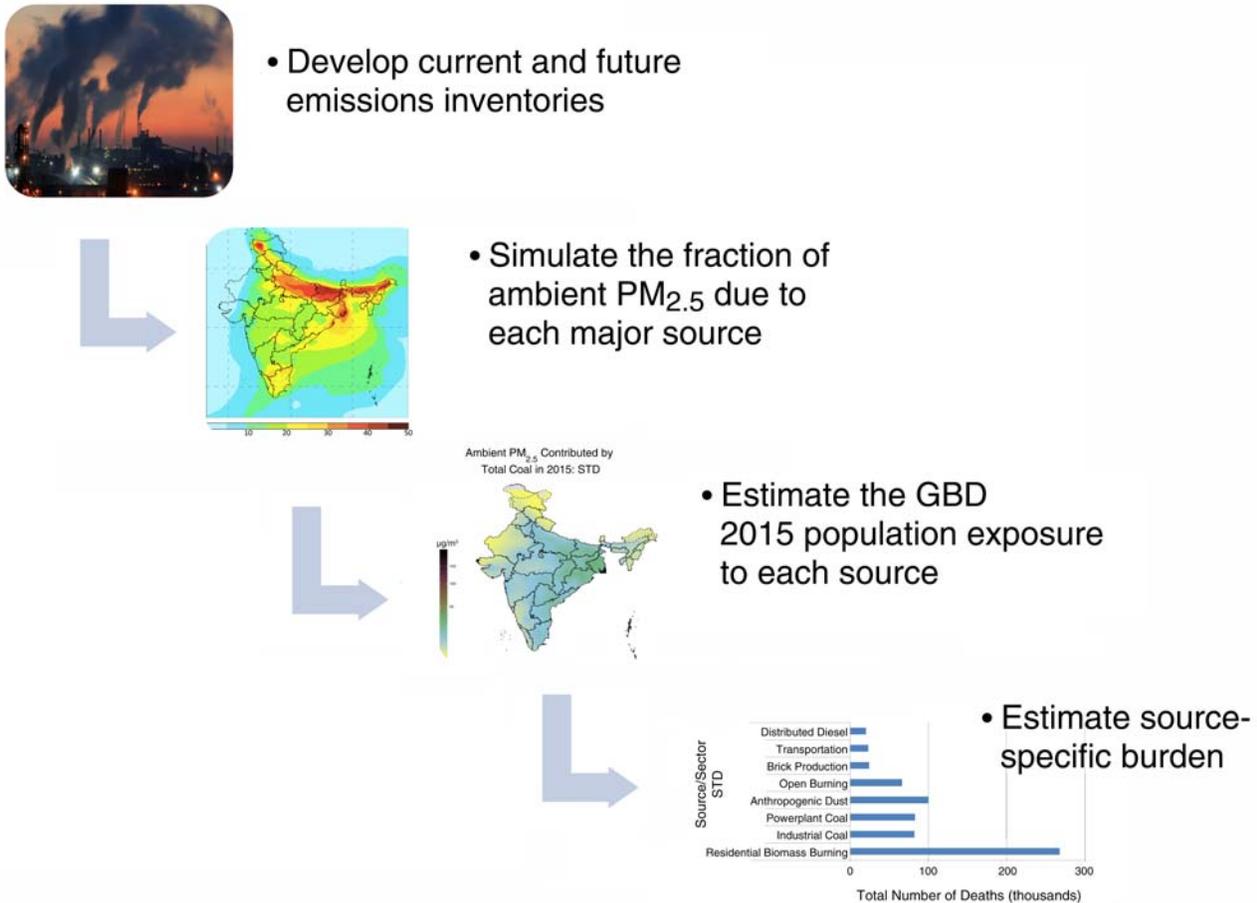
The GBD MAPS analysis involved four main stepwise components, which are illustrated schematically in Summary Figure 3.

In the first step, the GBD MAPS partners at IIT–Bombay developed detailed emissions inventories for 2015, the base

year of the study. The inventories include primary emissions of sulfur dioxide, nitrogen oxides, PM<sub>2.5</sub>, black carbon, organic carbon, ammonia, and non-methane volatile organic hydrocarbons. The emissions were drawn from a multipollutant database for India, covering the period 1996–2015, that included emissions from the industrial, transport, power generation, residential, and agricultural sectors, as well as from the “informal industry” sectors, which included fuel consumption, process and fugitive emissions (unintended or irregular emissions that escape from processes other than through pipes or stacks), and solvent use. The emissions from each sector were estimated at the sub-state (district) level using official Indian statistics and specialized reports. The emissions were then projected forward by IIT–Bombay to 2030 and 2050 under three different energy and policy scenarios that represent a range of assumptions, based on data from the Government of India and others, about shifts in population growth, energy supply and use, technology, and emissions control over time in each of the major sectors (see Summary Table 1). These projections are used to help estimate changes in emissions of PM<sub>2.5</sub>, its components (black carbon and organic carbon), and its gaseous precursors (sulfur dioxide, nitrogen oxides, ammonia, and non-methane volatile organic compounds).

With the emissions from step one as inputs, the second step used the South Asia nested version of GEOS-Chem, a global chemical transport model, to estimate first the ambient PM<sub>2.5</sub> concentrations from all sources or sectors and then the fraction of that total attributable to each of several major sources (see Summary Table 2). These sources were chosen given their inclusion in similar national- and global-level analyses and specific interest in potentially important sources within India. The simulations were conducted for the baseline year 2015, for 2030 (for total PM<sub>2.5</sub> only), and for 2050 under the three scenarios described in Summary Table 1.

The third step, illustrated in Summary Figure 3, combined the fractional contributions of each source (step two) with higher-resolution estimates (defined by approximately 11-km by 11-km grids) of ambient PM<sub>2.5</sub> concentrations developed for GBD 2015 to calculate the source contributions to population exposure (referred to as “population-weighted concentrations” of PM<sub>2.5</sub>) in each grid cell. The GBD 2015 estimates combine (1) satellite-based PM<sub>2.5</sub> estimates and GEOS-Chem data and (2) annual average PM measurements (2008–2014). This approach explicitly incorporated more than 400 Indian surface-level measurements (25 for PM<sub>2.5</sub> and 411 for PM<sub>10</sub> [the larger particulate size fraction that can also be used to



**Summary Figure 3. Schematic representation of GBD MAPS methodology for estimating the burden of disease attributable to major sources of air pollution in India in 2015 and for future scenarios in 2030 and 2050.**

estimate  $PM_{2.5}$ , a size fraction within  $PM_{10}$ ) — all the measurements that were then available.

The final step in the analysis (see Summary Figure 3) estimates the source-specific burden of disease in India. This step couples the source-specific exposures to  $PM_{2.5}$  with the GBD's integrated exposure–response relationships for specific diseases (ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower-respiratory infections) and with India-specific disease and mortality rates. This Summary focuses on the burden from mortality, expressed in terms of the number of deaths attributable to air pollution. The complete results, including DALYs, can be found in the full report. The analyses were conducted for 2015 and for 2050 for each of the three future scenarios taking into account projections of future population, demographics (e.g., age structure and

rates of illness), and economic activity. For 2030, the disease burden attributable to ambient  $PM_{2.5}$  in total was also estimated as an interim analysis. As with the exposure estimates, source-sector–specific contributions to disease burden were estimated for India as a whole and separately for urban and rural areas.

#### PREPARATION AND PEER REVIEW OF THE GBD MAPS REPORT

The draft final report prepared by the GBD MAPS Working Group was reviewed with regard to methodological approach, validity of estimates, and appropriateness of interpretation by independent external peer reviewers from India and other countries, who were selected by HEI for their expertise in different technology sectors and their emissions, in air quality measurement, in atmospheric

**Summary Table 1.** Future Scenarios of Energy and Emissions Control Policies

**REF, or Reference Scenario**

Where the sectoral energy demand is met through sectoral technology-mix evolution at rates corresponding to changes observed during 2005–2015.

**S2, or Ambitious Scenario**

Assumes that the technology mix will reflect (1) the energy-efficiency targets for thermal power and industry as desired in India’s INDC; (2) the emissions standards in transport as proposed in auto-fuel policy; and (3) the emissions controls expected from an influx of cleaner technologies in residential, brick production, and informal industry sectors.

**S3, or Aspirational Scenario**

Aimed at more profound energy efficiency targets, represented by published high-efficiency–low-carbon-growth pathways in industrial, electricity-generation, and transport sectors; high rates of shifting away from traditional biomass technologies (residential and informal industry); and including a complete end to agricultural field burning.

Note: INDC refers to India’s Intended Nationally Defined Contribution to greenhouse gases under the United Nations Framework Convention on Climate Change signed in Paris in 2015.

chemistry and modeling, and in health effects assessment. The list of reviewers can be found in the Contributors list at the beginning of this report. A draft final version of this report was also reviewed by experts on the GBD MAPS Steering Committee. The GBD MAPS Working Group prepared the final report in response to the comments received.

**MAIN FINDINGS**

**THE SITUATION IN 2015**

**Sources Related to Human Activities Were Responsible for the Largest Proportion of the Population Exposure to PM<sub>2.5</sub> in India.**

In 2015, the leading contributors to ambient PM<sub>2.5</sub> exposure (defined as “annual average population-weighted PM<sub>2.5</sub> concentration”) were the sources associated with combustion of biomass and coal and other human activities that generate dust (Summary Figure 4). The India-wide average PM<sub>2.5</sub> exposure in 2015 was 74.3 µg/m<sup>3</sup>. Residential biomass

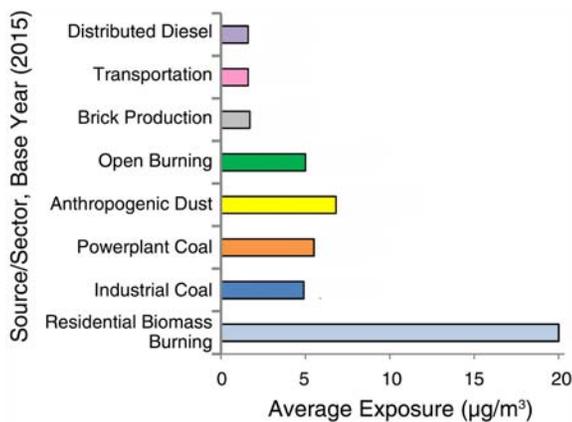
**Summary Table 2.** Major Sources or Sectors Evaluated

Source or Sector Name / Subcategories of Sources or Activities Included

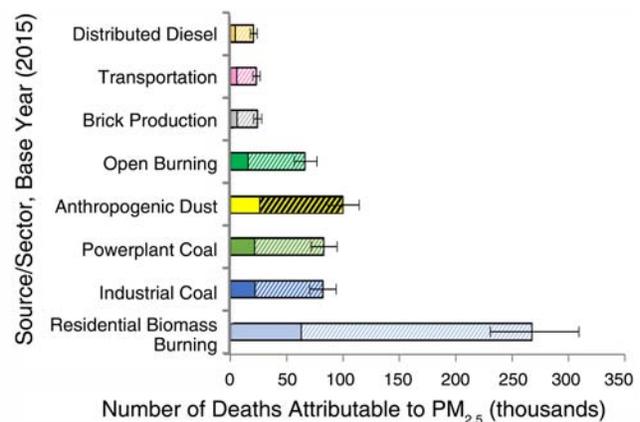
- **Residential Biomass**  
Residential cooking, lighting, heating, and water heating
- **Open Burning**  
Burning of agricultural residue
- **Total Coal**  
Heavy and light industry, electricity generation
- **Industrial Coal**  
Heavy and light industry
- **Power Plant Coal**  
Electricity generation
- **Transportation**  
Private passenger vehicles; public passenger vehicles; freight including light-duty and heavy-duty diesel vehicles; diesel railway locomotives. Shipping not included
- **Brick Production**  
Traditional brick kilns (predominantly)
- **Distributed Diesel**  
Agricultural pumps, agricultural tractors, and electric generator sets
- **Anthropogenic Dust**  
Dust related to human activities — fugitive, combustion, and industrial production
- **Total Dust**  
Windblown mineral dust and anthropogenic dust

burning contributed nearly 24% of the total (see Table 2 in the main report); coal combustion was the next largest contributor (with 7.7% from industry and 7.6% from power generation); and anthropogenic dust (dust related to human activities, including fugitive dust from roads and fly-ash from coal burning and waste burning) contributed about 9%. Also, agricultural burning contributed more than 5%, and transportation, brick production, and distributed diesel each contributed about 2%. Windblown mineral dust contributes to ambient PM<sub>2.5</sub> air pollution; however, the extent of the contribution varies greatly across India, with the most significant contribution in the northwest region.<sup>†</sup>

<sup>†</sup> Note that, although it was not included in the set of sources related to human activities, windblown dust also arguably results in part from human activities that contribute to desertification, for example, either directly through agricultural or forestry practices or indirectly through impacts on climate.



Summary Figure 4. Contribution by selected sources to average population exposure to PM<sub>2.5</sub> in India for 2015 (see Table 3 in the main report).



Summary Figure 5. Contributions (including 95% uncertainty intervals) by selected sources to mortality burden in India in the baseline year, 2015. Hatched bars indicate rural population, and solid bars indicate urban populations.

### Sources of Air Pollution Linked to Human Activity Are Also the Largest Overall Contributors to the 2015 Burden of Disease in India, and the Rural Population Faces the Highest Burdens.

Consistent with their contribution to exposure, sources associated with human activity contributed to nearly 70% of all PM<sub>2.5</sub>-attributable mortality in 2015. Summary Figure 5 shows that the PM<sub>2.5</sub>-attributable mortality estimates for India as a whole in 2015 were dominated by the mortality estimates for the rural population (as defined by the 2011 Indian Census and indicated by the hatched portion of the bars); that is, about 75% of the deaths in India occur among the rural population. This result reflects the fact that a large proportion of the Indian population lives in rural areas (about two-thirds in 2015) and that there are differences in mortality rates and age structures in these populations. Unlike the situation in many other countries, where urban exposures dominate, this study found that the PM<sub>2.5</sub> exposure levels in rural and urban areas in India were similar (i.e., both more than 70 µg/m<sup>3</sup>).

**Residential biomass burning is the largest individual contributor to the burden of disease in India.** Among all sources related to human activities, residential biomass burning was responsible for 267,700 deaths or nearly 25% of the deaths attributable to PM<sub>2.5</sub>, making it the most important single anthropogenic source related to mortality in 2015. These burden estimates do not include the additional substantial burden from indoor exposure to biomass burning.

**Coal combustion and open burning are also substantial contributors to disease burden.** Coal combustion, roughly evenly split between industrial sources and thermal power plants, was responsible for 169,300 deaths (15.5%) in 2015. The open burning of agricultural residue was responsible for 66,200 PM<sub>2.5</sub>-attributable deaths (6.1%).

**Transport, distributed diesel, and brick production are also important contributors to disease burden.** Compared with other sources in this nationwide analysis, transportation, brick kilns, and distributed diesel have relatively small percentage impacts on health burden in 2015. Nonetheless, the numbers of deaths in 2015 attributable to these sources in this study are substantial: 23,100 for transportation; 20,400 for distributed diesel; and 24,100 for brick production.

On a national basis, transportation's contribution to mortality burden was around 2% in both rural and urban areas. These national-level contributions to exposure and burden attributable to transportation are relatively low compared with some produced for city-specific analyses, in part because the geographic scale of the grid used for the analysis is relatively larger and less likely to capture detailed variation in traffic-related exposure within urban areas and near roads. Transportation and distributed diesel sources typically operate in closer proximity to populations than do large stationary sources such as power plants and industrial facilities; for that reason the approach taken in this analysis may underestimate actual exposures and the related disease burden attributable to these sources. Indeed, Indian analyses conducted at finer scales — albeit with their own uncertainties — have found transportation to be a more significant contributor to exposure in India's cities.

LOOKING AHEAD

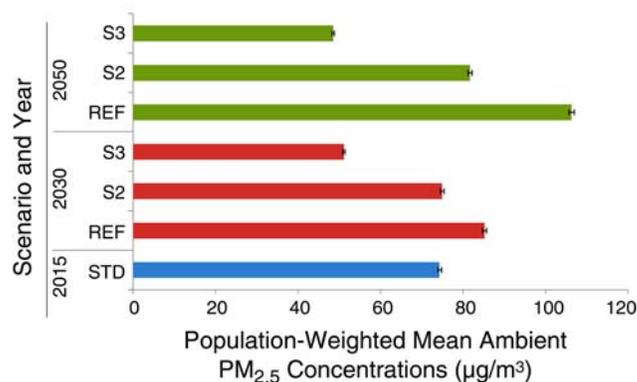
**If No Action Is Taken, Population Exposures to PM<sub>2.5</sub> Are Likely to Increase Substantially in India by 2050.**

As indicated in the introduction, the annual average levels of exposure to PM<sub>2.5</sub> in India are already high relative to guidelines for air quality set by the WHO and Indian national air quality standards. The analysis of alternative future energy and control scenarios shows that choices made on the actions taken to reduce emissions have important implications for reducing both exposure to (see Summary Figure 6) and disease burden from ambient PM<sub>2.5</sub>. Not surprisingly, the scenario with the least aggressive measures (REF) leads to the largest expected increases in the mean population-weighted exposures to PM<sub>2.5</sub> in both 2030 and in 2050 relative to current levels. Even the S2 scenario, an ambitious scenario that will require major commitments to emissions reductions in the face of continued economic growth, is projected just to hold PM<sub>2.5</sub> to current levels by 2030, and to a more modest increase (10%) by 2050. Only under the most active reductions envisioned in the aspirational S3 scenario are exposures projected to be reduced substantially by 2030 and 2050 compared with current levels. The 2050 population-weighted mean exposure for the S3 scenario, even excluding any impact from windblown mineral dust, is estimated to be nearly three times higher than the WHO Air Quality Guideline.

Summary Figure 7 illustrates the contributions of different sources to PM<sub>2.5</sub> under the three future scenarios. It shows that, in 2050, both the magnitude and relative importance of different sources would vary substantially by scenario, reflecting the impacts of the various energy, policy, and other actions assumed under the three scenarios. Although not shown here, the contributions of different sources to PM<sub>2.5</sub> can also vary substantially across India given differences in the location and prominence of those sources regionally. Details can be found in the full report.

**If No Action Is Taken, the Future Burden of Disease from All Sources Will Grow Substantially by 2050; Aggressive Action Could Avoid Nearly 1.2 Million Deaths.**

The burden of disease, in terms of the numbers of deaths attributable to total PM<sub>2.5</sub>, is substantial and expected to grow in the future, as the population ages and grows and leaves more people susceptible to air pollution, despite the projected exposure decreases in the both the S2 and S3 scenarios (Summary Figure 8). Compared with 1.09 million deaths in 2015, ambient PM<sub>2.5</sub> was projected to be responsible for 1.7 million, 1.6 million, and 1.3 million deaths in 2030, rising to 3.6 million, 3.2 million, and 2.5 million



Summary Figure 6. Projected average exposures to PM<sub>2.5</sub> from all study sources in India for 2015 and for the three scenarios in the years 2030 and 2050.

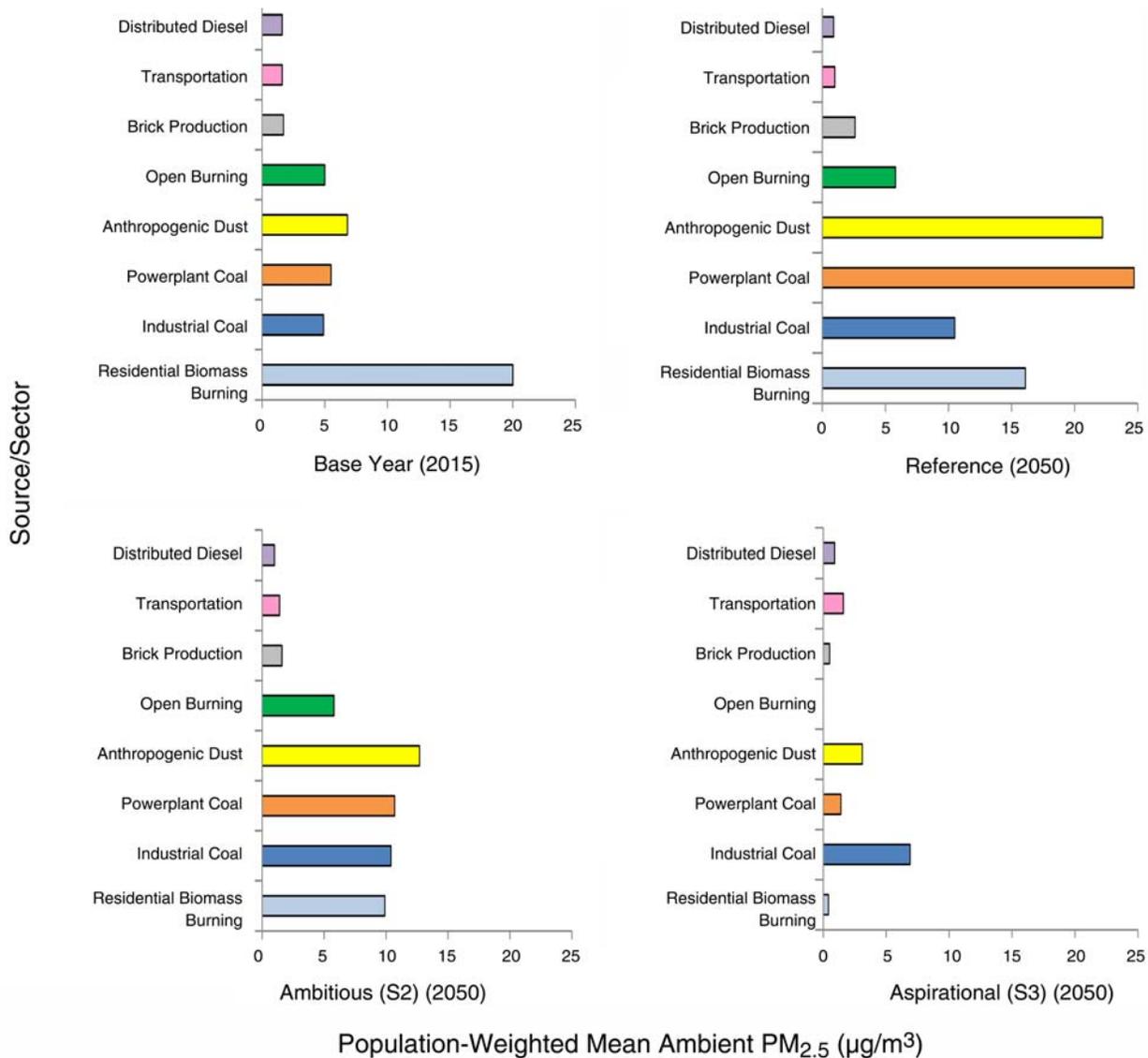
deaths in 2050 for REF, S2, and S3, respectively. Over time, some of the increases in mortality from 2015 can be explained by increases in the numbers and susceptibility of people exposed to air pollution. However, comparison among scenarios suggests that the number of deaths attributable to PM<sub>2.5</sub> was consistently lower in the more aggressive S2 and S3 scenarios than in the REF scenario. Nearly 100,000 to 400,000 deaths could be avoided in 2030 and as many as 340,000 to nearly 1.2 million deaths avoided in 2050 if the more aggressive measures described in scenarios S2 and S3 are implemented.

**Aggressive Action Will Need to Be Taken in All Major Sectors.**

Summary Figure 9 breaks down total contributions to disease burden by source for urban and rural areas in 2015 and in 2050 for all three scenarios.

**Residential biomass burning.** Left unaddressed, as it is under the REF scenario, the burden of disease from the burning of residential biomass to outdoor air pollution could grow to more than 500,000 annual deaths in 2050. There is, however, substantial opportunity to reduce these exposures and effects, especially through a major shift to use of cleaner fuels (e.g., liquefied petroleum gas).

**Combustion of coal by industries and power plants.** In all future scenarios, coal combustion is projected to replace residential biomass burning as the leading contributor to burden in India. Under the REF scenario, its contribution to disease burden is projected to increase considerably — to nearly 1.3 million annual deaths in 2050. In the REF scenario, this increase is attributable primarily to coal-fired power

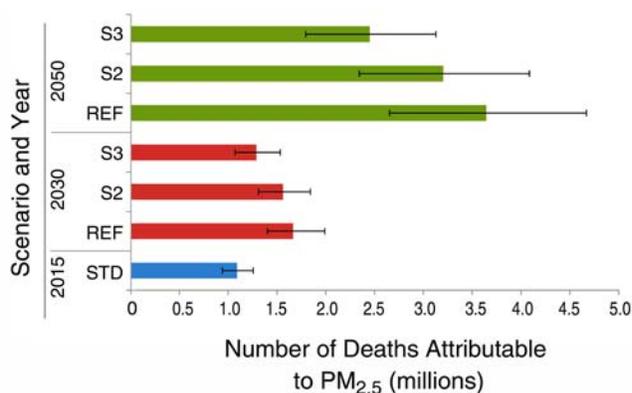


Summary Figure 7. Source contributions to PM<sub>2.5</sub> exposures in India in 2015 and for each of the three scenarios in 2050.

plants; however, in all three scenarios the contributions to burden from industrial burning of coal are also projected to increase. In the most aspirational scenario, S3, contributions from industrial burning of coal will exceed those from power plants. Aggressive emissions control measures, such as those incorporated into scenarios S2 and S3 for coal-burning thermal-power plants and industries, could help avoid between 400,000 and 850,000 coal-attributable deaths in 2050.

**Transportation, distributed diesel, and brick kilns.**

Although small in this analysis in comparison to other sources, the impacts of transportation and distributed diesel sources are projected to increase substantially under all future scenarios. The increases are attributable both to factors affecting emissions and to the growth and aging of the population, as discussed for other sectors. The relative contribution of transportation to disease burden was projected to increase in the S3 scenario in 2050 compared with 2015 (3% versus 2.1%, respectively), although the number of deaths



Summary Figure 8. Total number of deaths (including 95% uncertainty intervals) attributable to total PM<sub>2.5</sub> from all sources in 2015 and for each of the three scenarios in 2030 and 2050.

remained the same. For transportation, the future scenarios reflect a complex interplay. This analysis assumes decreased per-vehicle emissions as a result of the implementation of the more stringent Bharat Stage VI/6 emissions standards. The improvements in emissions per individual vehicle, however, will be offset in part by increases in the numbers of vehicles and in vehicle use. The analysis also assumes changes in transportation modes, especially in S2 and S3, which involve, for example, shifts to bus fleets powered by compressed natural gas and electricity in urban areas. The analysis assumes a continued reliance on diesel in rural areas.

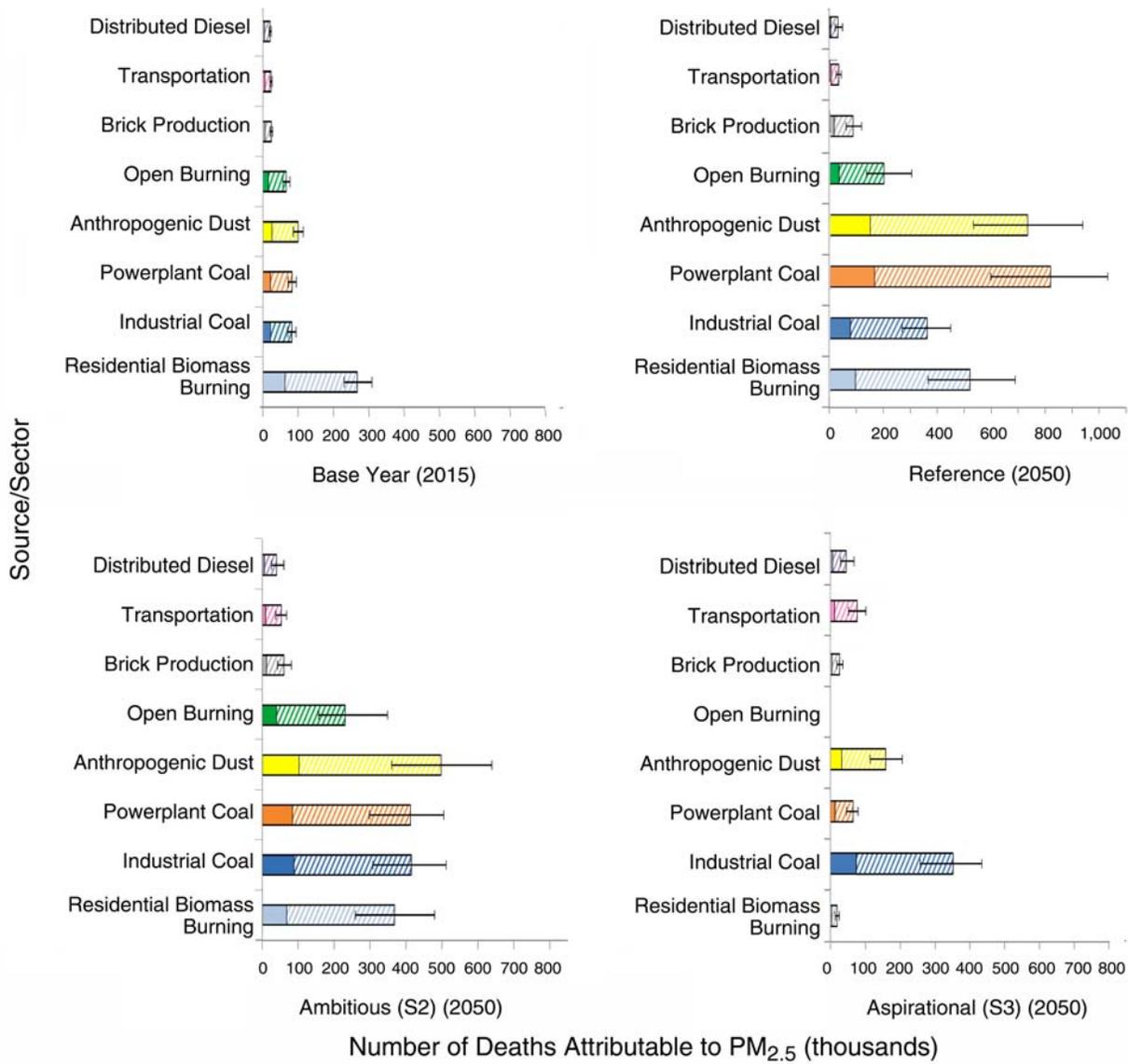
Brick production is projected to have increased impacts on disease burden under the REF and S2 scenarios. Under the aspirational scenario, S3, the impacts on mortality remained at levels similar to those estimated for 2015, reflecting a balance between the impacts of reductions in emissions and the impact of demographic trends on mortality.

**Anthropogenic dust.** The potential future impacts of anthropogenic dust are large. Anthropogenic dust includes fugitive dust and dusts from combustion and industrial production. Of the total 1.09 million deaths attributable to PM<sub>2.5</sub> in 2015 in India, approximately 99,900 deaths are attributable to dust from anthropogenic activities. In each of the future scenarios, the increases in population-weighted dust concentrations and the related burden on health are entirely attributable to changes in the anthropogenic component. For example, under the REF scenario, the anthropogenic component of dust more than tripled from 6.8 µg/m<sup>3</sup> in 2015 to 22.2 µg/m<sup>3</sup> in 2050. Specifically, road dust emissions are projected to nearly double between 2015

and 2030 and to stabilize (but not decrease) from 2030 to 2050 as emissions reductions from improvements to road quality are offset by increased vehicle use. Left unchecked, as in the REF scenario, dust emissions from anthropogenic activities are projected to be responsible for 743,000 attributable deaths. These projections from our analysis suggest that more attention should be directed toward reductions in anthropogenic dust emissions in particular.

## LIMITATIONS

Although this study has many strengths as the first detailed national-level analysis of source-sector-related exposure and burden of disease in India, it has — like any analysis — some limitations. The analysis necessarily required a number of decisions and assumptions, which were based on the best data available to the Working Group at the time. Some of the decisions may underestimate the true burden attributable to air pollution. For example, this report focused only on PM<sub>2.5</sub> exposures; however, the GBD project also evaluates the contribution of ozone exposure to the burden of disease from air pollution. Although ozone’s contribution has been much smaller than that of PM<sub>2.5</sub>, recent research suggests that exposures to ozone are likely to increase in India in the future. Other decisions may introduce uncertainties whose potential magnitude and biases are not yet known; these include the use of the integrated exposure–response curves to predict disease-specific burden and the assumption that all airborne particles smaller than 2.5 µm in aerodynamic diameter are equally toxic, among others. Similarly, our projections of pollution under future scenarios in 2030 and 2050 are based on a range of assumptions about planned initiatives, expected growth and development, and feasible policies and technology changes. The extent to which these will be realized or perhaps replaced by as-yet-unknown disruptive technologies and trends is unknown. As such, the reference scenario and the more aspirational S3 scenario are best viewed as bounding the likely path of changes in emissions in India. Finally, with the exception of windblown mineral dust, this report does not address the impact of specific emissions sources outside India on exposure and disease burden within India, nor does it estimate the impact of emissions that originate within India on the health of populations outside the country, as some recent analyses have done.



Summary Figure 9. Source contributions to disease burden (deaths) in urban (solid) and rural (hatched) areas of India in 2015 and in 2050 for each of the three scenarios. The 95% uncertainty intervals on the combined urban and rural deaths are also presented. (Note that the x-axis scales vary.)

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### CONCLUSIONS

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The analyses conducted in this study have shown that multiple air pollution sources contribute to a significant health burden attributable to ambient PM<sub>2.5</sub> air pollution in India today. They also pose major challenges for air quality management and for the reduction of air-pollution-related health burden in the future. As is the case for all countries that are growing and aging in ways that make them more susceptible to the effects of air pollution, future mortality attributable to air pollution in India is expected to grow even with reduction in air pollution levels. In India, given expected growth in economic activity and population, our estimates predict that future exposures to ambient PM<sub>2.5</sub> will increase by 2050 under the REF scenario and even under the ambitious S2 scenario. Reductions in exposure are projected in 2030 and 2050 only under S3, the most aspirational air pollution control scenario. When combined with the changes in population demographics, these exposures are predicted to increase the number of deaths attributable to air pollution in India in the future. However, our estimates also indicate that there are significant opportunities in both urban and rural India to avoid hundreds of thousands to more than a million deaths by 2050 if the emission control measures described in scenarios S2 and S3 are implemented. The Indian government has begun to initiate actions to improve air quality; ultimately, aggressive implementation of air quality management, such as that simulated for our aspirational S3 scenario, will be required to lead India to a reduction of disease burden and protection of public health from air pollution in the future.

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### REFERENCES

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- Dandona L, Dandona R, Kumar GA, Shukla DK, Paul VK, Balakrishnan K, et al. 2017. Nations within a nation: Variations in epidemiological transition across the states of India, 1990–2016 in the Global Burden of Disease Study. *Lancet* [http://dx.doi.org/10.1016/S0140-6736\(17\)32804-0](http://dx.doi.org/10.1016/S0140-6736(17)32804-0) [accessed 15 November 2017].
- GBD 2015 Risk Factor Collaborators. 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: A systematic analysis for the Global Burden of Disease study 2015. *Lancet* 388:1659–1724.
- Indian Council of Medical Research, Public Health Foundation of India, and Institute for Health Metrics and Evaluation. 2017. India: Health of the Nation's States — The India State-Level Disease Burden Initiative. New Delhi:ICMR, PHFI, and IHME.
- MoHFW (Ministry of Health and Family Welfare). 2015. Report of the Steering Committee on Air Pollution and Health-Related Issues. New Delhi, India:Ministry of Health and Family Welfare, Government of India. Available: <http://ehsdiv.sph.berkeley.edu/krsmith/publications/2015/MoHFW%20AP%20Steering%20Com.pdf> [accessed 11 August 2017].
- World Bank and Institute for Health Metrics and Evaluation. 2016. The Cost of Air Pollution: Strengthening the Economic Case for Action. Washington, DC:World Bank.

# Burden of Disease Attributable to Major Air Pollution Sources in India

GBD MAPS Working Group

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## 1.0 INTRODUCTION

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### 1.1 PROJECT RATIONALE AND OVERVIEW

The systematic analysis for the 2015 Global Burden of Disease study (2016) estimated that exposure to ambient fine particulate air pollution (PM<sub>2.5</sub>\*) contributed to 4.2 million deaths globally in 2015, with 65% of those deaths occurring in China, India, and other developing countries of Asia. The GBD effort is the largest and most comprehensive to date to measure epidemiological levels and trends worldwide ([www.healthdata.org/gbd](http://www.healthdata.org/gbd)). This update of the study involved more than 1,800 collaborators from more than 120 countries and 3 territories. GBD 2015 estimated the burden of disease attributable to 79 risk factors, including ambient and household air pollution, for 1990–2015 in 195 countries and territories and at subnational levels for China, the United States, and several other countries (GBD 2015 Risk Factor Collaborators 2016).

Estimating and communicating the burden of disease attributable to air pollution from major sources are critical next steps to support the control of *both* air pollution and climate-forcing emissions. The GBD analytic framework is uniquely suited to develop such estimates for coal-burning and other key emission sources, including, for example, thermal power plants, transportation, industrial activities, agricultural burning and residential combustion, all of which have been found in source apportionment studies to contribute to high levels of air pollution. The GBD methodology allows estimates of both current burden due to past exposure and predictions of future burden based on projected trends in mortality and air pollution emissions and concentrations at subnational, national, regional, and global scales.

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Correspondence may be addressed to Dr. Katy Walker, Health Effects Institute, 75 Federal Street, Suite 1400, Boston, MA 02110, USA; e-mail: [kwalker@healtheffects.org](mailto:kwalker@healtheffects.org).

\* A list of abbreviations and other terms appears at the end of this volume.

The Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) initiative was designed to estimate the current and future burdens of disease attributable to ambient air pollution from major PM<sub>2.5</sub> sources in China and India using the GBD framework and to disseminate the estimates in order to inform planned policy decisions in these locales. GBD MAPS is a multiyear collaboration between the Health Effects Institute (HEI), the Institute for Health Metrics and Evaluation (IHME), the India Institute of Technology (IIT) Bombay, Tsinghua University, the University of British Columbia, and other leading academic centers.

The GBD MAPS China report, titled *Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China*, was published by HEI in 2016 (GBD MAPS Working Group 2016). In China, coal combustion was the single largest source of air pollution–related health impact in 2013, contributing to some 366,000 deaths — 40% of the total number of deaths in 2013 attributable to PM<sub>2.5</sub> pollution. Industry and household combustion were major contributors as well. Based on an analysis of policy-relevant future scenarios, the report indicated that health burdens could grow substantially by 2030 in China if no further action is taken, but that aggressive action to reduce emissions from all major sources could reduce rates of air pollution–attributable mortality in the future.

The current report describes the objectives, methods, and results of the GBD MAPS analysis for India.

### 1.2 SPECIFIC OBJECTIVES

1. To estimate ambient PM<sub>2.5</sub> concentrations and the associated disease burden attributable to major air pollution sources in India for the year 2015 from major source sectors, including coal-burning from power generation and industry, residential combustion, transportation, and open burning.
2. To estimate ambient concentrations and disease burden attributable to major source sectors for the year 2050 — considering both future mortality projections and three future emissions scenarios. The scenarios were designed to reflect different strategies for reducing emissions from major sources; they differ with regard to the contributions of different energy sources and their prioritization and aggressiveness of source-specific emission reductions.

### 1.3 PROCESS

The GBD MAPS project was begun by HEI in 2014. HEI selected the Working Group — including experts from India and China — that designed and conducted the analyses and drafted this report. HEI also recruited an International Steering Committee that advised the Working Group and reviewed its work. The Working Group initially developed a detailed analytic plan in consultation with the International Steering Committee, which in turn reviewed the choice and design of future emission scenarios used in this report. Selected preliminary results for India were presented at the American Association for the Advancement of Science in February 2016 and the HEI Annual Conference in Denver in May 2016.

The draft final report was peer-reviewed with regard to methodologic approach, validity of estimates, and appropriateness of interpretation by independent external reviewers selected by HEI for their expertise in air quality, atmospheric chemistry and modeling, and health effects. The peer reviewers were Dr. Noelle Selin, Massachusetts Institute of Technology; Dr. Pallavi Pant, University of Massachusetts; Anup Bandivadekar, International Council on Clean Transportation; Bhargav Krishna, Public Health Foundation of India; and Kunal Sharma, Shakti Foundation. A draft final version of this report was also reviewed by experts on the GBD MAPS Steering Committee. The Working Group prepared the final report in response to the comments received.

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## 2.0 BACKGROUND

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### 2.1 AIR QUALITY IN INDIA

Ambient air pollution has increased in India over the last 25 years. India has maintained air quality monitoring stations at a number of locations throughout the country for several decades. The GBD project estimates current levels and trends in ambient PM<sub>2.5</sub>, a major component of air pollution, by incorporating ground measurements from these monitors and satellite-based estimates (Brauer et al. 2016). The latest GBD 2015 estimates indicate that the population-weighted mean PM<sub>2.5</sub> concentration for India as a whole was 74.3 µg/m<sup>3</sup> in 2015, up from about 60 µg/m<sup>3</sup> in 1990. At current levels, 99.9% of the Indian population is estimated to live in areas where the World Health Organization (WHO) Air Quality Guideline of 10 µg/m<sup>3</sup> was exceeded. Nearly 90% of people lived in areas exceeding the WHO Interim Target 1 of 35 µg/m<sup>3</sup>. In 2015, at the state level in India, population-weighted mean

concentrations ranged from a low of 27.2 µg/m<sup>3</sup> (in Arunachal Pradesh) to a high of 132.4 µg/m<sup>3</sup> (in Delhi). Nationally the population-weighted mean increased by 24% from 1990 to 2015. Between individual states there was variation in the trends since 1990, with increases observed in most of the country.

### 2.2 BURDEN OF DISEASE FROM AIR POLLUTION

#### 2.2.1 Air Pollution and Health

The air that people breathe is a complex mixture — including hundreds of individual gaseous compounds and particles of complex composition — that varies in composition both spatially and temporally. Therefore, indicator pollutants are typically used to estimate exposures for epidemiological analysis and disease burden assessment. Within the GBD framework, the disease burdens attributable to both PM<sub>2.5</sub> and ozone are considered, based on evidence of their independent adverse health impacts and on distinctions between the spatial and temporal patterns of concentrations of these two species. However, in this report we focus our assessment on only PM<sub>2.5</sub>, given that in the GBD 2015 report, the burden attributable to PM<sub>2.5</sub> (4.2 million deaths globally [1.09 million in India]) vastly exceeded that attributable to ozone (254,000 deaths globally [107,770 in India]). In populated regions, a large fraction of PM<sub>2.5</sub> originates from combustion processes, and it includes both primary particulate matter (PM) (direct emissions) and secondary PM (resulting from atmospheric transformations of precursor compounds such as nitrogen and sulfur oxides). One of those combustion sources is the residential burning of solid fuels (e.g., wood and other biomass) for cooking, lighting, and heating. Although the contribution of such residential pollution to concentrations of ambient PM<sub>2.5</sub> and to the resulting disease burden is estimated in this report, its contribution to exposures within the household and to the associated disease burden is not. The estimate of disease burden from these indoor exposures is substantial, with an estimated 977,000 attributable deaths in 2015. As such, the estimates of the disease burden attributable to such residential sources substantially underestimate the full attributable burden from this practice.

The health effects of exposure to PM in ambient air are widespread and substantial, and they have been reviewed and summarized in detail (U.S. Environmental Protection Agency [U.S. EPA] 2009; WHO 2005). The epidemiological observations of adverse health impacts associated with elevated ambient PM<sub>2.5</sub> concentrations are supported by

toxicological experiments, epidemiological analyses of acute exposures, and controlled exposure studies. For example, in its most recent comprehensive Integrated Science Assessment (ISA) document, the U.S. EPA concluded that short-term exposure to PM<sub>2.5</sub> was a cause of mortality and cardiovascular effects, such as hospitalization and emergency department visits, and was likely to be a cause of respiratory effects such as chronic obstructive pulmonary disease (COPD), respiratory infection hospitalizations, and emergency department visits for asthma. The U.S. EPA also concluded that long-term (months to years) exposure to PM<sub>2.5</sub> was a cause of cardiovascular mortality, whereas respiratory effects such as decreased lung function, increased respiratory symptoms, and development of new cases of asthma were likely to be causally linked to PM exposure. At the time of this assessment, reproductive and developmental effects, as well as cancer, were characterized by the U.S. EPA as suggestive of being caused by long-term exposure to fine PM. Of note, systematic reviews have since concluded that PM<sub>2.5</sub> exposure is associated with low birthweight and preterm birth (Shah and Balkhair 2011; Stieb et al. 2012) and diabetes (Eze et al. 2015). Detailed evaluations by the American Heart Association (Brook et al. 2010) and the European Society of Cardiology (Newby et al. 2015) have also concluded that PM<sub>2.5</sub> exposure is a cause of cardiovascular morbidity and mortality and that exposure for a few hours to weeks can trigger cardiovascular disease-related mortality and nonfatal events. Evidence for the effects of both short-term and long-term exposure to PM on respiratory disease has also strengthened in recent years. For example, evidence now suggests that exposure to PM is associated with hospitalization for asthma as well as for COPD and with incidence of asthma in children (Guarnieri and Balmes 2014; Sava and Carlsten 2012). Further, the International Agency for Research on Cancer (IARC) concluded in 2014 that airborne PM was a cause of cancer in humans (Loomis et al. 2013).

The evidence summarized above has not consistently indicated that variation in PM composition, individual PM components, or their sources results in different levels of toxicity or other health impacts, so this remains an area of active research. The most recent U.S. EPA synthesis (U.S. EPA 2009) concluded that “many constituents of PM can be linked with differing health effects and the evidence is not yet sufficient to allow differentiation of those constituents or sources that are more closely related to specific health outcomes.” Further, with respect to sources of PM, the WHO Review of Evidence on Health Aspects of Air Pollution (REVIHAAP) assessment (WHO 2013) concluded that evidence developed since the 2009 U.S. EPA ISA did not lead to any changes in conclusions regarding the inability to differentiate PM constituents or sources

that are more closely linked to specific health outcomes. IARC’s recent evaluation of the carcinogenicity of particulate air pollution concluded that its carcinogenicity was independent of source or composition (Loomis et al. 2013). These conclusions have most recently been corroborated in large-scale epidemiological and toxicological studies (HEI NPACT Review Panel 2013). Based on the current evidence, the GBD assessments of PM<sub>2.5</sub> have assumed all particulate matter to have the same toxicity; we consequently employ this assumption in this analysis.

### 2.2.2 Studies of Air Pollution and Health in India

Urban and rural populations in India experience a substantial burden of disease from exposures to ambient air pollution and household air pollution from the burning of solid fuels for cooking, lighting, heating, and warming water (Balakrishnan et al. 2014). Estimates of the burden these exposures impose on public health impact are supported by an extensive international literature, as well as by the Indian literature, which provides evidence that the adverse effects of exposure to air pollution seen in other global regions are also occurring in India. A recent authoritative report of the Steering Committee on Air Pollution and Health Related Issues of the Indian Ministry of Health and Family Welfare reviewed the current evidence on the health effects of exposure to ambient and household air pollution and noted the “... long history and substantive volume of studies in India that have examined the health effects of ambient and household air pollution,” commenting on the “...comparability of available study results to the global pool of evidence...” (Government of India Ministry of Health and Welfare [MoHFW] 2015, page 96). We briefly summarize this evidence below.

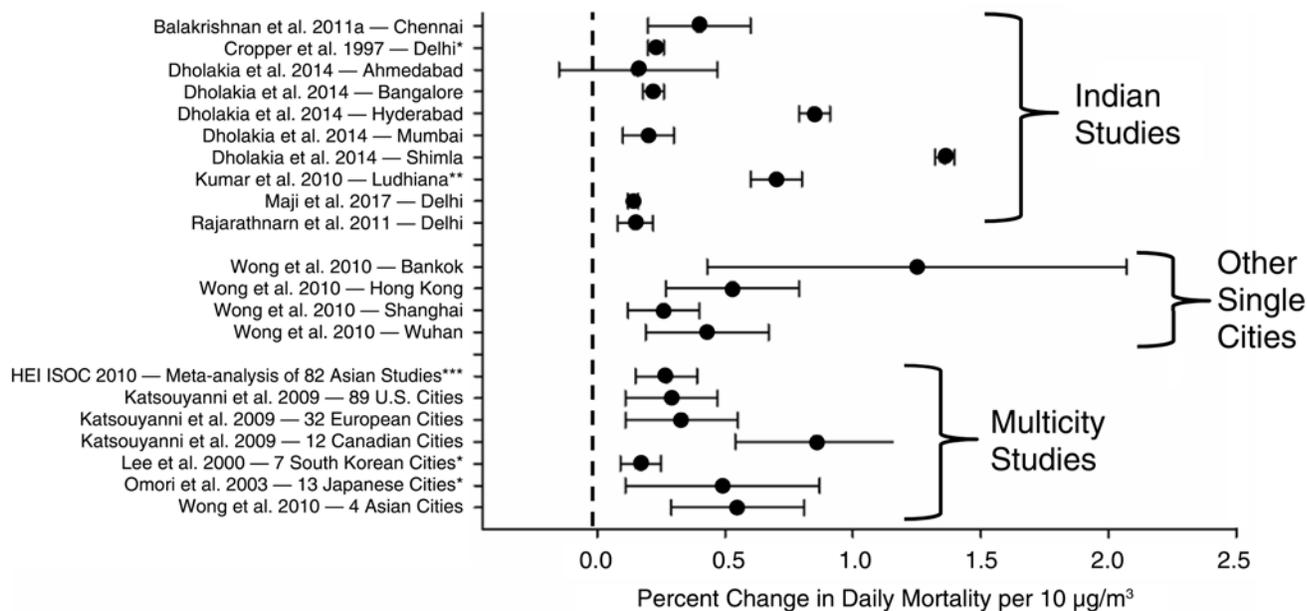
Indian studies conducted since 1980 have reported adverse effects of exposure to air pollution. A systematic review of the literature on the health effects of ambient air pollution in Asia published by HEI in 2010 identified 43 studies of the health effects of air pollution in India published from 1980 to 2008 (HEI International Scientific Oversight Committee 2010). These studies, largely concentrated in the cities of Delhi and Mumbai, reported that the prevalence of diminished lung function, acute and chronic respiratory symptoms such as cough and wheeze, and asthma in children and adults was increased in areas with elevated levels of air pollution. Three studies reported increases in acute respiratory illness (Bladen 1983), all-cause mortality (Cropper et al. 1997), and emergency room visits for cardiorespiratory conditions (Pande et al. 2002) related to short-term exposure to air pollution.

Indian studies published since 2010 consistently report increased rates of mortality due to short-term exposure to

PM and other pollutants. Figure 1 compares results from time-series studies of mortality associated with daily exposures to PM in several Indian cities with those from studies conducted in single and multicity analyses in Asia and around the world. HEI supported a coordinated set of time-series studies examining the association of natural all-cause mortality with short-term (daily) exposure to PM<sub>10</sub> in the cities of Chennai, Delhi, and Ludhiana (Balakrishnan et al. 2011a; Kumar et al. 2010; Rajarathnam et al. 2011). Studies using similar methods have also been reported from other cities and other time periods (Dholakia et al. 2014; Maji et al. 2017). These studies estimate changes in daily rates of mortality associated with short-term PM exposure that are similar to those reported in multicity studies conducted in China, South Korea, Japan, Europe, and North America (Wong et al. 2008). The figure shows that the Indian time-series studies found similar percentage increases in daily mortality associated with ambient PM as did studies in the other countries. In addition, a growing body of literature reported on acute health effects associated with episodic extreme air pollution events such as crop burning (Awasthi et al. 2010; Gupta et al. 2016; Pande et al. 2002), use of fireworks during Diwali (the Hindu festival of lights) (Pal et al. 2014), and in

critically polluted areas within large cities (Kumar et al. 2007; Siddique et al. 2010).

To date, there have been no direct epidemiological studies in India of long-term exposure to ambient PM<sub>2.5</sub> and mortality from chronic respiratory and cardiovascular disease, the type of evidence used to estimate the burden of disease from air pollution in the GBD project. For this reason, the results of studies conducted in North America and Western Europe have been used to estimate disease burden in India (Burnett et al. 2014; MoHFW 2015, page 13). However, the similarity between Indian risk estimates for effects of short-term exposure on daily mortality and global estimates is noteworthy — especially given the differences in concentration ranges, source mixtures, demographics, and underlying disease rates — and supports the use of international studies to estimate Indian disease burden. In addition, a limited number of Indian studies corroborate the broader global evidence for pathophysiological effects that may underlie the development of chronic non-communicable respiratory and cardiovascular disease. These Indian studies report findings that air pollution has been associated with a range of underlying effects, including cytopathological changes (such as increased prevalence of mucus plugs and siderophages,



**Figure 1. Comparison of Indian and international time-series studies of ambient air pollution and changes in daily mortality.** The Indian studies were all conducted in individual cities; their results are compared with those of individual studies in other Asian countries and with those of multicity studies in Asia, Europe, and North America. The dashed line indicates no increase in daily mortality. Studies that relied on measures of exposure other than PM are indicated by \* (suspended particulate matter) and \*\* (visibility). The \*\*\* indicates that various metrics were used in the multicity studies.

goblet cell hyperplasia, and nuclear anomalies of columnar epithelial cells), airway inflammation (indicated by increased counts of neutrophils, lymphocytes, eosinophils, and alveolar macrophages, and by higher sputum levels of IL-6, IL-8, and TNF- $\alpha$ ) and oxidative stress (indicated by enhanced ROS generation and depletion of SOD activity) (Basu et al. 2001; Dutta et al. 2012; Lahiri et al. 2008; Ray et al. 2006; Roy et al. 2001; Roychoudhury et al. 2012).

Since 1980, numerous epidemiological studies have also examined health effects associated with household air pollution (HAP) exposures in India, especially among women and children (Balakrishnan et al. 2011b). However, unlike studies of ambient air pollution that characterize exposure to air pollution in terms of estimated levels of PM and other pollutants, most epidemiological studies concerning HAP have used qualitative indicators to characterize exposure, such as type of fuel used (solid fuels as opposed to clean cooking fuels), involvement in cooking, or proximity to a stove. Several Indian studies are currently included in systematic reviews and meta-analyses used by the GBD efforts to estimate HAP-related risks. For example, for COPD, estimated relative risks (comparing use of solid fuels with clean fuels) ranged from 2.1 to 4.5 (Behera 1997; Dutt et al. 1996; Jindal et al. 2006; Qureshi 1994); for lung cancer, from 1.52 to 3.59 (Gupta et al. 2001; Sapkota et al. 2008); for acute lower respiratory infections (LRI), from 1.58 to 3.67 (Mishra and Retherford 1997; Mishra et al. 2005; Pandey et al. 1989); and for cataracts, from 1.61 to 4.91 (Badrinath et al. 1996; Mohan et al. 1989; Saha et al. 2005; Sreenivas et al. 1999; Zodpey and Ughade 1999).

A small but growing number of HAP studies in India have also reported associations of residential biomass fuel use with increases in a range of additional health outcomes, including low birth weight and stillbirths (Mavalankar et al. 1991; Tielsch et al. 2009), asthma (Mishra 2003), and tuberculosis (Kolappan and Subramani 2009; Lakshmi et al. 2012; Mishra et al. 1999). Given the smaller evidence base for these outcomes, none are currently included in HAP-attributable disease burden estimates.

Recently, the Indian Council of Medical Research, Government of India, has supported the launch of epidemiological cohort studies to estimate the effects of long-term exposure to ambient and HAP on a range of maternal (birthweight), child (acute respiratory infections), and adult (chronic respiratory symptoms and lung function) health outcomes in populations residing in both urban and rural locations (Balakrishnan et al. 2015). The exposure estimates from these studies are being applied in other long-term cohort studies examining cardiovascular risk factors such as high blood pressure, brachial artery hyperreactivity, and carotid intima-media thickness (Thanikachalam et al. 2015)

### 2.2.3 Integrated Exposure–Response Functions

In the GBD framework, the relative risks of mortality from ischemic heart disease (IHD), stroke, COPD, lung cancer (LC), and acute LRI in children and adults associated with PM<sub>2.5</sub> were estimated using cause-specific integrated exposure–response functions, or IERs (Burnett et al. 2014; Cohen A. et al. 2017). Each cause-specific IER integrates published relative risk estimates for PM<sub>2.5</sub> from a variety of exposures to inhaled PM (outdoor air pollution, second-hand smoke, household air pollution, and active smoking) to estimate the relative risk of mortality from exposure to PM<sub>2.5</sub> over the entire global range. This analysis relies on the assumption, consistent with the evidence summarized in section 2.2.1, that risk is a function of the dose of inhaled PM<sub>2.5</sub>, regardless of exposure source. The IER functions are non-linear, especially for IHD and stroke, meaning that the change in the relative risk is greater at lower concentrations than at higher ones (Pope et al. 2011). The IER functions are necessary to estimate the relative risk of air pollution exposure in countries with high levels of air pollution, such as India, but where no epidemiological studies of long-term exposure to PM<sub>2.5</sub> have yet been completed. At the low concentrations of the IER, the functions reflect the change in risk observed in cohort studies conducted at low concentrations of ambient PM<sub>2.5</sub> and are nearly linear. Extrapolation of the risks based on these studies alone would result in unrealistically high risk estimates in countries like India where the concentrations of PM<sub>2.5</sub> are high. The predicted risks for the highest PM<sub>2.5</sub> concentrations on the IER curves are consistent with the risks from tobacco smoking (Pope et al. 2011). The applicability of the IER model in the Indian context was recently reviewed and endorsed by the Steering Committee on Air Pollution and Health Related Issues of the Indian Ministry of Health and Family Welfare (MoHFW 2015, pages 13 and 96). More detail on the development and application of the IER functions for PM<sub>2.5</sub> is provided in the accompanying Sidebar 1.

### 2.2.4 Estimation of the Burden of Disease

Within the GBD framework, the process for estimating the burden of disease in India is illustrated in Figure 2, which shows how India-specific data on exposure to PM<sub>2.5</sub> or other pollutants are coupled with the IERs discussed above and with India-specific health data in order to estimate the burden of disease. Each of these steps is described in further detail in subsequent sections of the report. The burden of disease attributable to exposure to a pollutant or to other risk factors is defined in terms of deaths (mortality) and disability-adjusted life-years (DALYs). The number of deaths attributable to air pollution in a given year includes deaths that have likely occurred months or even years

**SIDEBAR 1: IER MODEL FOR PM<sub>2.5</sub>**

Risk estimates attributable to exposure to outdoor concentrations of fine particulate matter (i.e., PM<sub>2.5</sub>) for mortality from ischemic heart disease, stroke, the lung diseases of chronic obstructive pulmonary disease and lung cancer, and acute lower respiratory infection in both children and adults are constructed by integrating information on risk from multiple sources of PM<sub>2.5</sub> exposure such as ambient air pollution, secondhand smoke, household air pollution from burning of solid fuels for heating and cooking, and active smoking. This approach was taken because no direct evidence of risk over the entire global concentration range was available. Exposure to each of these sources was integrated using an equivalent 24-hour average ambient concentration (µg/m<sup>3</sup>). The IER model was developed following the assumption that the effect of each type of PM<sub>2.5</sub> exposure (i.e., ambient air pollution, secondhand smoke, household air pollution from burning of solid fuels for heating and cooking, and active smoking) was independent each of the others. That is, exposure to ambient air pollution is based solely on the ambient air exposure estimates of the specific cohort studies examined. The same assumption was made for the other types of PM<sub>2.5</sub> exposures. We used this type of risk information as a tool to extend the concentration–response curve beyond that observed in cohort studies in North American and Western Europe.

The IER function has the mathematical form

$$IER(\beta, z) = 1 + \alpha \times \left( 1 - e^{-\beta(z-z_{cf})^{\gamma}} \right)_{+}$$

where  $z$  is the level of PM<sub>2.5</sub> and  $z_{cf}$  is the theoretical minimum risk exposure level (TMREL), below which no additional risk is assumed, with  $(z - z_{cf})_{+} = (z - z_{cf})$  if  $z > z_{cf}$

and is equal to zero otherwise. Here  $1 + \alpha$  is the maximum risk,  $\beta$  is the ratio of the IER at low to high concentrations, and  $\gamma$  is the power of PM<sub>2.5</sub> concentration.

Observed relative risks were related to the IER within a Bayesian framework. Given the true values of the four parameters,  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $z_{cf}$ , we assumed that the logarithm of each study’s observed relative risk was normally distributed, with mean defined by the IER and variance given by the square of the observed standard error of the study-specific log-relative risk estimate plus an additional variance term for each of the four sources on PM<sub>2.5</sub> exposure (ambient air pollution, secondhand smoke, household air pollution from burning of

solid fuels for heating and cooking, and active smoking) (Cohen et al. 2017).

The counterfactual concentration  $z_{cf}$ , or TMREL, was assigned a uniform distribution, with lower and upper bounds given by the average of the minimum and fifth percentiles of outdoor air pollution cohort studies exposure distributions, with the assumption that it is impractical to characterize the shape of the concentration–response function below the fifth percentile of any exposure distribution. The specific outdoor air pollution cohort studies selected for this averaging were chosen based on the criterion that their fifth percentiles were less than that of the American Cancer Society Cancer Prevention II (CPS II) cohort’s fifth percentile of 8.8 µg/m<sup>3</sup>. This criterion was used because the GBD 2010 report (Lim et al. 2012) had used the minimum, 5.8 µg/m<sup>3</sup>, and fifth percentile solely from the CPS II cohort. The resulting lower and upper bounds for the GBD 2015 report were 2.4 µg/m<sup>3</sup> and 5.9 µg/m<sup>3</sup>, respectively.

One thousand sets of IER parameter estimates were generated from the estimated uncertainty distributions for  $\alpha$ ,  $\beta$ , and  $\gamma$ , and the pre-specified uniform uncertainty distribution for  $z_{cf}$ . One thousand predicted values of the IER curve were calculated for each PM<sub>2.5</sub> concentration based on these 1,000 sets of parameter estimates. The distribution of these predicted values characterizes the uncertainty in the estimates of the IER function. The arithmetic mean of the 1,000 IER predictions at each concentration was used as the central estimate, and the upper and lower bounds were defined by the 0.975 and 0.025 percentiles, respectively.

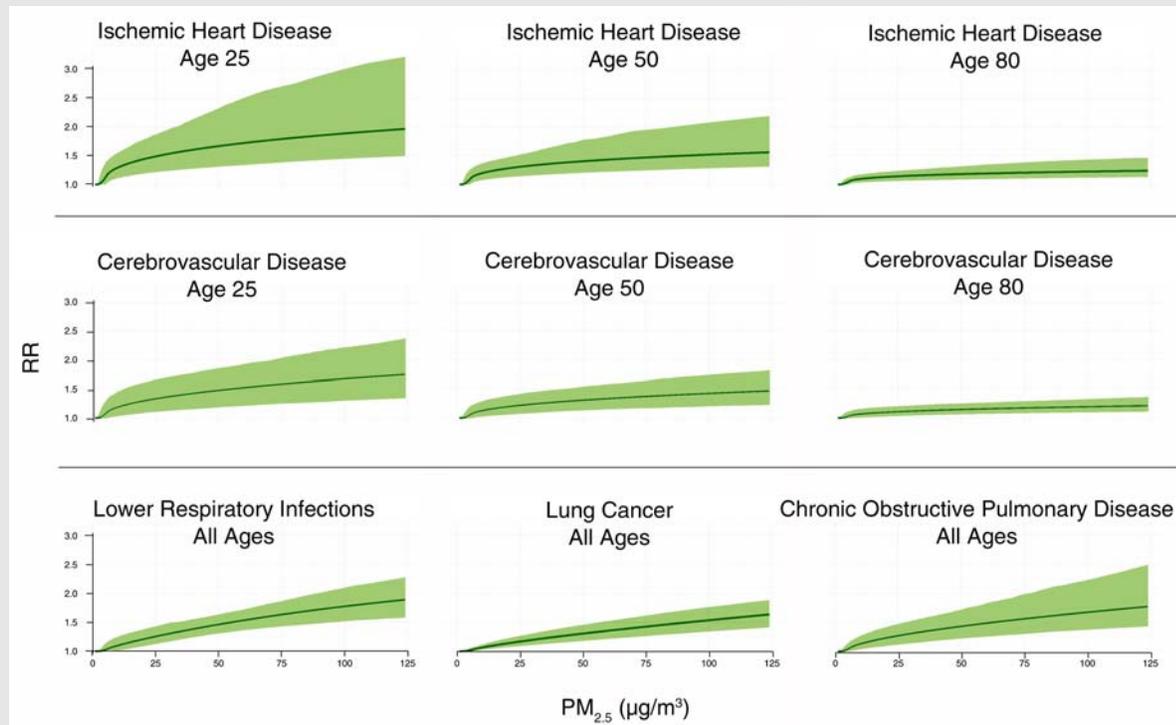
Sidebar 1 Figure below displays the resulting mean IER function, with the upper and lower uncertainty bounds for ischemic heart disease, lung cancer and chronic obstructive pulmonary disease, cerebrovascular disease (stroke), and acute lower respiratory infection over the range of annual average PM<sub>2.5</sub> concentrations that have been observed in countries across the world, up to 125 µg/m<sup>3</sup> (Cohen et al. 2017). The IER curves are all supra-linear with a greater change in relative risk for lower concentrations compared with higher values. Ischemic heart diseases, stroke, and lower respiratory infection graphs display greater curvature than lung disease. For both ischemic heart disease and stroke, we present IER functions for three age groups (25–20, 50–55, and 80+ years) with decreasing relative risk for increasing age.

*Sidebar continues next page*

earlier than might be expected in the absence of air pollution (as in the case of a child dying from an acute LRI). DALYs provide an overall measure of the loss of healthy life expectancy and are calculated as the sum of the years of life lost from a premature death and the years lived with disability (for example, blindness caused by diabetes). An

important insight gained by using DALYs rather than just the numbers of deaths is that DALYs account for the age at which disease or death occurs. For example, air pollution contributes to LRIs in children, but the number of deaths is small relative to the numbers of primary air pollution–related deaths from heart disease, which tend to occur in

Sidebar 1: IER Model for PM<sub>2.5</sub> (Continued)



Sidebar 1 Figure. IER functions for ischemic heart disease, lung disease (lung cancer and chronic obstructive pulmonary disease), cerebrovascular disease, and lower respiratory infection. Curves depict the central estimate of the IER (line) and their uncertainty (shaded area). Note the relative risk = 1 for PM<sub>2.5</sub> concentrations from 0 to 2.4 µg/m<sup>3</sup> (lower bound of the TMREL uncertainty distribution). Adapted from Cohen et al. 2017.

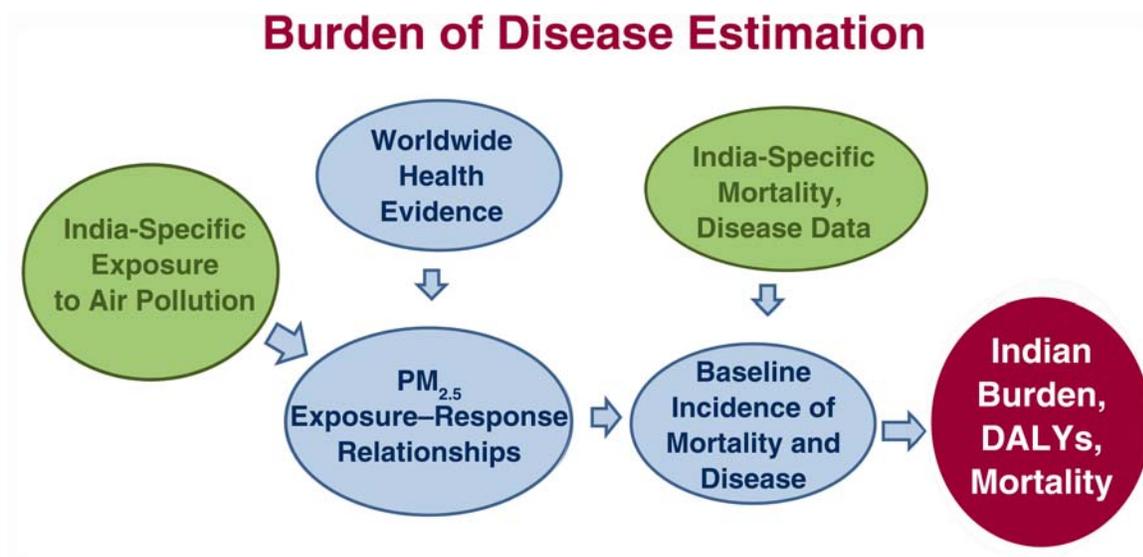


Figure 2. Overview of the methods for estimation of the burden of disease in India.

older adults. However, because children who die from LRIs have lost many more years of healthy life, this burden is appropriately reflected in a larger number of DALYs.

Burden is also measured in terms of age-standardized death rates and DALY rates (i.e., the number of deaths or DALYs per 100,000 people). Age-standardized rates are important because they adjust for population size and the age structure of each country’s population. This means that the rates in two countries can be compared as if the countries had the same population characteristics. Otherwise, in a country with a large and older population, the total number of deaths attributable to air pollution would be larger than that in a country with a smaller or younger population, even if exposure levels were the same.

**2.3 STATUS (2015) OF AND TRENDS (2009–2015) IN THE BURDEN OF DISEASE ATTRIBUTABLE TO PM<sub>2.5</sub> FOR INDIA**

**2.3.1 Burden of Disease Status in 2015**

Among all the risk factors evaluated in the GBD 2015 for their impact on mortality in India, exposure to ambient PM<sub>2.5</sub> ranked third highest (Figure 3, Panel A). Exposure to PM<sub>2.5</sub> contributed to 1.09 million deaths in India in 2015 (10.6% of total deaths in India), a 48% increase from 1990. The deaths of 644,000 men and 447,000 women were attributed to exposure to PM<sub>2.5</sub> in 2015. In India in 2015, PM<sub>2.5</sub> was responsible for 21% of IHD deaths, 17% of

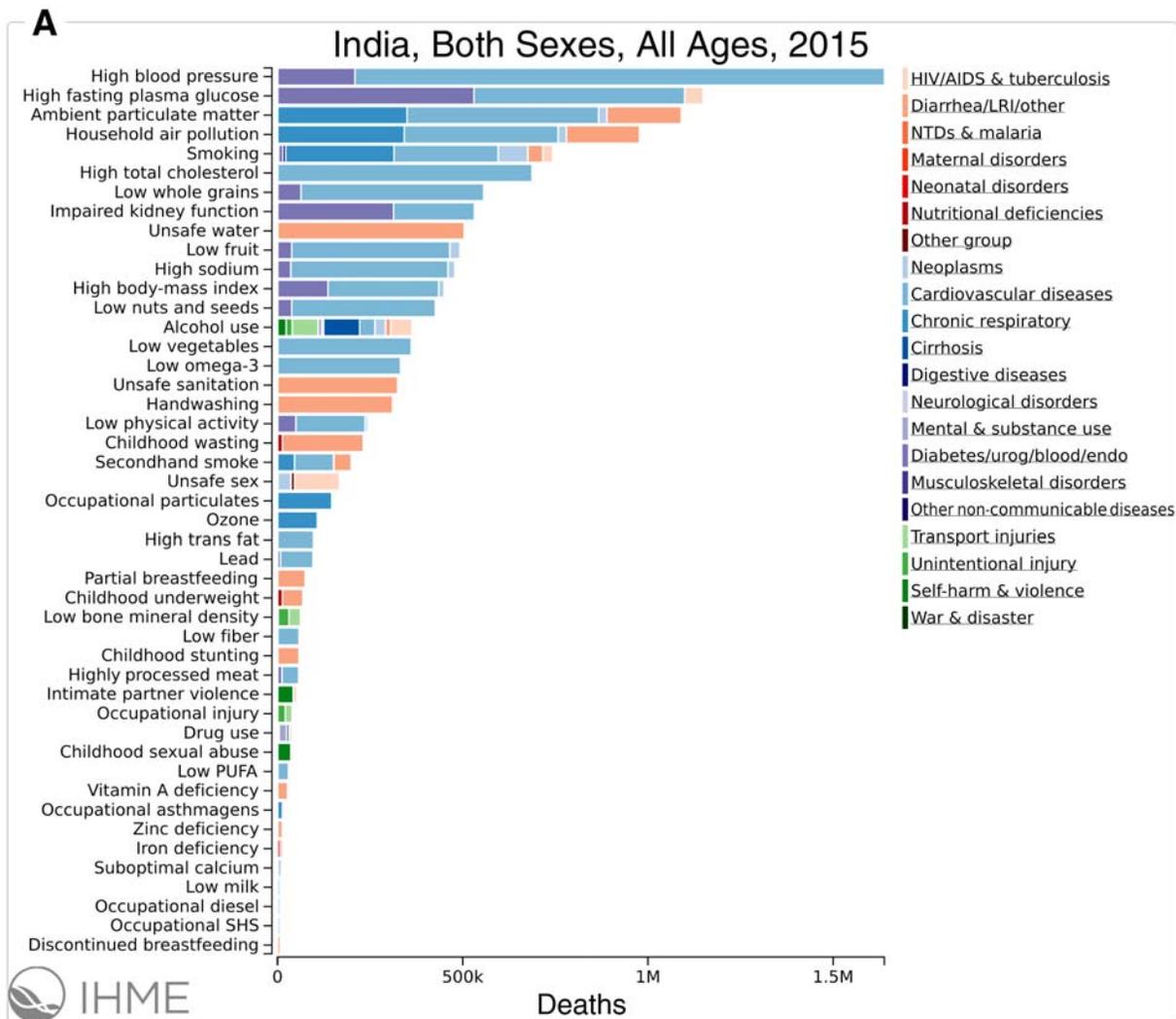


Figure 3. Top risk factors for India in 2015 (A) for numbers of deaths and (B) for numbers of DALYs (both sexes, all ages). Data downloaded from GBD Compare (2 February 2017). (Figure continues next page.)

stroke deaths, 24% of LC deaths, 29% of COPD deaths, and 36% of acute LRI deaths.

Exposure to ambient PM<sub>2.5</sub> was also the risk with the third highest disease burden for DALYs in India in 2015 (Figure 3, Panel B). Nearly 6% (5.9%) of total DALYs in 2015 were attributable to exposure to PM<sub>2.5</sub>. This percentage represents an increase in the disease burden attributable to ambient PM<sub>2.5</sub> since 1990 when ambient PM<sub>2.5</sub> accounted for 5.2% of total DALYs and ranked sixth among all risk factors. The main diseases that were affected by PM<sub>2.5</sub> in India were cardiovascular diseases, including IHD and stroke, which in 2015 together accounted for 44% of the DALYs attributable to PM<sub>2.5</sub> exposure in India. These were closely followed by acute LRI and COPD, which were responsible for 29% and 25% of DALYs, respectively. The

predominance of cardiovascular disease in 2015 represents a major shift in the patterns of disease in India since 1990 when acute LRI was the main disease affected by PM<sub>2.5</sub>, responsible for 61% of DALYs, and cardiovascular diseases was the next largest contributor.

Although this report focuses on contributions to ambient air pollution and disease burden from several types of sources — including residential biomass combustion (for cooking, lighting and heating) — it does not address the indoor exposures in homes resulting from the same biomass combustion. Shown in Figure 3 as “household air pollution” just below ambient particulate matter, it is also a substantial risk factor for disease burden in India so focusing only on its contribution to ambient air pollution most certainly underestimates its total impact on

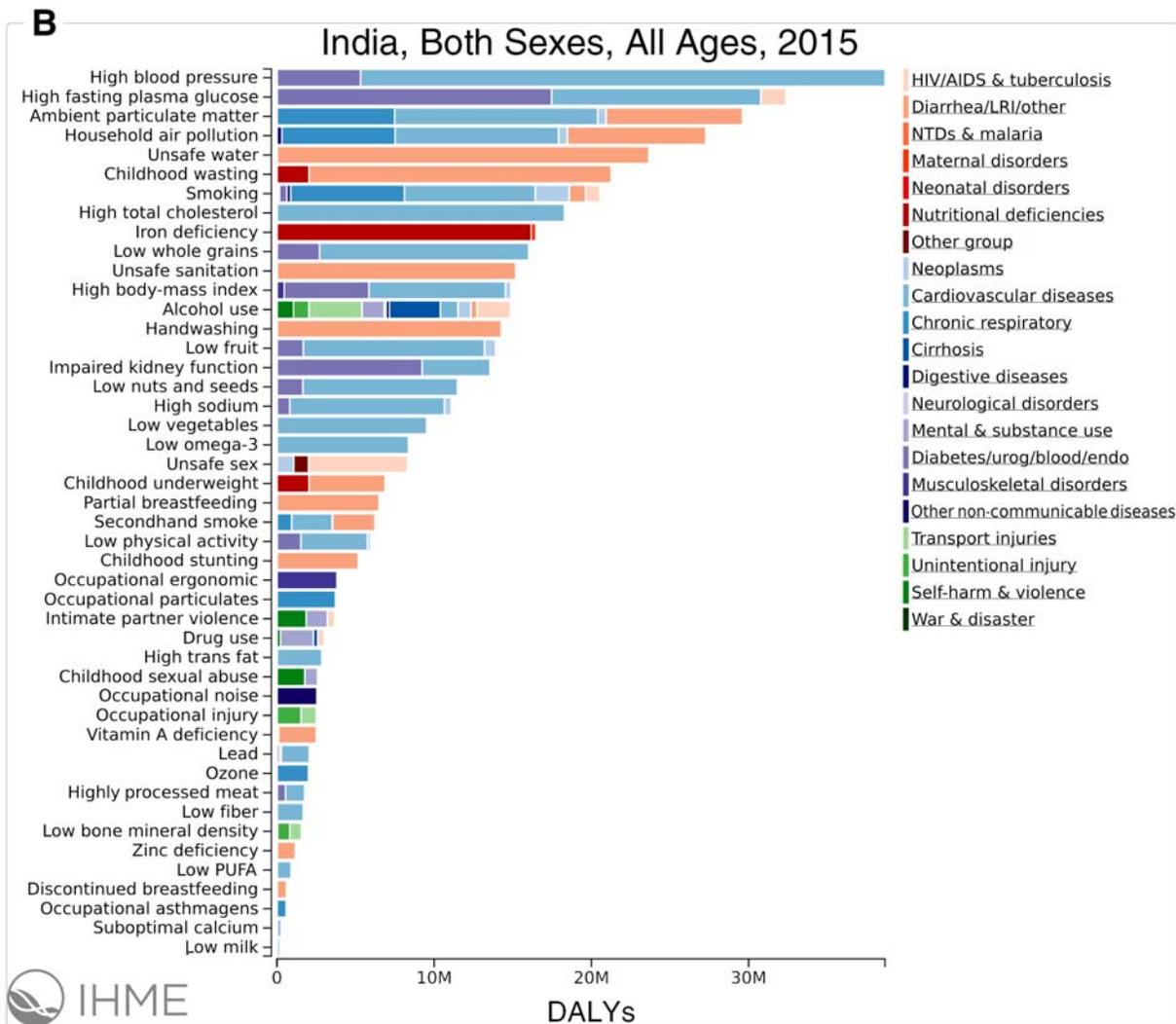


Figure 3. (Continued)

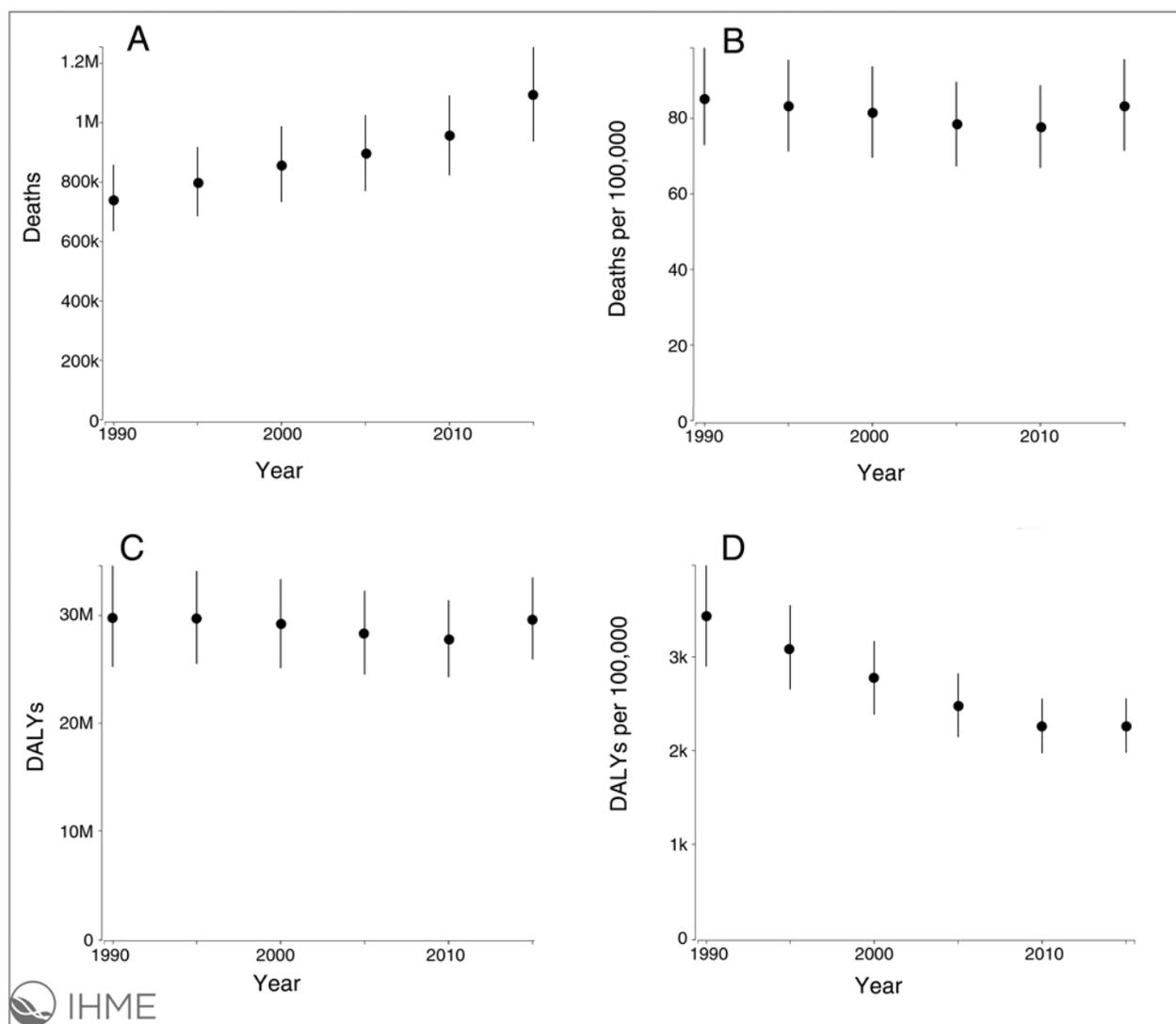


Figure 4. Trends in the burden of disease attributable to ambient PM<sub>2.5</sub> in India from 1990 to 2015 for (A) numbers of deaths, (B) death rates, (C) numbers of DALYs, and (D) DALY rates (both sexes, all ages). Data downloaded from GBD Compare (2 February 2017).

public health. However, the estimation of the combined impact of HAP via indoor exposures and its contributions to ambient air pollution is an area of uncertainty; at present there are no studies that estimate the joint effects of exposure to ambient and HAP. Consequently, the GBD project assumes the effects of these two risk factors to be independent, and thus additive.\* In India, air pollution from HAP and ambient air pollution (PM<sub>2.5</sub> and ozone)

combined is the second leading risk factor for mortality (1.8 million deaths in 2015; 17.6% of all deaths) and the leading risk factor for DALYs (48.7 million DALYs; 9.6% of all DALYs). However, this assumption of independence is unlikely to be valid in all settings, including those where residential combustion makes large contributions to ambient air pollution, as is the case for northern India.

### 2.3.2 Trends in Health Burden (2005–2015)

Figure 4 provides an overview of the trends in health burden attributable to PM<sub>2.5</sub> in India from 1990 to 2015, measured in deaths, DALYs, and their associated rates per 100,000 population. Figure 4 (Panel A) shows that there has

\*Following standard approaches, the combined effect of multiple independent risk factors is estimated by combined PAF = 1 - (1 - PAF<sub>1</sub>) (1 - PAF<sub>2</sub>) (1 - PAF<sub>3</sub>)..., where PAF is the Population Attributable Fraction for risk factors 1, 2, and 3. The Population Attributable Fraction is the proportional reduction in burden of disease that would occur if exposure to the risk factor was reduced to a theoretical minimum risk level.

been a strong increasing trend in the numbers of deaths attributable to air pollution in India over the past 25 years with some acceleration since 2010. In 1990 there were 737,000 PM<sub>2.5</sub>-associated deaths, increasing (by about 1.5% per year) to 957,000 in 2010, followed by an approximately 2.8% per year increase to 1,090,000 deaths in 2015. Attributable death rates have remained relatively stable (Figure 4, Panel B). The age-standardized attributable death rates (not shown) indicate a modest decrease, from 164 deaths per 100,000 people in 1990 to 134 per 100,000 in 2015, with an annual decline of about 0.9% from 1990–2010 and essentially no change between 2010 and 2015.

Panels C and D of Figure 4 show trends in the numbers of DALYS and in the DALY rates, respectively, over the same time period. While the total numbers of DALYs remained essentially constant, the DALY rates declined.

The reasons for the differences between the trends in these metrics can be understood by looking more closely at the underlying, and sometimes competing, factors that contribute to them. Four factors play a role in the upward trend in PM<sub>2.5</sub>-attributable deaths:

- increases in PM<sub>2.5</sub> exposures,
- population growth,
- population aging, and
- changes in the rates of diseases affected by air pollution.

Figure 5 shows the results of a decomposition analysis in which the percent change in mortality (annual number of deaths) attributable to PM<sub>2.5</sub> from 1990 to 2015 is broken down, or decomposed, into the contributions from

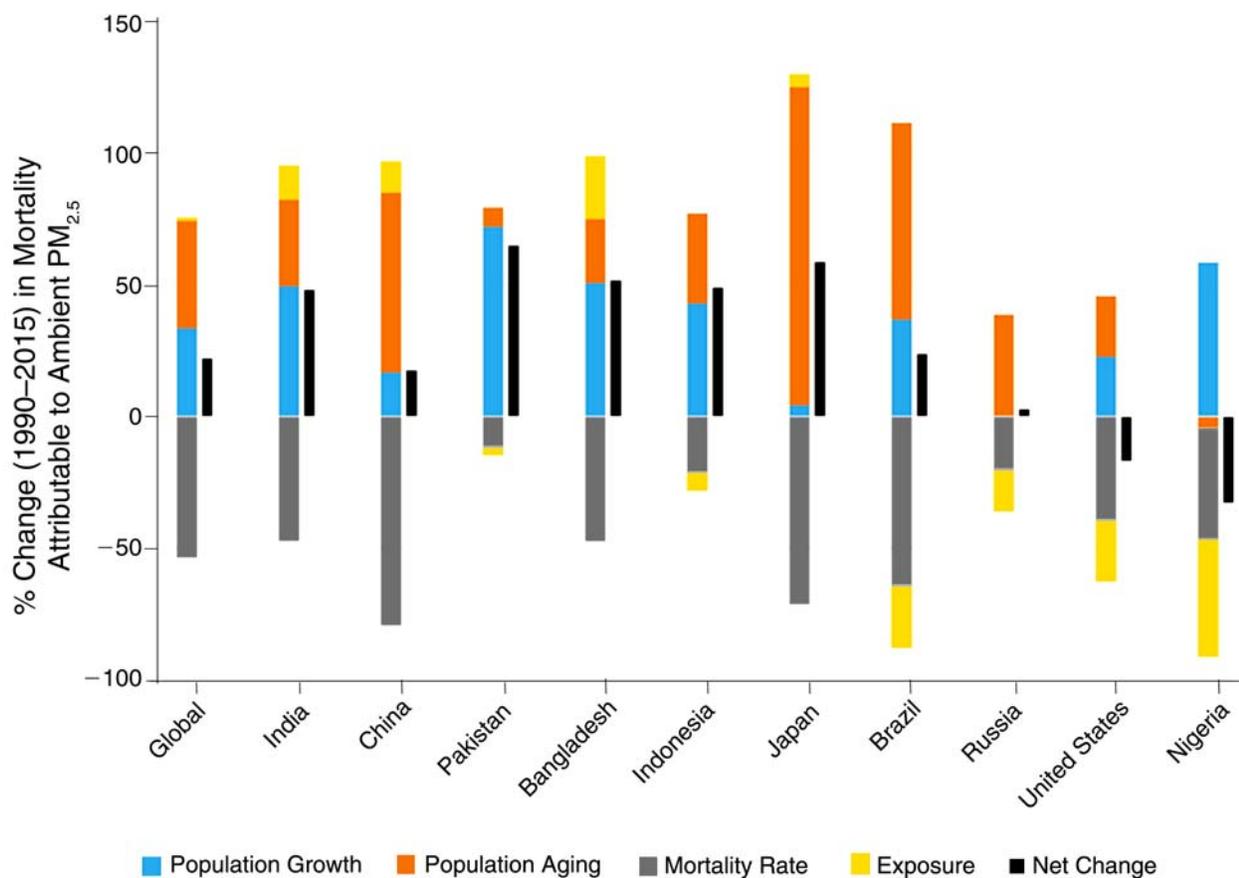


Figure 5. Contribution of population growth (blue), population aging (orange), risk-deleted age-standardized rates of mortality (ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower-respiratory infection) (gray) and exposure (yellow) to changes in mortality attributable to ambient PM<sub>2.5</sub> from 1990 to 2015 (black bars represent the net changes) for the ten most populous countries and globally. Countries are ordered left to right by the magnitude of the absolute net increase in attributable mortality between 1990 and 2015 (India: 370,620 deaths; China: 172,710; Pakistan: 52,839; Bangladesh: 41,224; Indonesia: 25,457; Japan: 22,556; Brazil: 10,088; Russia: 3,693; United States: -17,554; Nigeria: -25,951). Adapted from Cohen et al. 2017.

each of these four factors for the 10 most populous countries and for the world. For India, the analysis identified population growth (blue) followed by population aging (orange) as the main factors contributing to the increased  $PM_{2.5}$ -attributable mortality over this time period, although increasing exposure also contributed. The increases in mortality from those factors were offset somewhat by a decrease in the risk-deleted age-standardized rates of mortality (gray bars) from IHD, stroke, COPD, LC, and LRI combined in India. (Risk-deleted mortality rates in this case refer to the mortality rates from all risk factors minus the rates attributable to the risk factor  $PM_{2.5}$ ). Despite those decreases in mortality rates from all other causes, India experienced a net increase in  $PM_{2.5}$ -attributable mortality (black bars).

Figure 5 also provides some insight into how 25-year trends in demography and patterns of disease in India affect the estimates of mortality attributable to  $PM_{2.5}$ . The figure shows the change in the total numbers of deaths in India from diseases for which exposure to  $PM_{2.5}$  is a risk factor (IHD, LC, stroke, COPD, and acute LRI) from 1990 to 2015. The increasing mortality from these diseases in the growing and aging Indian population, in combination with increasing exposure to  $PM_{2.5}$  has meant that the fraction of mortality attributable to  $PM_{2.5}$  in India has not improved over the past 25 years; in fact, the population attributable fraction has increased from 7.9% in 1990 to 10.6% in 2015. These factors, which are assumed to be additive and independent, contribute to the increasing trend in the numbers of deaths seen in Panel A of Figure 4. The relative stability of attributable death rates over this period (Figure 4, Panel B) reflects the net effect of increases in rates of attributable deaths from IHD, stroke, COPD, and LC offset by decreases in rates of attributable deaths from acute LRI, a condition that has been a major cause of death in young children.

The patterns in cause-specific mortality shown in Figure 6 also help explain the different trends in the numbers and rates of DALYs attributable to  $PM_{2.5}$  (shown earlier in Panels C and D, respectively, of Figure 4). The decrease in the incidence of LRI between 1990 and 2010 has driven the consistent decreases in the rates of  $PM_{2.5}$ -attributable DALYs over that time period (Panel D of Figure 4). Since 2010, however, attributable DALY rates have stabilized while attributable death rates have increased, reflecting the diverging trends in the incidence of LRI (which on the one hand has decreased) and the incidence of COPD, IHD, stroke, and LC (which on the other hand have increased in combination with increasing exposures). Because the numbers of DALYs are in part based on years of life lost, they are sensitive to deaths among the very young (e.g., who are especially affected by LRI), and consequently the trend in

total  $PM_{2.5}$  attributable DALYs in India has remained rather flat (Panel C of Figure 4).

## 2.4 AIR QUALITY MANAGEMENT IN INDIA

This section of the report provides a brief overview of the legislation in place and proposed policies that informed the characterization of baseline and future scenarios at the outset of this study. However, the management of air quality in India is evolving rapidly as India increasingly recognizes the need for more immediate and forceful action to address what has become a growing threat to public health and the environment. Consequently, we note some of the most recent developments that may need to be considered in the interpretation of our results.

India has had legislation in place for several decades that requires major sectors to monitor and reduce emissions. The Air (Prevention and Control of Pollution) Act formed and assigned powers to Central and State Pollution Control Boards to issue regulatory standards and to monitor air pollutants (Ministry of Environment and Forest [MoEF] 1981). Under this Act, the Central Pollution Control Board adopted in 1982 the first ambient air quality standards, the National Ambient Air Quality Standards (NAAQS), for major pollutants like CO,  $NO_2$ ,  $SO_2$ , and ozone (Central Pollution Control Board [CPCB] 2004). These were then revised in 2009 to be closer to the WHO guidelines for ambient air quality, although they are not set at the most stringent levels for all pollutants. In addition, the NAAQS, especially those standards for PM, have not been enforced strictly (Guttikunda et al. 2014).

The CPCB introduced the Continuous Emission Monitoring System (CEMS) in February 2014 to be used by 17 categories of highly polluting industries to monitor and

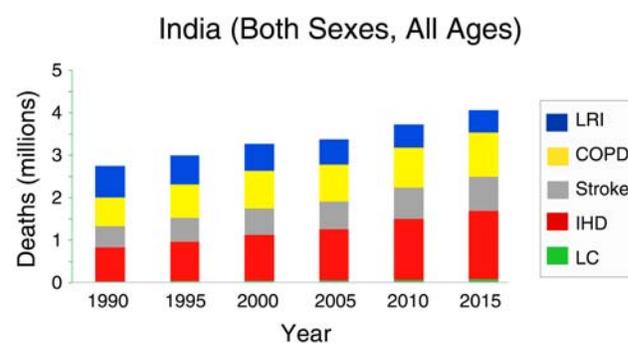


Figure 6. Total deaths in India (1990–2015) from diseases for which exposure to  $PM_{2.5}$  is a risk factor. LC = lung cancer, IHD = ischemic heart disease, COPD = chronic obstructive pulmonary disease, LRI = lower respiratory infection. Data downloaded from IHME’s GBD Compare website (<http://vizhub.healthdata.org/gbd-compare/>) on 2 February 2017.

control their emissions. Even though the installation target has been met, implementation of the CEMS remains a challenge and the data are not available in the public domain for further analysis (Bhushan et al. 2016). A survey conducted by the Centre for Science and Environment (CSE) (2016a) highlighted the problems faced by stakeholders, the most important being lack of knowledge and capacity to install and maintain monitors. In 2014, National Air Quality Index monitoring was launched under the National Ambient Air Quality Monitoring Programme (NAMP) to issue a multipollutant-based health alert in real time. The index calculations are currently limited to the cities with at least one continuous monitoring station and retroactively applied to calculate the index based on data collated from the manual stations. In 2017, 264 cities are covered under the NAMP program with 629 operational manual stations measuring PM<sub>10</sub>, SO<sub>2</sub>, and NO<sub>2</sub> and with 60 continuous monitoring stations measuring all the criteria pollutants. The GBD 2015 project included Indian PM<sub>10</sub> and PM<sub>2.5</sub> air monitoring data as part of its estimation of population-weighted PM<sub>2.5</sub> concentrations (see Section 3.3 for details).

In recent years, several separate initiatives have begun to address emissions from individual sources and sectors. To address emissions from public transport (buses), the Ministry of Urban Development launched new programs in 2012 to increase and upgrade their fleets under the Jawaharlal Nehru National Urban Renewal Mission (JNNURM) (Guttikunda et al. 2014). Dedicated bus corridors, known as the bus rapid transport (BRT) system, have been implemented in Delhi, Ahmedabad, Jaipur, Pune, and Indore in order to make public transport more efficient and thus more likely to be used instead of individual passenger vehicles (JNNURM 2012). The Petroleum and Natural Gas Regulatory Board Act (2006) set fuel standards for on-road diesel and petrol, mandating that all vehicles should upgrade to the Bharat stage (BS)-IV fuel standards by April 2017 (CPCB 2010). However, more recently, the National Institution for Transforming India (NITI) Aayog released a plan, India Leaps Ahead, in May 2017. This plan requires the implementation of new strategies designed to accelerate reductions of emissions from the transport sector, including moving directly to BS-VI fuel standards, bypassing BS-V entirely, and promoting large-scale electrification of public transport fleets (NITI Aayog 2017). The Ministry of Transport confirmed the switch in fuel standards by issuing a draft notification on February 19, 2016. According to the policy draft, the BS-VI standards will go into effect for all vehicles manufactured on or after April 1, 2020. Apart from this, the draft specifies mass emission standards, reference and commercial fuel specifications, type approval requirements, and on-board

diagnostic (OBD) system and durability levels for each vehicle category and subclass (MoRTH [Ministry of Road Transport and Highways] 2016).

To mitigate HAP, under the Direct Benefit Transfer for LPG consumer (DBTL) program created in 2014, the Ministry of Petroleum and Natural Gas (MoPNG) introduced the Pradhan Mantri Ujwala Yojana (PMUY) in 2016, a liquefied petroleum gas (LPG) subsidy program for extremely poor households below the poverty line (income of less than \$1.90 per day). Under the PMUY, households below the poverty line receive a free LPG connection. To further aid the uptake and use of LPG, the LPG subsidy program was launched in which wealthier households who did not need a government subsidy for LPG were urged to give it up, so that it could be made available to poor households. This program has been fairly successful in increasing LPG coverage from 56% of households in 2014–2015 to 73% in 2015–2016, with 198.8 million active consumers as of April 1, 2017 (Kumar 2017; MoPNG 2017). The scheme has been extended until 2019, with additional funds appropriated to support free distribution of LPG cylinders to households below the poverty line (MoPNG 2016).

The Perform, Achieve and Trade (PAT) (MoP 2008) initiative for energy efficiency has also helped reduce emissions from heavy industries like steel, cement, and fertilizer production (discussed further in Section 5.2). Other major sources of air pollution, such as open burning of agricultural residues, construction, and roadside dust are not monitored and are largely unaddressed by any centralized policies. However, there are some attempts at the state and municipality level to curb emissions. For example, the states of Punjab, Haryana, and Uttar Pradesh levy fines for agricultural field burning. Punjab has proposed offering subsidies for alternative technologies to seed and compost agricultural wastes (Goyal 2016; Times of India 2017).

In the brick manufacturing industry, the MoEF made emission standards more stringent in 2008, and in 2013 it mandated a complete shift to adapt newer technologies like the Fixed Chimney, Zig-Zag, and a complete ban on clamp-style baking of bricks by 2018. These technologies are not only cost-effective but also significantly reduce PM emissions (Lalchandani and Maithel 2013). The Municipal Solid Waste (Management and Handling) rules set emission standards in 2000 for PM, nitrous oxide, and volatile organic compounds for landfills and mandated a landfill gas control system (MoEF 2000).

In 2015, the Steering Committee on Air Pollution and Health Related Issues released a report with detailed recommendations of actions that could be taken by various ministries to reduce sector-wise emissions (Steering Committee on Air Pollution and Health Related Issues 2015). In

response to this report, a number of rules were passed. Coal power plants installed after January 1, 2017, were mandated to reduce their PM emissions by 40% from the levels allowed by the 2003 standards. The same rule regulates emissions of mercury, sulfur dioxide (SO<sub>2</sub>), and oxides of nitrogen (NO<sub>x</sub>) from coal power plants (MoEF 2015).

India aspires to expand and strengthen its electricity generation and distribution system to provide reliable electricity to the largest possible population. In 2016, coal-based power plants provided 60.8% of India's installed electricity capacity, with gas providing about 7% and diesel less than 0.5%. At the 2015 Paris climate conference, under its Intended Nationally Determined Contributions (INDC), India committed to increase its use of renewable solar and wind power substantially to meet these goals, setting a target that 40% of India's energy would come from renewable sources by 2030, up from about 30% currently (India's INDC 2015). India's draft National Electric Plan 2017–2022 (MoP 2016) outlines a path forward and recent actions suggest that with the effective implementation of this new plan and recent advances in policy, this target is likely to be achieved 8 years ahead of schedule (Climate Action Tracker 2017; MoP 2016). However, India is likely to continue to rely on coal and actually to increase its use for electricity generation into the middle of this century (NITI Aayog 2017). For existing power plants, India has also taken steps to improve their efficiency. Since 2015, 144 old coal plants have been assigned compulsory energy efficiency targets and offered upgrades to increase the energy production by 50% (MoEF 2015; MoP 2015).

Thermal power plants produce a large quantity of fly ash, itself a major source of anthropogenic dust. In 1994, India's Technology Information Forecasting and Assessment Council (TIFAC) under the Department of Science & Technology (DST) started the Fly Ash Mission, later the Fly Ash Utilization Programme (FAUP), to address the problem of fly ash from thermal power plants. At the time, utilization was as low as 3% of the fly ash production (40 million tonnes [MT] in 1994) but increased to 40% by 2005 (even as fly ash production increased to 112 MT) (Dhadse et al. 2008). Individual states have undertaken their own additional initiatives: the state of Maharashtra has been the first to formally adopt a Fly Ash Utilization Policy which makes it mandatory that fly ash and fly ash-based products be used in the construction industry within 100 km from a coal- or lignite-based thermal power plant.

The National Green Tribunal (NGT), since its founding in 2010, has played an important role in upholding environmental issues. The NGT is a specialized judicial body equipped with the necessary expertise to handle environmental disputes involving multidisciplinary issues in order to expedite environmental justice. In 2016, during

the Delhi air pollution emergency, the NGT took strict actions to restore air quality. These included de-registration of older diesel vehicles and strict regulations on incineration plants. The NGT also established a special committee to inspect gas stations and banned construction activity during the peak of the emergency.

Individual cities, like Delhi, and the National Capital Region (NCR) have undertaken several policies to make sure the air quality in the Delhi area meets the NAAQS. (Environment Protection, Prevention and Control Authority [EPCA] 2017). Short-term policies include improved physical and satellite monitoring of air quality, expansion of the compressed natural gas (CNG) program, enforcing stricter emission standards and taxes on diesel vehicles, and stricter parking and penalty laws. Medium- to long-term interventions include expediting development of expressways, developing plans for improved interstate freight transport, checking for fuel adulteration, and effective traffic management (Centre for Science and Environment [CSE] 2016b). The EPCA report also states that older thermal power plants will be progressively closed and research funds will be granted for air pollution inventory studies (EPCA 2017).

Smaller businesses and companies in the private sector are also taking steps toward lowering greenhouse gas emissions, which could also influence some of the emissions relevant to this study in the future. Organizations such as the Carbon Disclosure Project and the India Green House Gas Program are supporting businesses in India with tools to evaluate and disclose their own emissions and apply relevant solutions to lower them further (India Green House Gas Program 2015). The India Green House Gas Program led to an estimated reduction of 165 million metric tonnes of CO<sub>2</sub> emissions by private industries in the period between 2005 and 2015.

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### 3.0 METHODS FOR ESTIMATING BURDEN OF DISEASE RELATED TO MAJOR AIR POLLUTION SOURCES

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The overall analytic approach to estimating the burden of disease related to major air pollution sources in India has four main components, which were conducted sequentially:

1. Development of emissions inventories for the base year 2015 and projection of emissions inventories for 2030 and 2050.
2. Estimation of the fractional contributions from major source sectors to ambient PM<sub>2.5</sub> using the South Asia nested version of the global chemical transport model GEOS-Chem (see Sidebar 2) for the years 2015, 2030,

and 2050 under three alternative scenarios of energy use and pollution control.

3. Combination of these fractional contributions with high-resolution estimates of ambient  $PM_{2.5}$  concentration that were developed for GBD 2015 in order to estimate the fractional contributions to population exposure.
4. Estimation of the sector contributions to the burden of disease in India at the country level and stratified by urban and rural locations. This step combines the sector-specific ambient  $PM_{2.5}$  from step 3 with (a) estimates of cause-specific disease burden for India from the GBD 2015 study, including separate estimates for urban and rural locations, and (b) IER functions describing air pollution risk estimates for adult IHD, stroke, COPD, and LC, and childhood and adult LRI.

Each of these steps is described in more detail in the following sections.

### 3.1 DEVELOPMENT OF EMISSIONS INVENTORIES

The first step was to develop emission inventories of  $SO_2$ ,  $NO_x$ ,  $PM_{2.5}$ , black carbon (BC), organic carbon (OC), and nonmethane volatile organic compounds (NMVOCs) for India for the year 2015. The inventory developed for this analysis relied on data and methods from previous publications on multipollutant emissions inventories for India, covering the period 1996–2015 (Pandey and Venkataraman 2014; Pandey et al. 2014; Sadavarte and Venkataraman 2014). Collectively, these studies provided data on five major sectors: industry, transport, residential, agriculture, and “informal industry” sectors (including data

## SIDEBAR 2: GEOS-CHEM AND THE HIGH-RESOLUTION SIMULATION FOR INDIA

GEOS-Chem ([www.geos-chem.org](http://www.geos-chem.org)) is a chemical transport model used by about 100 research groups around the world. The model solves for the temporal and spatial evolution of aerosols and gaseous compounds using meteorological data sets, emission inventories, and equations that represent the physics and chemistry of the atmosphere. Version 10.01 is used here. The simulation of  $PM_{2.5}$  includes the sulfate–nitrate–ammonium–water system (Park et al. 2004), primary (Park et al. 2003) and secondary (Henze and Seinfeld 2006; Henze et al. 2008; Liao et al. 2007; Pye et al. 2010) carbonaceous aerosols, mineral dust (Fairlie et al. 2007), and sea salt (Alexander et al. 2005).

The South Asia nested version of GEOS-Chem used here was developed by Sreelekha Chaliyakunnel and Dylan Millet (both of the University of Minnesota) to cover the area from 55°E to 105°E and from 0°S to 40°N, and to resolve the domain of South Asia at a resolution of  $0.5^\circ \times 0.67^\circ$  (approximately  $56 \times 74$  km at equator) with dynamic boundary conditions using meteorological fields from the NASA Goddard Earth Observation System (GEOS-5). The boundary fields are provided by the global GEOS-Chem simulation with a resolution of 4° latitude and 5° longitude (approximately  $445 \times 553$  km at equator), which are updated every three hours. The GEOS-Chem model has been previously applied to study  $PM_{2.5}$  over India (e.g., Boys et al. 2014; Kharol et al. 2013; Philip et al. 2014b) including by related satellite observations of aerosol optical depth to ground-level  $PM_{2.5}$  for the GBD assessment (Brauer et al. 2012, 2016; van Donkelaar et al. 2010, 2015, 2016). Philip and colleagues (2014b) used the GEOS-Chem model together with satellite observations in a global analysis to find that across India biofuel combustion makes an even larger contribution than does fossil fuel combustion to ambient  $PM_{2.5}$ .

The GEOS-Chem model has fully coupled oxidant-aerosol simulation. The simulation includes the sulfate ( $SO_4^{2-}$ ), nitrate ( $NO_3^-$ ), ammonium ( $NH_4^+$ ) system as originally described by Park and colleagues (2004) with thermodynamics computed with ISORROPIA II (Fountoukis and Nenes 2007) as implemented by Pye and colleagues (2009). Alexander and colleagues (2012) describe the treatment of in-cloud sulfate formation. The organic carbon and black carbon simulation was originally developed by Park and colleagues (2003), with the subsequent addition of secondary organic aerosol following Pye and colleagues (2010). The sea salt (Jaeglé et al. 2011) and mineral dust (Fairlie et al. 2007) simulations both follow the standard implementation for nested simulations in version 10.01. For these simulations we added  $SO_4^{2-}$  chemistry introduced by Wang and colleagues (2014). We have corrected the too-shallow nighttime mixing depths and overproduction of  $HNO_3$  in the model following Heald and colleagues (2012) and Walker and colleagues (2012). Secondary organic aerosol formation includes the oxidation of isoprene (Henze and Seinfeld 2006), monoterpenes and other reactive volatile organic compounds (Liao et al. 2007), and aromatics (Henze et al. 2008). We applied the organic mass:organic carbon ratio in accordance with findings from Philip and colleagues (2014a). A relative humidity of 50% was used to relate simulated  $PM_{2.5}$  measurements in India. To select the year of meteorology, we conducted standard simulation using the same emissions and different meteorology from the year 2010 to 2012, as the meteorological fields are not available after 2012. We chose the year 2012 as our meteorology year, with which the simulation results best represented the mean  $PM_{2.5}$  concentration from 2010 to 2012. A three-month initialization period was used to remove the effects of initial conditions.

on fuel consumption, process and fugitive emissions, and solvent use). Emissions modeling required apportioning national fuel use in each sector into defined source categories and technologies, with each technology having a specific emission factor. The five sectors were disaggregated further into 13 source categories and about 75 technologies or activities for estimating 2010 emissions, which were then projected forward to 2015. The pyrogenic or combustion emissions, included from all sectors, along with process, urban and on-road fugitive emissions, together typically account for more than 97% of PM<sub>2.5</sub> emissions (Cao et al. 2011; Olivier et al. 1996; Purohit et al. 2010; Zhang et al. 2009). The inventory includes neither emissions from paddy farming and animal husbandry, which account largely for methane emissions, nor fugitive dust from construction activities, for which data are unavailable.

The emissions from each sector were estimated at the district (sub-state) level, from activity data (energy consump-

tion, industrial products, solvent use, etc.), technology-based emission factors, and current levels of deployment of control technologies. Activity data and technology distribution for each sector were derived from Indian statistics (Census 2011; National Sample Survey Organization 2012), a variety of sectoral technology reports (CEA 2010; CMA 2007a, 2007b, 2012; CMIE 2010; FAI 2010; MoC 2007; MoPNG 2012; MoWR 2006–2007), and an energy-projection modeling approach. The schematic of the overall methodology followed for development of the inventory is illustrated in Figure 7.

Fuel consumption in individual sectors and the amounts of agricultural residue burned was estimated using bottom-up methodologies for the base year 2010, and projected for the 1996–2015 period, using suitable proxies at each source-category level (Pandey et al. 2014). For sector-level technology divisions, dynamic emission factors related to technology penetration in industry and to emission

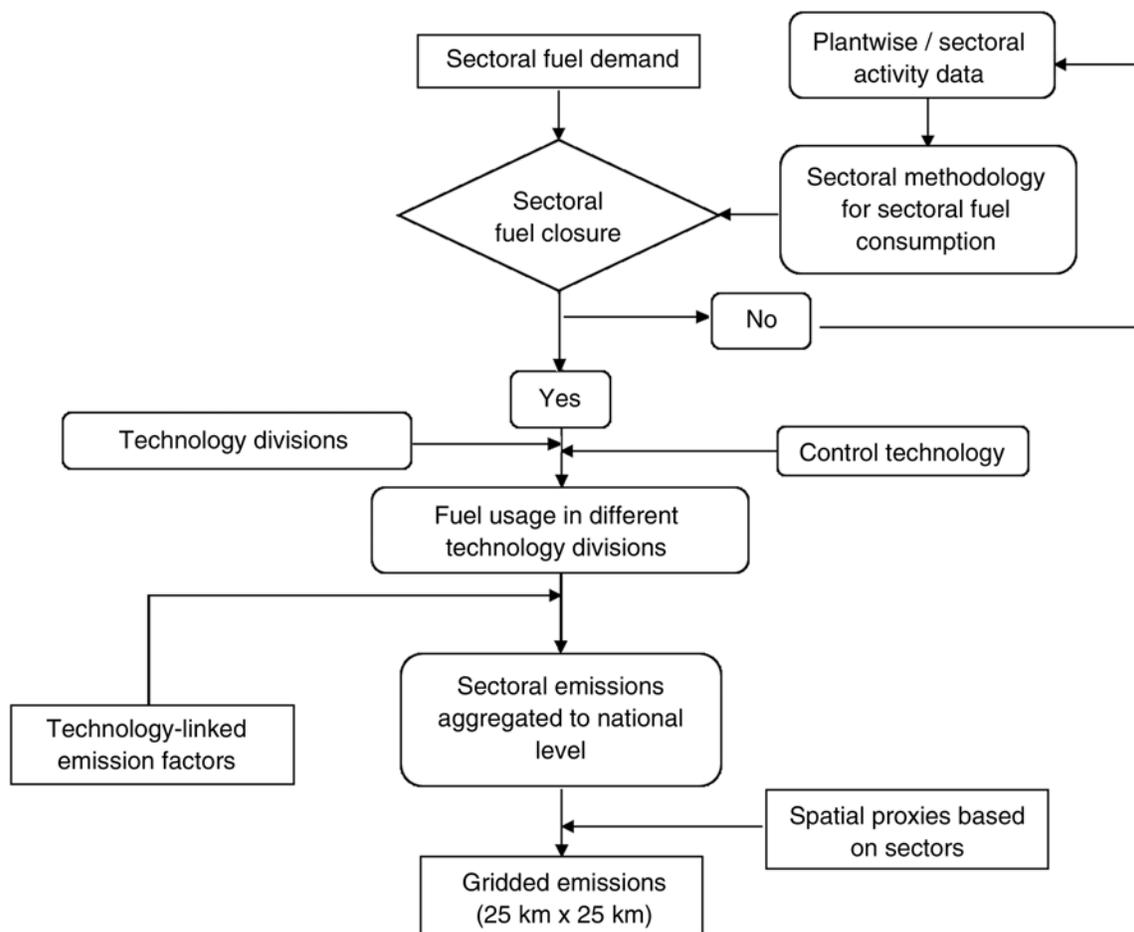


Figure 7. Methodological flowchart for development of Indian emission inventories.

standards in the transport sector were used to estimate 2015 emissions.

Estimates of fuel consumption in technology categories in each sector were aggregated to achieve closure with sectoral fuel demand and supply figures at the national level. In thermal power and industry sectors, fuel use is estimated using plant-by-plant data (installed capacity, plant load factor, and annual production) for 830 individual large point sources. In addition to fuel combustion, emissions are estimated from industrial “process” activities (predominant in industries such as those producing cement and non-ferrous metals, and refineries producing iron and steel).

Note that ammonia ( $\text{NH}_3$ ) is also a precursor to  $\text{PM}_{2.5}$ ; however, the level of  $\text{NH}_3$  emissions is relatively stable and no control measures are generally applied, so the  $\text{NH}_3$  emissions are assumed to be constant across all the simulation scenarios. The  $\text{NH}_3$  emission inventory was taken from the MIX emission inventory (Li et al. 2017; <http://meicmodel.org/dataset-mix.html>).

Vehicular emissions include consideration of vehicle technologies, vehicle age distributions, and super-emitters among on-road vehicles (Pandey and Venkataraman 2014). Residential sector emission estimates include seasonality in water and space heating, based on ambient temperature and typical practices. The “informal industries” sector includes brick production (in traditional kiln technologies like the Bull’s trench kiln and clamp kilns, using both coal and biomass fuels) and food and agricultural product processing operations (like drying and cooking operations related to sugarcane juice, milk, food-grain, jute, silk, tea, and coffee). In addition, monthly mean data on agricultural residue burning in fields, a spatiotemporally discontinuous source of significant emissions, are used from the Global Fire Emissions Database, version 4 (GFED-4s) database

(Akagi et al. 2011; Andreae and Merlet 2001; Giglio et al. 2013; Randerson et al. 2012; van der Werf et al. 2010). Technology-linked emission factors used were described in previous publications (Pandey et al. 2014; Sadavarte and Venkataraman 2014).

Spatial distribution of on-road diesel transport uses geographic information system (GIS)–based shape files with road densities of national super-highway and highway networks, state highways, and city level grids. Spatial distribution of light industry and gasoline transport follows urban population density, with large point sources assigned to a specific latitude and longitude. Spatial distribution of cooking emissions from the residential sector is based on the district-level population use of six different cooking fuels, while emissions from agricultural residue burning, based on the GFED-4s, relies on the global burned area product (Giglio et al. 2013). Other sources included in the inventory but not individually treated in sensitivity simulations described in the next section include residential lighting with traditional kerosene lamps, informal industry (food and agro-product processing), and waste burning. Uncertainties in the activity rates were calculated analytically using methods described more fully in previous publications (Pandey et al. 2014; Sadavarte and Venkataraman 2014). A spreadsheet-based approach for analytical propagation of uncertainties was developed for combining uncertainties in activity rates and emission factors. A normal/lognormal distribution was assumed when the standard deviation was less than or greater than 30% of the mean. Uncertainty propagation in the product of two variables was followed using the sum-of-quadrature rule, calculated analytically. The upper and lower emission bounds, shown in Table 1, were calculated using the resultant lognormal parameters (geometric mean and geometric standard deviation).

**Table 1.** Uncertainty Bounds for Indian Emissions of Individual Pollutants by Sector<sup>a</sup>

| Sector            | $\text{NO}_x$<br>(95% CL) | $\text{SO}_2$<br>(95% CL) | $\text{PM}_{2.5}$<br>(95% CL) | NMVOGs<br>(95% CL) |
|-------------------|---------------------------|---------------------------|-------------------------------|--------------------|
| Industry          | (−85 to 256)              | (−22 to 26)               | (−81 to 217)                  | (−80 to 209)       |
| Transport         | (−63 to 122)              | (−71 to 157)              | (−54 to 91)                   | (−59 to 107)       |
| Residential       | —                         | (−59 to 107)              | (−61 to 113)                  | (−66 to 133)       |
| Agricultural      | (−60 to 111)              | (−58 to 105)              | (−46 to 70)                   | (−63 to 121)       |
| Informal industry | (−85 to 260)              | (−10 to 11)               | (−74 to 173)                  | (−79 to 204)       |
| Total emissions   | (−65 to 125)              | (−20 to 24)               | (−49 to 78)                   | (−44 to 66)        |

<sup>a</sup> CL = Confidence limit.

### 3.2 ESTIMATION OF FRACTIONAL CONTRIBUTIONS TO PM<sub>2.5</sub> FROM INDIVIDUAL SOURCES

In order to estimate the fractional, or percentage, contribution of individual sources to ambient PM<sub>2.5</sub>, GEOS-Chem (see Sidebar 2) was first run to simulate total PM<sub>2.5</sub> concentrations across India for 2015 at a spatial (grid) resolution of  $0.5^\circ \times 0.667^\circ$  including the total emissions from all sources developed in Section 3.1. This simulation is referred to as the standard (STD) simulation. Then, sensitivity analyses were conducted in which emissions from individual major sectors or sources were sequentially removed from the inventory used in the simulation. The global and nested grid models of GEOS-Chem were then run in sequence using each of these new inventories. The sensitivity simulations thus estimate the ambient PM<sub>2.5</sub> concentrations with emissions from each source sector shut off. The difference between the STD simulation and each sensitivity simulation provides an estimate of the contribution of each individual sector to ambient PM<sub>2.5</sub> concentrations. This approach to estimating sector contributions to ambient PM<sub>2.5</sub> is a widely used method to account for the complex atmospheric physics and chemistry between precursor emissions and ambient particle concentrations. The sum of the individual sector contributions to total PM<sub>2.5</sub> approach 90%, implying that this method well represents the sensitivity of PM<sub>2.5</sub> to sources. Sensitivity simulations were conducted for the following sources:

1. Residential biomass (residential cooking, lighting, heating, and water heating)
2. Open burning (agricultural residue)
3. Total coal (electricity generation and heavy and light industry)
4. Industrial coal (heavy and light industry)
5. Power plant coal (electricity generation)
6. Transportation (on-road private passenger including two-, three-, and four-wheeled vehicles fueled by diesel, petrol, and CNG); public passenger vehicles including three and four-wheeled cars, minivans and buses fueled by diesel and CNG; freight including light-duty and heavy-duty diesel vehicles; and passenger and freight trains),\*
7. Brick production (predominantly in traditional brick kilns)
8. Distributed diesel (agricultural pumps, agricultural tractors, and electric generator sets)

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\* Transportation did not include shipping.

9. Anthropogenic dust (dust from fugitive, combustion, and industrial activities, including coal fly ash, iron and steel production, cement production, resuspension from paved and unpaved roads, mining, quarrying, and agricultural operations.)<sup>†</sup>
10. Total dust (including both windblown mineral dust and dust from anthropogenic activities)<sup>‡</sup>

These sectors were selected for evaluation given their inclusion in similar national level and global analyses (e.g., Lelieveld et al. 2015) and based on in-country interest as potentially important sources that might be targeted for specific policies (for example, brick production and distributed diesel sources). Primary PM is largely composed of carbonaceous constituents (BC and organic matter) and mineral matter. Primary PM<sub>2.5</sub> emissions, along with those of species BC and OC, are calculated in the inventory from their respective measured emission factors from different sources, along with corresponding fuel consumption. Using reported organic matter/OC ratio for sources, anthropogenic dust emissions are calculated as the difference between emitted primary PM<sub>2.5</sub> mass and the sum of BC and organic matter, each calculated from respective emission factors (Philip et al. 2017). Open burning emissions, from the GFED-4s database, largely reflect agricultural residue burning, since forest burning is not a significant source in the region.

Note that ambient ozone also contributes to the disease burden attributable to air pollution in the GBD project. Although ozone precursors are emitted in many of the source sectors considered here and also simulated in GEOS-Chem, we did not estimate the contribution of these source sectors to disease burden via ozone production. For GBD 2015, the impact of ozone on mortality in India was 10% of that from PM<sub>2.5</sub>. In addition, several of the sectors that were evaluated emit additional pollutants (e.g., NO<sub>2</sub>), which are also associated with adverse health impacts, but which were not included in the GBD 2015 effort or in this analysis.

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<sup>†</sup> Residential and commercial construction sources of dust were not included.

<sup>‡</sup> Although not included in the set of sources attributed to human activities, windblown mineral dust also arguably results in part from human activities, either directly through agricultural or forestry practices or indirectly through impacts on climate that increase desertification both outside and inside India, for example.

### 3.3 ESTIMATION OF $PM_{2.5}$ CONCENTRATIONS ATTRIBUTABLE TO DIFFERENT SOURCE SECTORS

The spatially resolved fractional contributions of the different source sectors estimated with GEOS-Chem simulations were then multiplied by the high-resolution ambient  $PM_{2.5}$  concentration estimates developed for the GBD 2015 project to estimate the ambient  $PM_{2.5}$  concentrations attributable to each source sector. Specifically, the sector contributions to ambient  $PM_{2.5}$  are calculated by multiplying the gridded values of  $PM_{2.5}^{GBD2015}$  by the gridded fractions of ambient  $PM_{2.5}$  attributable to each sector ( $f_{sector}$ ) as estimated from GEOS-Chem simulations in the previous section:

$$PM_{2.5}^{sector} = f_{sector} \times PM_{2.5}^{GBD2015} \quad (1)$$

The GBD 2015 concentration estimates combine (1) satellite-based estimates with GEOS-Chem to provide information on the relationship between aerosol optical depth and surface  $PM_{2.5}$  (van Donkelaar et al. 2016) with (2) annual average PM measurements (for 2008–2014), along with additional information on chemical composition and geography (e.g., elevation and distance to nearest urban center) in a Bayesian hierarchical model to provide global estimates of  $PM_{2.5}$ , along with uncertainty in the estimates, at  $0.1^\circ \times 0.1^\circ$  resolution (Shaddick et al. 2016).

These estimates explicitly incorporate available surface measurements of  $PM_{2.5}$  for the locations of interest. For India, this analysis included 25 direct  $PM_{2.5}$  measurements and 411  $PM_{10}$  measurements; the ratios of  $PM_{2.5}$  to  $PM_{10}$  were used to estimate  $PM_{2.5}$  concentrations from the  $PM_{10}$  measurements using methods described in Brauer and colleagues (2016). Indication of whether a specific measurement is estimated from the  $PM_{2.5}:PM_{10}$  ratio or directly measured is included in a variable in the above model to account for potential differences in accuracy between measurements. In general, the decision to rely on the larger number of  $PM_{2.5}$  estimates derived from  $PM_{10}$  represents a tradeoff in which absolute accuracy is reduced in favor of improved spatial representativeness.

Comparisons between the results of the STD (2015) simulation and the GBD 2015 estimates are provided in Appendix A (Figures A.1 and A.2), available on the HEI website, and show overall good agreement in spatial patterns with a general tendency for the simulations to underpredict the GBD 2015 estimates, especially in the areas surrounding the Uttar Pradesh–Bihar boundary. Despite this underprediction, the spatial patterns of the estimates remain similar, which supports the approach used here to scale the simulated proportional sectoral contributions with the GBD 2015 concentration estimates. In addition to

improving the spatial resolution of the analyses and adjusting for bias in the simulations, the normalization to the GBD 2015 concentration estimates explicitly includes available ground measurements from India, thereby enhancing the local relevance of these analyses. Further, this normalization makes the sectoral contributions directly relevant to the GBD 2015 disease burden estimates, which in turn place the sectoral contributions in the context of other risk factors (e.g., dietary and behavioral factors) included in the GBD assessment, with an overall goal of increasing the health policy relevance of these analyses.

### 3.4 ESTIMATION OF SECTOR CONTRIBUTIONS TO DISEASE BURDEN

Based on prior analyses conducted for GBD 2010 for household cooking (Chafe et al. 2014) and road transportation (Bhalla et al. 2014), and as in the GBD MAPS analysis for China (GBD MAPS Working Group 2016), the nominal assumption is that the proportional contribution of a source sector,  $p$ , to the air pollution disease burden is a simple proportion of that sector’s contribution, represented by the population attributable fraction,  $PAF(p)$ , to ambient  $PM_{2.5}$ . That is,  $PAF(p) = PAF \times p$ , where  $PAF$  is the population attributable fraction associated with  $PM_{2.5}$ . As described in detail in the GBD MAPS China report, this assumption is mathematically equivalent to averaging the  $PAF$  over all possible changes in concentration of size  $p \times z$  within the concentration interval from the counterfactual concentration,  $z_{cf}$ , to  $z$  (see Sidebar 1). We have employed this strategy for estimating the contribution for overall burden associated with  $PM_{2.5}$  exposure attributable to any single source or multiple sources by decomposing the attributable risk of  $PM_{2.5}$ , as measured by the IER, into specific sources proportional to their contribution to total  $PM_{2.5}$  concentration. This method of source attribution is based on the average derivative of the IER evaluated at concentration  $z$  over the concentration range from the counterfactual,  $z_{cf}$ , to  $z$ . We note that we are not linearizing the IER itself, only calculating the average derivative. We take this approach because we do not know where in the exposure distribution such a change of  $p \times z$  occurs, as we are exposed to  $PM_{2.5}$  from all sources simultaneously. We use the  $PAF$  approach when evaluating both current and future scenarios.

This approach provides more robust findings in that it is insensitive to the order in which each source is removed from the total concentration. It also has the advantage that the sum of burden estimates from all sources equals the burden from ambient  $PM_{2.5}$  exposure. The approach therefore provides a more direct method of communicating

results that are more readily understandable and informative to decision makers.

The population-weighted fraction of  $PM_{2.5}$  attributable to each of the sectors was used together with the IER functions (described in Sidebar 1) and the underlying disease burden for each state, stratified by urban and rural locations, to calculate the PAF. To calculate disease burden attributable to ambient  $PM_{2.5}$  and specific source sectors, the resulting PAF is multiplied by the underlying cause-specific disease burden as estimated separately for urban and rural populations of each state. Briefly, the relative risk for each cause was calculated at the  $PM_{2.5}$ -exposure grid-cell level from the cause- and age-specific exposure-response relationship. The location-specific PAF is the proportion of outcomes (e.g., deaths from lung cancer) attributable to long-term exposure to ambient air pollution at a level greater than a theoretical minimum risk exposure level (TMREL). Because estimated deaths and DALYs were not available at the grid-cell level, the state-level PAFs were calculated using gridded population data and estimated by

$$PAF = 1 - \frac{1}{\frac{\sum Pop_{io} (1 / [1 - paf_{io}])}{\sum Pop_{io}}} \quad (2)$$

where  $Pop_{io}$  is population and  $paf_{io}$  is the PAF of outcome  $o$  in grid cell  $i$ . Estimates were aggregated to the national level and reported stratified by urban and rural status for attributable deaths and the age-standardized rate of attributable DALYs (DALYs/100,000).

Note that the total numbers of deaths are a function of the risk functions for each outcome, the size of the affected populations in urban compared with rural areas, and the underlying prevalence of diseases affected by air pollution. Age-standardized DALY rates are adjusted for the population size and age distribution and are therefore more appropriate for comparing the relative impacts of  $PM_{2.5}$  between specific source sectors and by urban and rural locations over time.

### 3.5 ESTIMATION OF UNCERTAINTY IN ATTRIBUTABLE DISEASE BURDEN

Although estimates of attributable disease burden are presented with corresponding uncertainty intervals, a formal evaluation of all sources of uncertainty was not conducted in this analysis. The overall uncertainty in the burden estimates is a function of uncertainty in the  $PM_{2.5}$  estimates, the IER, and the baseline health rates as described in detail elsewhere (Cohen et al. 2017). For example, the population-weighted mean concentrations

for ambient  $PM_{2.5}$  and for  $PM_{2.5}$  attributable to specific source sectors are presented with 95% uncertainty intervals around their mean values. This uncertainty, which is based only on uncertainty in the GBD estimates of ambient  $PM_{2.5}$  concentrations and does not reflect uncertainty in the estimation of sector specific contributions, is estimated by sampling 1,000 draws of a distribution for each grid cell based on the model output mean and standard deviation. Uncertainties in the total ambient and sector-specific  $PM_{2.5}$  (here calculated as a direct proportion of the ambient  $PM_{2.5}$  uncertainty) are propagated, along with uncertainty in the IER and uncertainty in the baseline disease rates, to arrive at uncertainty in attributable burden.

No uncertainty in the attribution of ambient  $PM_{2.5}$  to the various source sectors was included, as this would be a major undertaking beyond the scope of this analysis. Uncertainty in the emissions estimates was described in Table 1. As in the overall GBD project, all estimates were developed starting with the highest resolution inputs and aggregating up in order to limit spatial misalignment. Specifically, exposure estimates and population are available at the  $0.1^\circ \times 0.1^\circ$  grid-cell level and are used with the IER functions to estimate the PAF. Source contributions are available at approximately  $56 \text{ km} \times 74 \text{ km}$ , the level of resolution dictated by the simulations. Baseline disease burden is estimated at the state level (stratified by urban and rural populations), which is then aggregated to national-level estimates.

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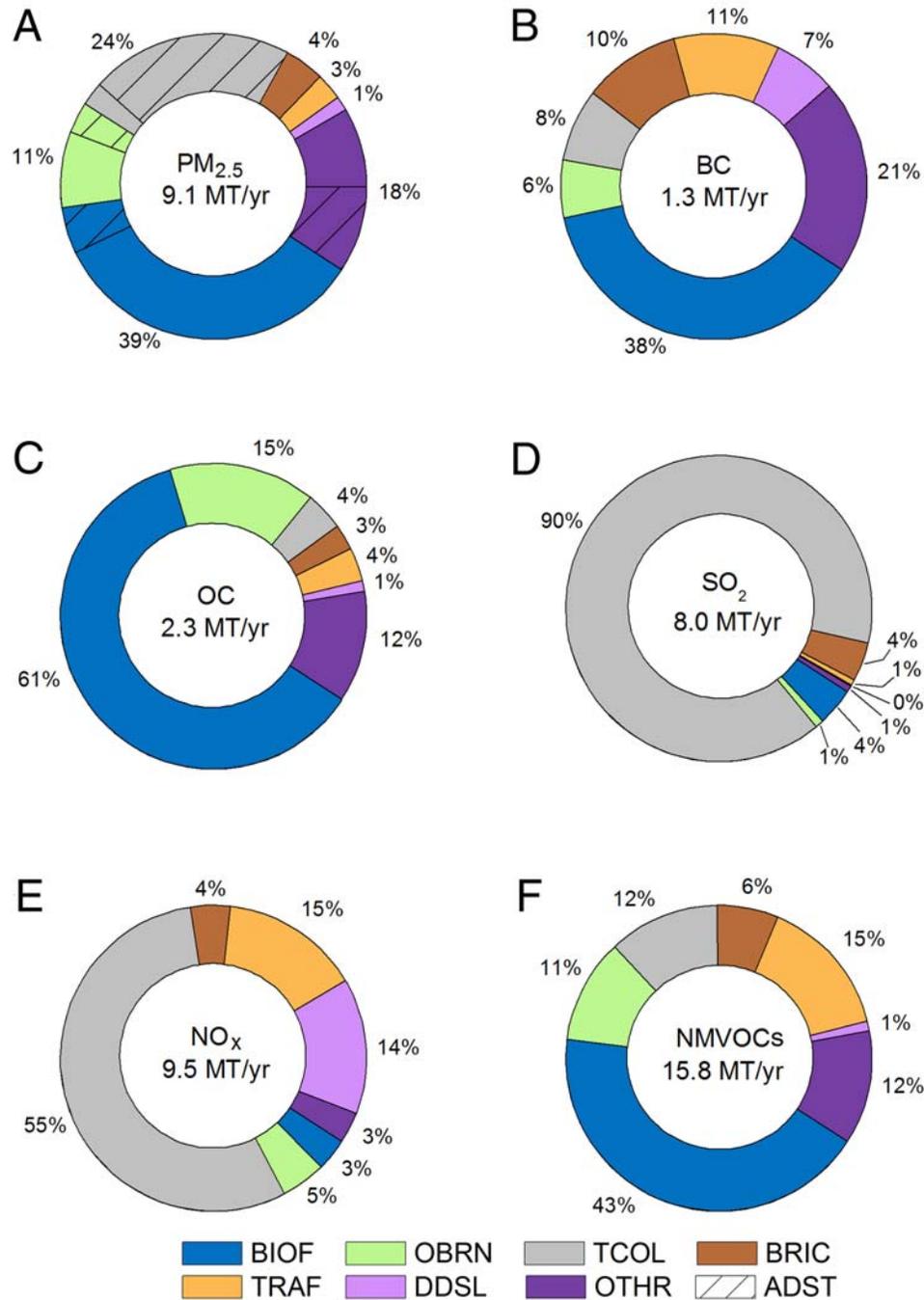
## 4.0 RESULTS: THE CURRENT BURDEN OF DISEASE RELATED TO MAJOR AIR POLLUTION SOURCES

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### 4.1 EMISSIONS ESTIMATES FOR SOURCE SECTORS IN 2015

National-level emissions estimates of  $PM_{2.5}$ , BC, OC,  $SO_2$ ,  $NO_x$ , and NMVOCs by sector are given in Figure 8. Appendix B, available on the HEI website, includes detailed tabulations of 2015 emissions of each pollutant at the state level (Table B.1) and by sector (Table B.2).

In 2015, Indian emissions of  $PM_{2.5}$  (9.1 million tonnes per year [MT/yr]) and total precursor gases —  $SO_2$ ,  $NO_x$ , and NMVOCs (33.3 MT/yr) — arose from three main sources: (1) biomass-fueled traditional technologies in individual homes (residential biomass), brick production, and informal industry; (2) coal burning in power generation and heavy industry; and (3) open burning of agricultural residues for field clearing. BC and OC are important constituents of  $PM_{2.5}$ , whose emissions in 2015, respectively, were



**Figure 8. National emissions in million tonnes (MT) of (A)  $PM_{2.5}$ , (B) BC, (C) OC, (D)  $SO_2$ , (E)  $NO_x$ , and (F) NMVOCs by sector (2015).** BIOF, biomass fuel (residential cooking, lighting, and heating); OBRN, open burning (agricultural residue and forest); TCOL, total coal (electricity generation, heavy and light industry); BRIC, fired-brick production (predominantly in traditional brick kilns); TRAF, transportation (on-road and off-road transport — diesel/gasoline/CNG vehicles and trains); DDSL, distributed diesel (agricultural pumps, agricultural tractors, and electric generator sets); OTHR, other sources, not individually treated (residential lighting, cooking with gas/kerosene, informal industry in food and agricultural product processing); and ADST, anthropogenic dust (designated by hatchmarks within major emitting source categories: coal fly-ash and mineral-based pollution particles).

1.3 MT/yr and 2.3 MT/yr. BC and co-emitted OC have very similar sources, with the largest emissions arising from traditional biomass technologies in the residential sector (for cooking, lighting, and heating) and in the informal industry sector (for brick production and for food and agricultural produce processes), as well as from agricultural field burning. Coal combustion in power generation and industry is not a major emitter of BC and OC.

Secondary PM forms from reactions of precursor gases, including SO<sub>2</sub>, NH<sub>3</sub>, NO<sub>x</sub>, and NMVOCs, which adds to ambient PM<sub>2.5</sub> concentrations. Emissions of SO<sub>2</sub> lead to the production of particulate sulfate, whereas those of the ozone precursors (NO<sub>x</sub> and NMVOCs) lead to atmospheric chemical reactions that increase ozone levels, but also form nitrate and secondary OC aerosols. In 2015, SO<sub>2</sub> emissions of 8.0 MT/yr arose primarily from coal combustion in thermal power and industry sectors and from on-road transport using diesel and petrol. Emissions of NO<sub>x</sub> of 9.5 MT/yr were dominated by thermal power and transport sectors, whereas those of NMVOCs (15.8 MT/yr) largely arose from traditional biomass-fuel stoves, followed by fugitive emissions from energy extraction (coal mining and oil exploration) and open burning of agricultural residues in fields.

### 4.1.1 Evaluation of 2015 Emissions

Emissions during 1996–2015 were evaluated with other bottom-up emissions estimates for India (Garg et al. 2006; Klimont et al. 2009 [Greenhouse gas – Air pollution INteractions and Synergies model, or GAINS]; Lu et al. 2011; Zhang et al. 2009 [Intercontinental Chemical Transport Experiment — Phase B, or INTEX-B]). The estimated PM<sub>2.5</sub> emissions were in good agreement (within a factor of 1.3) for 2006 (Zhang et al. 2009). The differences observed for emissions trends for industry were attributable to the inclusion of process emissions in this work, particularly in the cement and iron and steel industries. The emission levels from the transport sector were comparable to those in previously published works for the base year 2005 (Baidya and Borken-Kleefeld 2009).

Our estimated trends in BC emissions were also in good agreement (within 10%) with published values for several years during 1996–2015 (Klimont et al. 2009; Lu et al. 2011) because of similar assumptions related to coke ovens, diesel in heavy equipment use, and the fraction of vehicle superemitters. Industrial BC emissions were greater than those for 2006 (Zhang et al. 2009) and for 2015 (Klimont et al. 2009) because of the inclusion of new sources. BC emissions from the residential, agricultural, and brick production sectors were in agreement (within a factor of 0.9 to 1.2) with those reported by Lu and

colleagues (2011) and Klimont and colleagues (2009). Industrial OC emissions, however, were somewhat lower (within 20%) than previously published values because of the high rates of air pollution control devices used in the industry sector and the implementation of Bharat Stage (BS) norms in the transport sector, which reduced emissions of PM<sub>2.5</sub> and its constituents. OC emissions from the residential, agricultural, and brick sectors were a factor of 0.6 to 0.8 times those in the study by Lu and colleagues (2011), with increasing differences in recent years (i.e., 2015) attributable to the assumption of higher biomass fuel fraction in the residential sector and to differences in OC emission factors.

SO<sub>2</sub> emissions agreed (within 20%) with those in Garg and colleagues (2006), INTEX-B (Zhang et al. 2009), Lu and colleagues (2011), and GAINS (Klimont et al. 2009) for the years 2000, 2004, 2005, 2006, 2008, and 2010. The somewhat lower SO<sub>2</sub> emissions estimated here resulted from both lower overall energy consumption (0.85) and lower emission factors used for industry and thermal power (0.95 and 0.73 for coal-based emissions) (Lu et al. 2011) with the inclusion of process emissions. Emissions of SO<sub>2</sub> from the residential, agriculture, and brick sectors agreed (within 10%) with those in the study by Klimont and colleagues (2009) but were somewhat lower compared with those in the study by Lu and colleagues (2011).

NO<sub>x</sub> and NMVOC emissions compared well with those from other inventories for the years 2000, 2005, 2006, and 2010 (Garg et al. 2006; Klimont et al. 2009; Sharma et al. 2015; Zhang et al. 2009). NO<sub>x</sub> emissions from industry were close to those from earlier studies, approximately 0.97 times those in GAINS for 2010 (Klimont et al. 2009). NO<sub>x</sub> emissions from transport agreed within a factor of 1.3 with those in Baidya and Borken-Kleefeld (2009) and Guttikunda and Mohan (2014). Overall NO<sub>x</sub> emissions were somewhat lower than in previous studies (Baidya and Borken-Kleefeld 2009; Fulton and Eads 2004; Zhang et al. 2009) due to our choice of emission factors (from Klimont et al. 2009) in order to obtain agreement with a top-down NO<sub>x</sub> emission inventory for India (Ghude et al. 2013).

## 4.2 SPATIAL CONTRIBUTION OF MAJOR SOURCES TO PM<sub>2.5</sub> CONCENTRATIONS

Figure 9 shows the simulated annual mean PM<sub>2.5</sub> concentrations in 2015. It illustrates that the ambient PM<sub>2.5</sub> concentration has a clear regional distribution with high values in northern India. The highest concentrations were projected for Uttar Pradesh, Bihar, and West Bengal.

The results of the sensitivity analyses conducted to simulate the impact of different sectors on PM<sub>2.5</sub> concentrations in 2015 are shown in Figure 10. The figure shows the

simulated percentage contributions to  $PM_{2.5}$  from residential biomass combustion (“domestic biomass”), open burning, total coal combustion, fired-brick production, industry coal combustion, distributed diesel, power plant coal combustion, and transportation. Among these emission sources, residential biomass burning, coal combustion, and open burning contribute the greatest percentages to ambient  $PM_{2.5}$ .

The spatial distribution of particulate species reflects the interplay of emission density distributions with transport processes, with sulfate showing a predominance in central India and to the east, where there is a predominance of thermal power generation, whereas carbonaceous species and nitrate and ammonium predominate in the northern Indo-Gangetic plains, where biomass fuel use for residential cooking and heating as well as animal rearing activities are dominant.

The contributions to ambient  $PM_{2.5}$  concentrations from each sector differ between regions. The contribution from residential biomass combustion has a similar spatial distribution to that of the annual mean  $PM_{2.5}$  concentrations in India (Figure 9), which illustrates the large influence that residential biomass burning has on air quality. Because of the dense population and high emissions in Uttar Pradesh

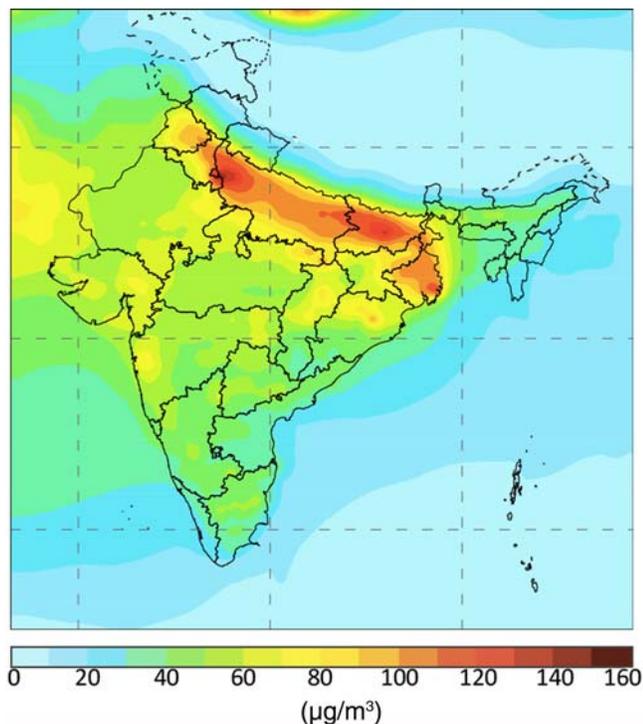


Figure 9. Simulated annual mean  $PM_{2.5}$  concentrations in 2015.

and Bihar, residential biomass accounts for 30%–50% of ambient  $PM_{2.5}$  in those states. Overall, coal combustion has the greatest impact on southeast India (Orissa, Chhattisgarh, Andhra Pradesh, etc.), accounting for more than 25% of the total ambient  $PM_{2.5}$  concentrations. The contributions of coal burning by industrial sources and by power plants have similar influences on  $PM_{2.5}$ , except that the contribution from industrial sources has a wider range than that of power plants; power plants had the strongest effect on  $PM_{2.5}$  in the northern part of Chhattisgarh. Open burning emissions mainly affect the  $PM_{2.5}$  concentrations in Punjab, Haryana, and the northwest of Uttar Pradesh, accounting for 15% to 35% of ambient  $PM_{2.5}$ .

Emissions from fire-brick production, distributed diesel, and transportation also contribute to air pollution. Fire-brick production emissions impact a large area of northeast and southern India and account for 3%–6% of ambient  $PM_{2.5}$ . Distributed diesel mainly affects the eastern part of Uttar Pradesh, where it accounts for 4%–6% of ambient  $PM_{2.5}$ . Transportation emissions influence ambient  $PM_{2.5}$  concentrations widely across several regions, including the northeast, northern, and southern areas, accounting for 2%–5% of ambient  $PM_{2.5}$ . The transportation estimates in this nationwide analysis are relatively low compared with some produced for city-specific analyses, in part because geographic scale of the grid used for the national analysis is larger and is less likely to capture finer-scale variation in exposure within urban areas and near roads.

Note that the sum of the concentrations attributed to each of the subsectors does not add up to the simulated ambient concentration from all emission sources. This difference results both from the nonlinearities in the relationships between emissions and ambient concentrations and from the sensitivity simulations used to estimate the fractional contribution from each source, as described in Section 3.2.

Additional sensitivity analyses were conducted to understand the potential contribution of regional transport of pollution outside India to  $PM_{2.5}$  concentrations within India. This contribution was estimated from the difference between the base case (STD 2015) and a “control” case in which pollution emissions from outside India were excluded. Figure 11 shows the absolute (Panel A) and percentage contributions (Panel B) from regional transport of pollution from outside India to simulated  $PM_{2.5}$  concentrations within the country.  $PM_{2.5}$  pollution attributable to sources outside of India mainly originates from regions to the west. Transboundary pollution contributes more than  $12 \mu\text{g}/\text{m}^3$  to ambient  $PM_{2.5}$  in the northwest region of India and accounts for approximately 15%–30% of ambient  $PM_{2.5}$  in that region. Contributions from transboundary transport were somewhat lower ( $8\text{--}12 \mu\text{g}/\text{m}^3$ , about 15%–20%)

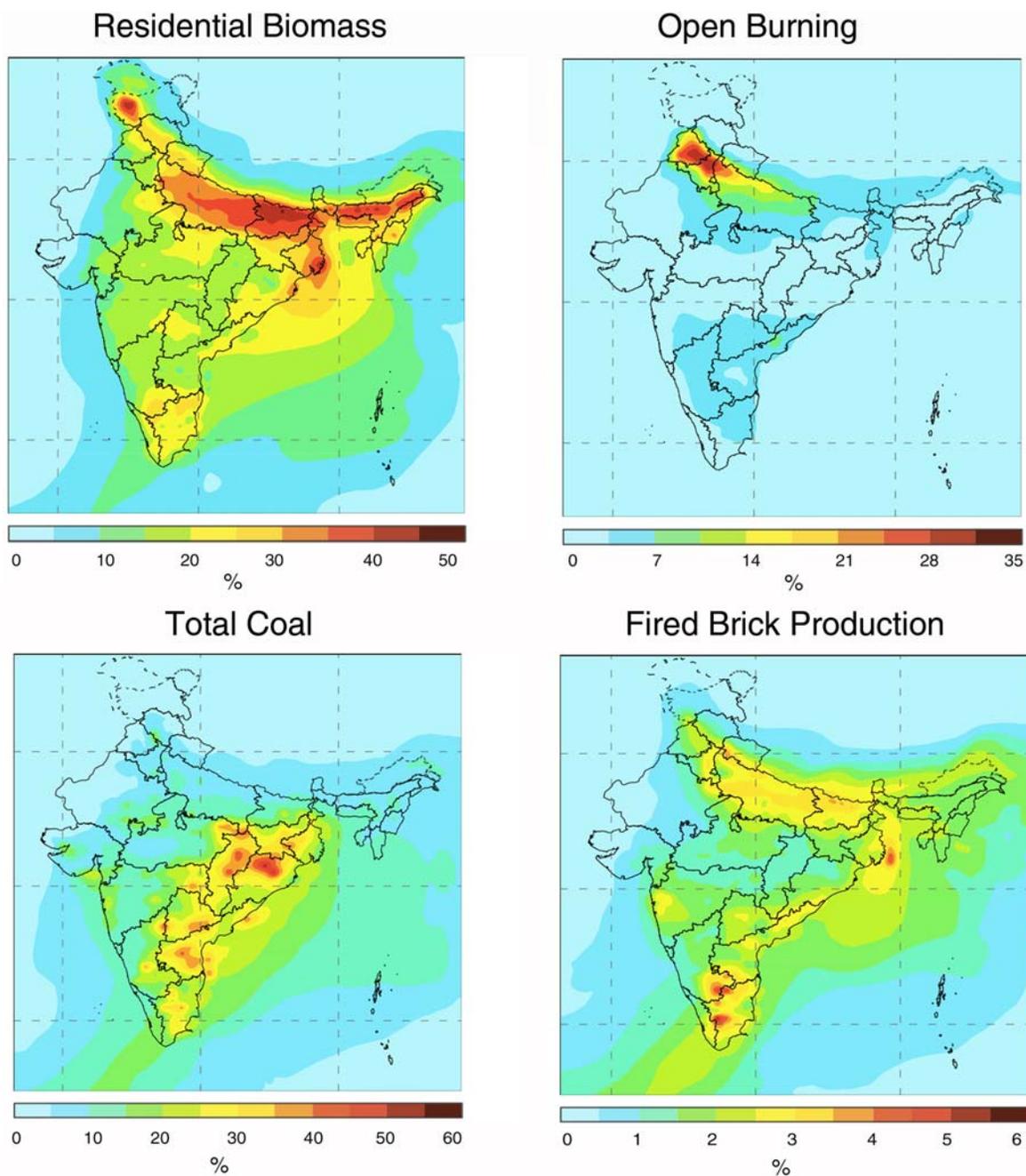


Figure 10. Simulated percentage contributions from different sectors to ambient PM<sub>2.5</sub> concentrations in the base year (2015). Each figure has a different scale in order to best depict the spatial patterns of the different sectoral contributions and therefore should not be used to compare sectors. (Figure continues next page.)

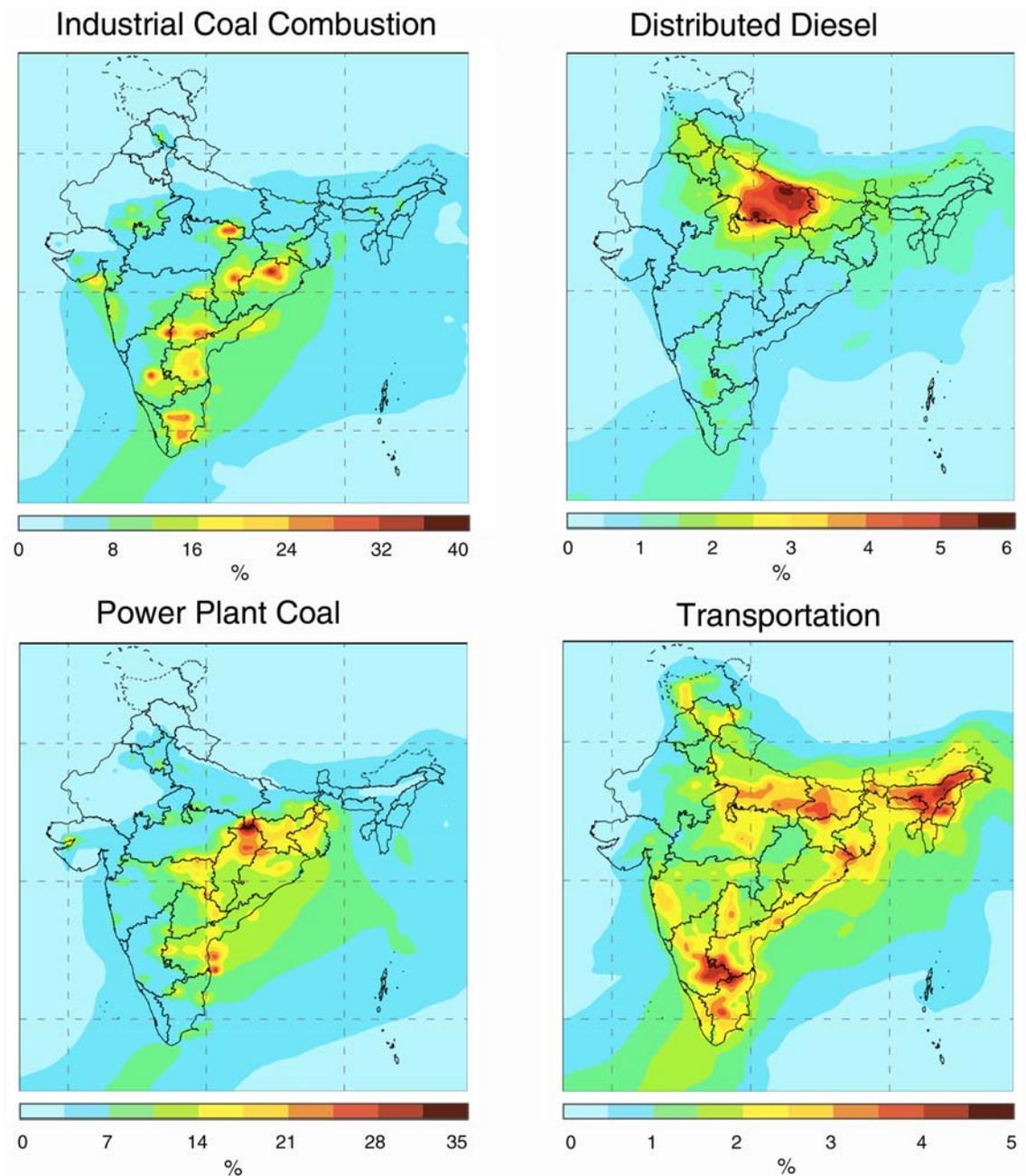


Figure 10. (Continued.)

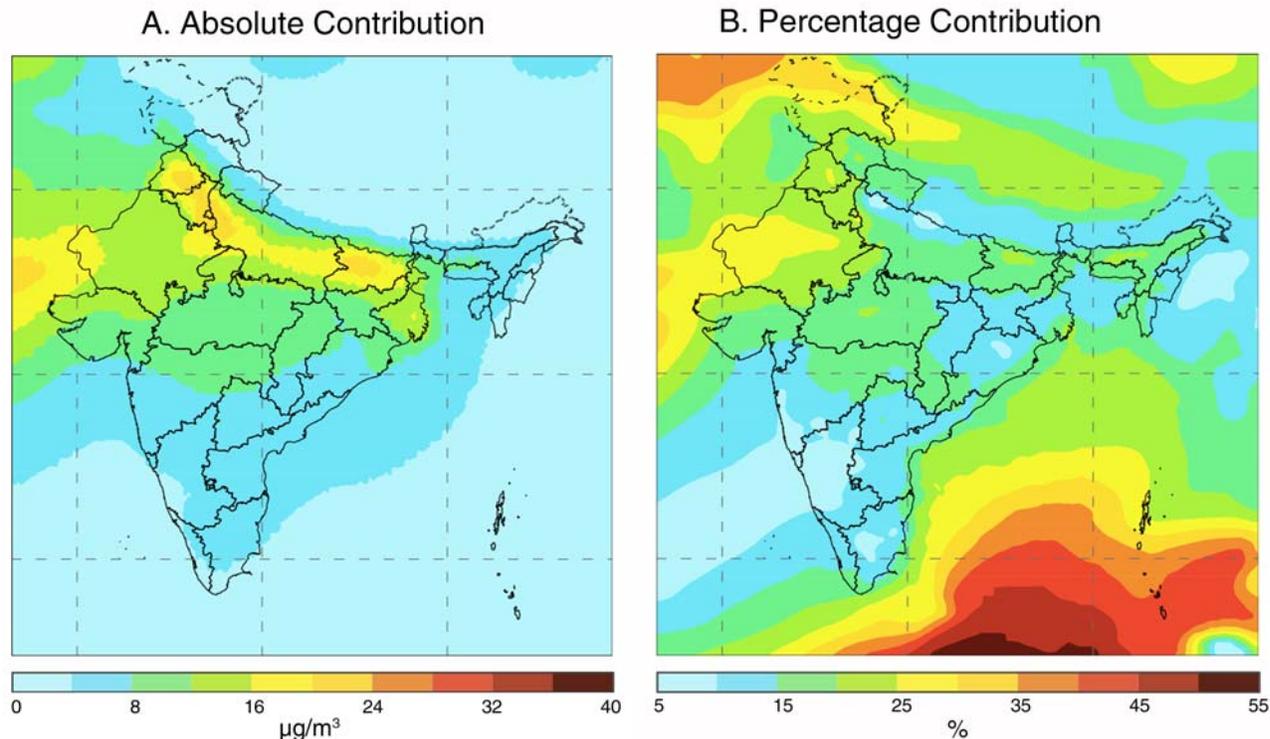


Figure 11. Contributions from sources outside India to  $\text{PM}_{2.5}$  concentrations: (A) absolute contributions ( $\mu\text{g}/\text{m}^3$ ) and (B) percentage contribution (%).

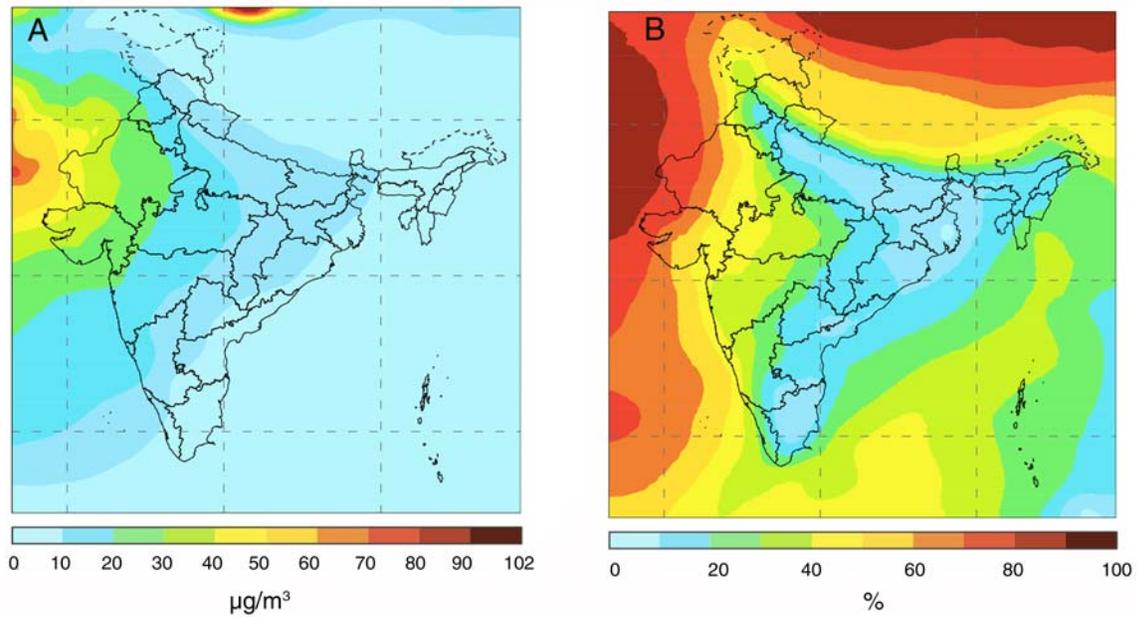
elsewhere in northern India and relatively low ( $4\text{--}8 \mu\text{g}/\text{m}^3$ ,  $<15\%$ ) in southern India.

Because total dust can be an important contributor to ambient  $\text{PM}_{2.5}$  in some areas, we conducted an additional simulation to estimate the separate contributions to total dust from (1) windblown mineral dust and (2) anthropogenic activities (fugitive emissions such as resuspension from road dust, and industrial activities — largely, coal fly ash). The results of this analysis can be found in Figure 12 for windblown mineral dust (Panels A and B) and for anthropogenic dust (Panels C and D). Each set of panels shows the concentrations (in  $\mu\text{g}/\text{m}^3$ ) of each type of dust source across India and its percentage contribution to total ambient  $\text{PM}_{2.5}$  in 2015. In the nested simulation domain (delineated by the boundaries of the figures shown), windblown mineral dust was a significant contributor to ambient  $\text{PM}_{2.5}$ . The highest concentration within the domain was  $95.7 \mu\text{g}/\text{m}^3$ , although the domainwide (area) average concentration was  $14 \mu\text{g}/\text{m}^3$ . Within India, windblown mineral dust is mainly distributed in the northwest, and its impact elsewhere in the country is limited because the highest concentration in the simulation domain occurs

outside of India. In most parts of the country, the windblown mineral dust concentration ranged between 0 and  $20 \mu\text{g}/\text{m}^3$  and accounted for 0% to 40% of the ambient  $\text{PM}_{2.5}$  concentration. In contrast to the findings for windblown dust, the simulations for dust from anthropogenic activities show that it contributes 15 to  $30 \mu\text{g}/\text{m}^3$  throughout India, accounting for 10% to 30% of total  $\text{PM}_{2.5}$ . Taken together the sum of the contributions of the individual source sectors that were included account for 90% of the simulated ambient  $\text{PM}_{2.5}$ , suggesting limited nonlinearities in the relationship between ambient concentrations and emissions and relatively good simulation of the important chemistry related to the spatial distribution of  $\text{PM}_{2.5}$  mass concentrations.

Analogous maps of the  $\text{PM}_{2.5}$  concentrations, scaled to the GBD 2015 estimates, are provided in Figures 13 and 14. The spatial patterns of the ambient concentrations show a strong north–south gradient, with the highest concentrations in the northern states of Uttar Pradesh, Delhi, Bihar, and Haryana as well as Punjab, West Bengal, and Assam (Figure 13). Figure 14 shows spatially how four sources contributed to ambient  $\text{PM}_{2.5}$  in 2015. Total dust concentrations are high

## Windblown Mineral Dust



## Anthropogenic Dust

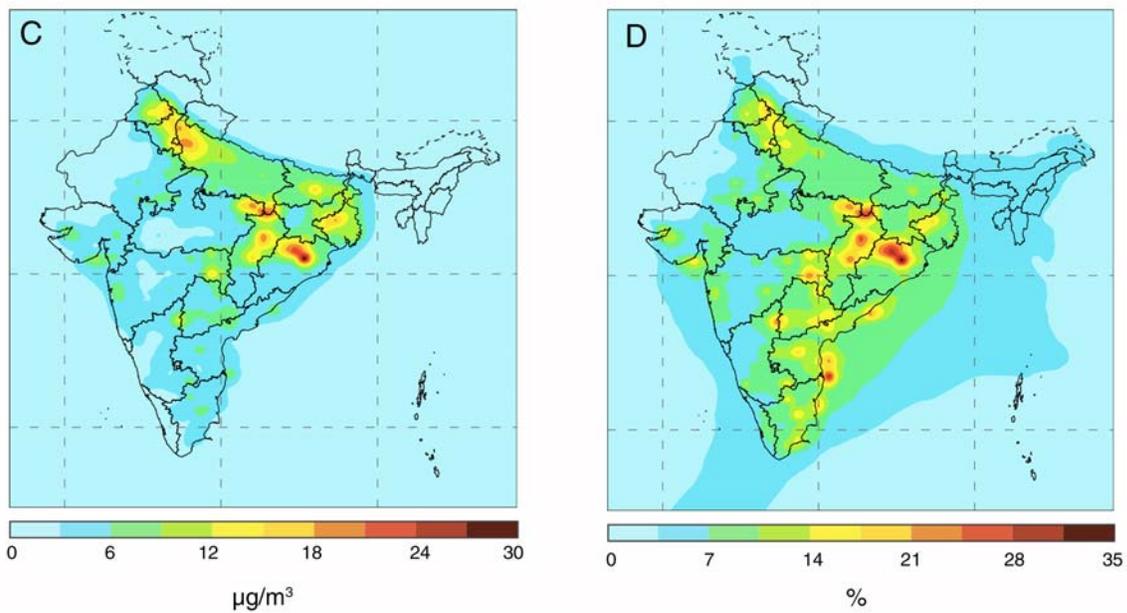


Figure 12. Absolute ( $\mu\text{g}/\text{m}^3$ ) and percentage (%) contributions to ambient PM<sub>2.5</sub> concentrations from windblown mineral dust (A and B, respectively) and anthropogenic dust (C and D, respectively).

throughout northwestern and central India, including the states mentioned above, as well as Gujarat, Rajasthan, and to a lesser degree Madhya Pradesh (Figure 14A). Biomass contributions are highest in Uttar Pradesh and Bihar, as well as West Bengal and Jharkhand (Figure 14B), whereas coal contributions affect the eastern portions of the country, in the states of Gujarat and Rajasthan, and the far northern states (Figure 14C) with little or no contributions in the west. Open burning most heavily impacts Punjab, Haryana, Delhi, and Uttar Pradesh (Figure 14D). Although contributions are small, transportation impacts are largest in Delhi, Uttar Pradesh, and Bihar; impacts of brick production are largest in Delhi, Uttar Pradesh, Bihar, and West Bengal; and distributed diesel impacts are largest in Uttar Pradesh and Bihar (Appendix D, available on the HEI website).

#### 4.2.1 Evaluation of GEOS-Chem Model Performance

The GEOS-Chem simulations made for this study include those for primary aerosol emissions, secondary sulfate, nitrate, and ammonium, and secondary organic aerosol. They therefore go beyond previous simulations made on regional scales over India (e.g., Sadavarte et al. 2016), which were limited to secondary sulfate and a

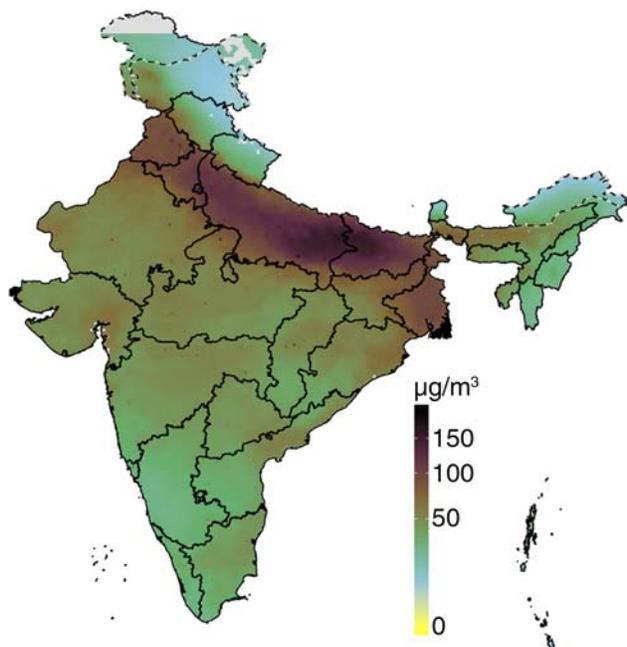


Figure 13. Spatial pattern of ambient  $PM_{2.5}$  concentrations in India, scaled to GBD 2015. Comparisons with the simulations shown in Figure 9 may be found in Appendix A, available on the HEI website.

smaller list of sources in the emissions inventory and addressed only a few months in the year. Atmospheric organic aerosol mass is estimated from model calculated OC fields, accounting for an organic mass:organic carbon ratio of about 2.0 based on a parameterization developed from aerosol mass spectrometer measurements and satellite  $NO_2$  concentrations (Philip et al. 2014a).

Model predicted concentrations of  $PM_{2.5}$  and its chemical constituents were evaluated against available  $PM_{2.5}$  measurements, satellite observations of columnar aerosol optical depth (AOD), and available monthly chemical composition measurements (Kumar and Sunder Raman 2016; Ramachandran and Kedia 2010; Ramachandran and Rajesh 2007). Model performance was evaluated through normalized mean bias (NMB) for pairs of model predicted concentrations ( $M$ ) and corresponding observed concentrations ( $O$ ), at given locations and for the same averaging period:

$$\text{Normalized Mean Bias} = \frac{\sum_1^n (M - O)}{\sum_1^n (O)} \quad (3)$$

Figure 15 compares simulated annual mean  $PM_{2.5}$  concentrations over India (shown earlier in Figure 9) with available in-situ observed concentrations (denoted by circles). The simulated concentrations ranged from 50 to 140  $\mu g/m^3$  across India, with the highest concentrations seen in the northern Indo-Gangetic plains. The evaluation of model performance found that the simulations satisfactorily captured both the magnitude and spatial variation of  $PM_{2.5}$  concentrations over India (that is, with NMB of  $-11.2\%$ ). However, some of the highest concentrations, observed in Delhi and in Kanpur, were somewhat underestimated by the model. The relatively low NMB compared with in-situ concentrations and the use of a comprehensive, locally derived emissions inventory suggests that all major sources were included in the simulation.

However, comparison of the modeled annual mean aerosol optical depth with observations from the moderate-resolution imaging spectroradiometer (MODIS), shown in Figure 16, found a normalized mean bias of  $-33\%$ , which provides evidence that there could be missing sources affecting  $PM_{2.5}$ . An attribute of the method used here — of scaling simulated  $PM_{2.5}$  by the ratio of observed to simulated AOD (van Donkelaar et al. 2010) — is that the scaled result will better represent observed  $PM_{2.5}$ .

The evaluation of the seasonal cycle of simulated  $PM_{2.5}$  is inhibited by the paucity of measurements for  $PM_{2.5}$  and its constituents. Simulated concentrations of  $PM_{2.5}$  and some of

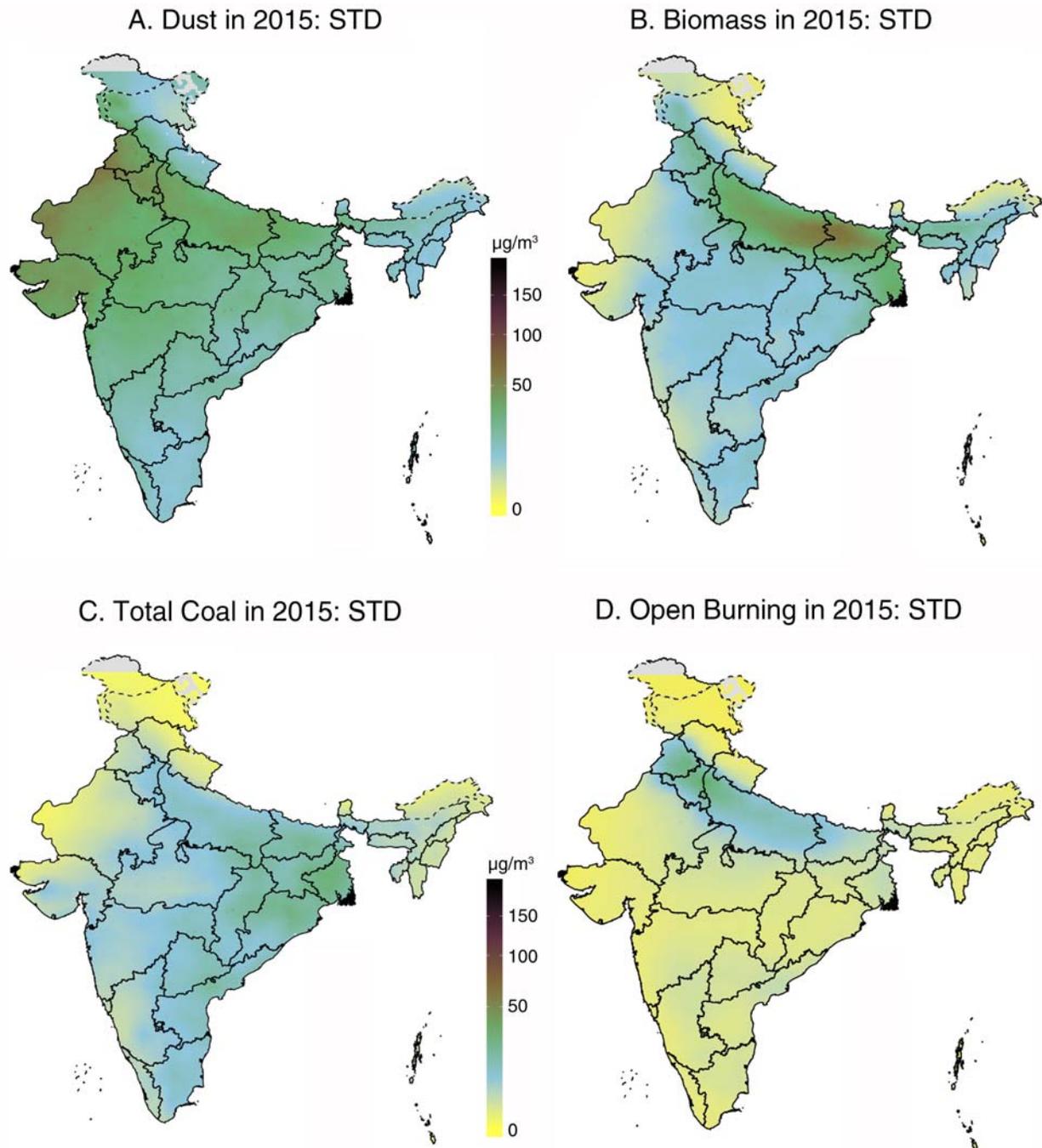


Figure 14. Spatial patterns of ambient PM<sub>2.5</sub> concentrations in India, 2015, contributed by various sectors: (A) Total dust, (B) biomass, (C) total coal combustion, and (D) open burning. Maps for all other sectors in 2015 are provided in Appendix D, available on the HEI website.

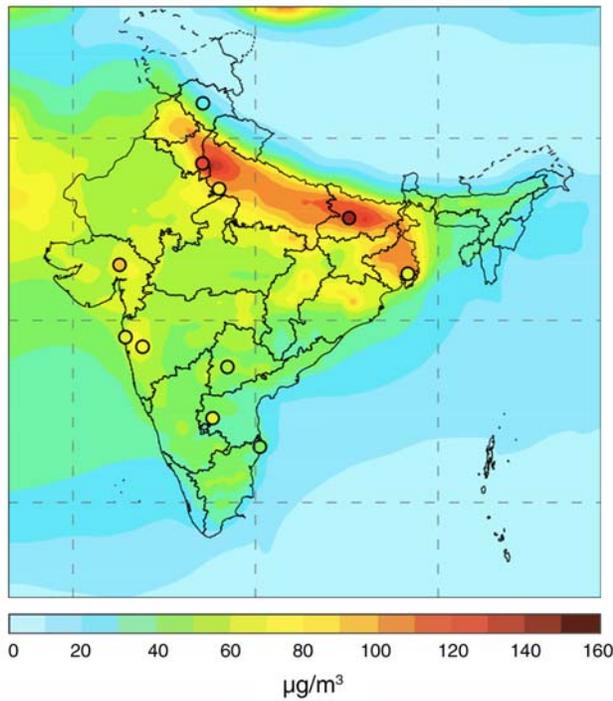


Figure 15. Evaluation of simulated annual mean  $PM_{2.5}$  concentrations by comparison with in situ observations (circles = observations).

its constituents were compared with monthly mean chemical composition measurements from a regional background site (Bhopal:  $PM_{2.5}$ , nitrate [ $NO_3^-$ ], and sulfate) and a western urban site (Ahmedabad: BC) (Figure 17). The model simulations appear to capture monthly mean concentrations satisfactorily during non-winter months, but to underestimate them in the winter months. As an additional evaluation, simulation results from this study were also compared with monthly  $PM_{2.5}$  concentrations for Bhubaneswar in eastern India extracted from Das and colleagues (2009). This comparison found the simulated concentrations to vary more seasonally and to be much greater than observed concentrations from that earlier study. One explanation may be the rapid growth of anthropogenic emissions in India, leading to discrepancies between observation data from earlier years — 2007 and 2008 in the study by Das and colleagues (2009) — and simulated concentrations based on emissions from 2015.

The overestimate of nitrate, seen here for Bhopal, is a common issue in many atmospheric models (Fairlie et al. 2010). One possible reason is the uncertainty of  $NH_3$  emissions. The emissions of  $NH_3$  usually have large uncertainties,

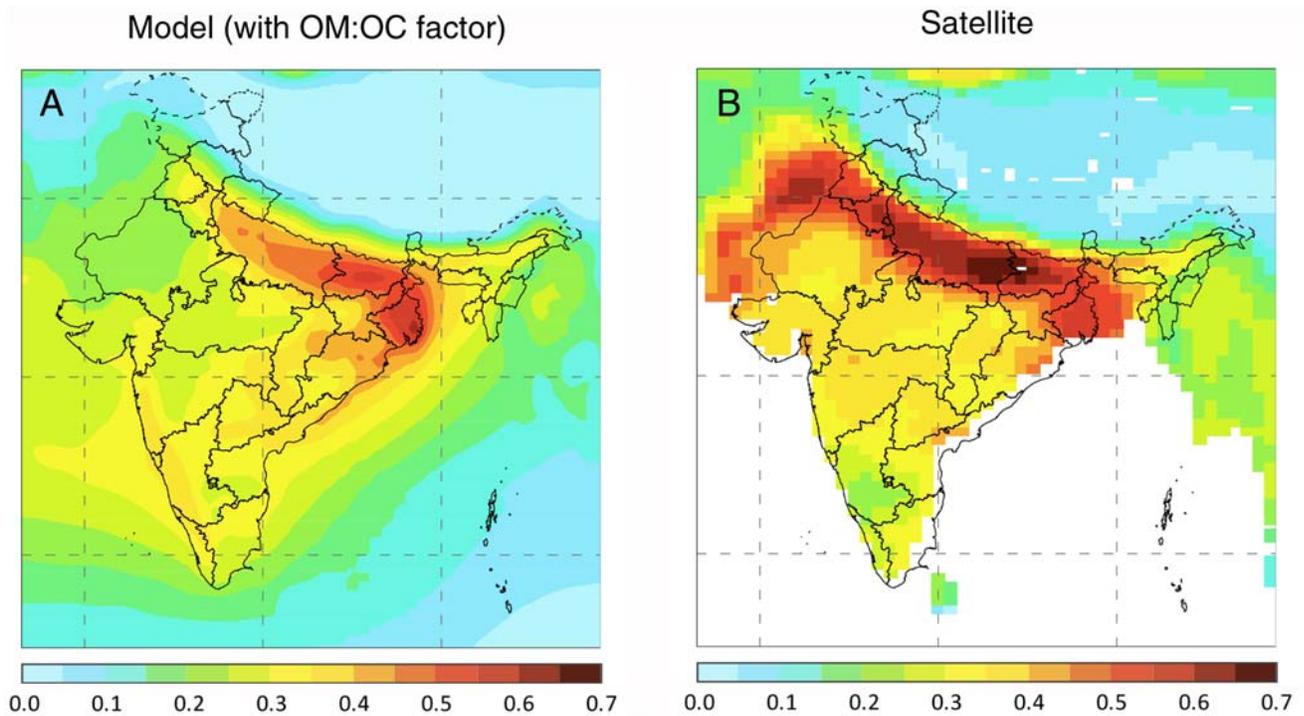


Figure 16. Comparison of (A) modeled annual mean aerosol optical depth (AOD) over India with (B) satellite observations from moderate-resolution imaging spectroradiometer (MODIS) showing a normalized mean bias of  $-33\%$ .

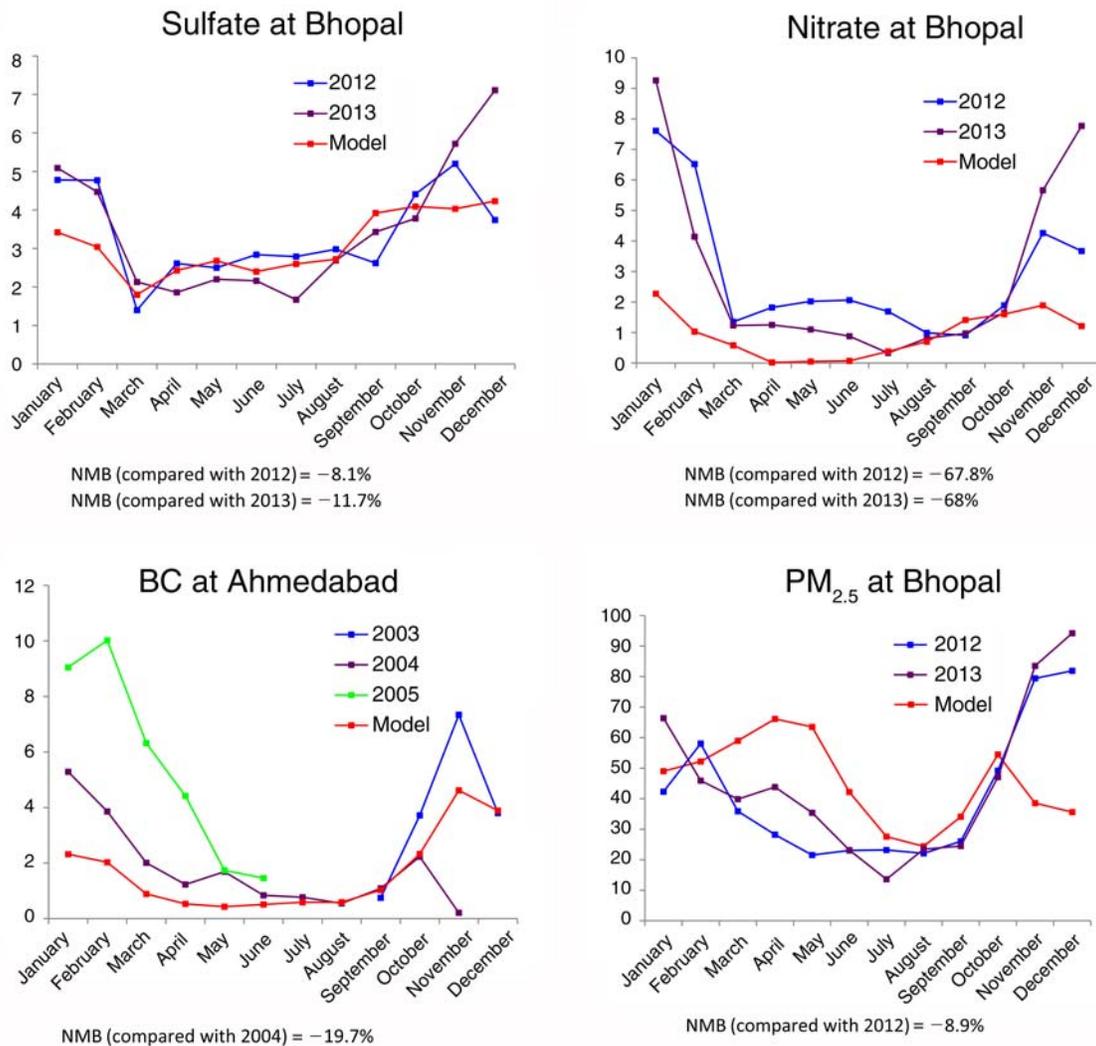


Figure 17. Evaluation of model performance (normalized mean bias, NMB) in capturing seasonal variation in chemical species concentrations at two sites in India.

and a high ammonium ( $\text{NH}_4^+$ ) concentration in the atmosphere would result in a high concentration of nitrate. The other important reason may be imperfections in the model mechanisms. The model may overestimate  $\text{N}_2\text{O}_5$  hydrolysis in aerosols (Zhang et al. 2012) and underestimate the dry deposition of  $\text{HNO}_3$  (Heald et al. 2012). But so far these studies cannot completely explain the overestimate of nitrate.

#### 4.3 ESTIMATES OF THE POPULATION-WEIGHTED $\text{PM}_{2.5}$ CONCENTRATIONS

Table 2 provides the population-weighted percentage contribution to ambient  $\text{PM}_{2.5}$ , or exposure, from each of

the source sectors for all of India (see first column); the corresponding population-weighted ambient concentrations attributable to each sector are shown in the first column of Table 3. Residential biomass combustion and total coal combustion are the largest anthropogenic contributors to ambient  $\text{PM}_{2.5}$ . Although total dust, from both windblown mineral dust and anthropogenic sources (such as coal fly ash and resuspended road dust), is also substantial, the contribution from anthropogenic activities contributed 9%, a larger percentage than either industrial or power plant coal combustion. Industrial coal combustion and power plant coal combustion contribute nearly equally to ambient  $\text{PM}_{2.5}$  and roughly at the same level as open burning of agricultural residues. At national and

**Table 2.** Mean Percentage Contribution of Different Source Sectors to Population-Weighted Ambient PM<sub>2.5</sub> in India for 2015<sup>a</sup>

| Source Sector                   | All India (%) | Rural India (%) | Urban India (%) |
|---------------------------------|---------------|-----------------|-----------------|
| Residential biomass             | 23.9          | 24.2            | 22.1            |
| Total coal                      | 15.7          | 15.5            | 17.1            |
| Industrial coal                 | 7.7           | 7.6             | 8.5             |
| Power plant coal                | 7.6           | 7.5             | 8.0             |
| Open burning                    | 5.5           | 5.5             | 5.6             |
| Transportation                  | 2.1           | 2.1             | 2.1             |
| Brick production                | 2.2           | 2.1             | 2.2             |
| Distributed diesel              | 1.8           | 1.8             | 1.4             |
| Anthropogenic dust <sup>b</sup> | 8.9           | 8.8             | 9.6             |
| Total dust <sup>c</sup>         | 38.8          | 38.7            | 39.5            |

<sup>a</sup> Appendix C Table C.1 (available on the HEI website) provides the breakdown of these sector contributions to PM<sub>2.5</sub> for each of the Indian states.

<sup>b</sup> Anthropogenic dust includes anthropogenic fugitive, combustion, and industrial dust.

<sup>c</sup> Total anthropogenic dust and windblown mineral dust.

regional levels, contributions from transportation, brick production, and distributed diesel are small (<2.5% and <2 µg/m<sup>3</sup>). Together, the sectors that were considered in the simulations account for 90% of the ambient PM<sub>2.5</sub> concentration nationally, with the remainder attributable to combustion emissions from sources outside of India (the dust contribution includes emissions originating both within and outside of India) and from diverse sources within India that were not evaluated individually.

Tables 2 and 3 also provide a breakdown of the percentage contribution and absolute contribution of each sector to PM<sub>2.5</sub>, respectively in urban and rural areas. For this analysis, urban areas were defined in accordance with the 2011 Indian Census as “all places with a municipality, corporation, cantonment board or notified town area committee, etc.” and “all other places which satisfied the following criteria: i) A minimum population of 5,000; ii) At least 75 per cent of the male main working population engaged in non-agricultural pursuits, and iii) A density of population of at least 400 persons per square km” (Source: [http://censusindia.gov.in/2011-prov-results/paper2/data\\_files/India2/1.%20Data%20Highlight.pdf](http://censusindia.gov.in/2011-prov-results/paper2/data_files/India2/1.%20Data%20Highlight.pdf)). All other areas were designated as rural.

There were only minor differences in the percent contributions of the different sectors to urban and rural PM<sub>2.5</sub> exposures. The contributions from anthropogenic dust and coal combustion were somewhat higher for urban populations than from residential biomass, distributed diesel, and transportation (as noted above, this relatively larger

scale analysis may not have fully captured the degree of transport-related exposure within cities).

#### 4.4 ESTIMATES OF THE CURRENT BURDEN OF DISEASE BY SECTOR

In this section, we present estimates of the burden of disease attributable to PM<sub>2.5</sub> by source. The burden of disease is expressed in two ways: in terms of the numbers of deaths attributable to PM<sub>2.5</sub> (Table 4) and of age-standardized disability-adjusted life-years per 100,000 population (DALYs/100,000) attributable to PM<sub>2.5</sub> (Table 5).

Of the total 1,090,400 deaths attributable to PM<sub>2.5</sub> in 2015 in India, 267,700 (24.5%) were attributable to residential biomass, the most important source related to human activities. Coal combustion, roughly evenly split between industrial sources and thermal power plant combustion, contributed to 169,300 deaths (15.5%) in 2015. Total dust, including both windblown mineral and anthropogenic dust (mainly from coal fly ash and resuspended road dust) was responsible for 38% (412,500 deaths) of the deaths attributable to PM<sub>2.5</sub>. Anthropogenic dust specifically contributed nearly 100,000 deaths, about 9.2% of the total deaths attributable to PM<sub>2.5</sub>. Open burning was responsible for 66,200 deaths (6.1%), with contributions of about 2% each from transportation, brick production, and distributed diesel sources (agricultural pumps, agricultural tractors, and diesel generator sets).

**Table 3.** Mean Population-Weighted Ambient PM<sub>2.5</sub> Concentrations and Sector Contributions in India for 2015<sup>a, b</sup>

| Source Sector                   | All India,<br>µg/m <sup>3</sup> (95% CI) | Rural India,<br>µg/m <sup>3</sup> (95% CI) | Urban India,<br>µg/m <sup>3</sup> (95% CI) |
|---------------------------------|--|--|--|
| All ambient PM <sub>2.5</sub>   | 74.3<br>(73.9 to 74.8)                   | 74.4<br>(74.0 to 74.8)                     | 73.2<br>(71.1 to 75.5)                     |
| Residential biomass             | 20.0<br>(19.9 to 20.2)                   | 20.3<br>(20.1 to 20.4)                     | 17.9<br>(17.3 to 18.5)                     |
| Total coal                      | 10.7<br>(10.6 to 10.8)                   | 10.6<br>(10.5 to 10.6)                     | 11.5<br>(11.1 to 11.9)                     |
| Industrial coal                 | 4.9<br>(4.9 to 5.0)                      | 4.9<br>(4.9 to 4.9)                        | 5.2<br>(5.0 to 5.3)                        |
| Powerplant coal                 | 5.5<br>(5.5 to 5.5)                      | 5.4<br>(5.4 to 5.5)                        | 5.9<br>(5.7 to 6.2)                        |
| Open burning                    | 5.0<br>(5.0 to 5.1)                      | 4.9<br>(4.9 to 5.0)                        | 5.4<br>(5.2 to 5.7)                        |
| Transportation                  | 1.6<br>(1.6 to 1.6)                      | 1.6<br>(1.6 to 1.6)                        | 1.5<br>(1.5 to 1.5)                        |
| Brick production                | 1.7<br>(1.7 to 1.8)                      | 1.7<br>(1.7 to 1.8)                        | 1.7<br>(1.6 to 1.7)                        |
| Distributed diesel              | 1.6<br>(1.6 to 1.6)                      | 1.7<br>(1.7 to 1.7)                        | 1.2<br>(1.2 to 1.3)                        |
| Anthropogenic dust <sup>c</sup> | 6.8<br>(6.8 to 6.9)                      | 6.7<br>(6.7 to 6.7)                        | 7.5<br>(7.2 to 7.7)                        |
| Total dust <sup>d</sup>         | 26.3<br>(26.2 to 26.4)                   | 26.2<br>(26.0 to 26.3)                     | 27.1<br>(26.2 to 27.9)                     |

<sup>a</sup> As the relationships between emissions and ambient concentrations are nonlinear, and given the approach to estimate sector contributions by comparing standard (all sources) and sensitivity (with a specific source sector removed), the sum of each of the subsectors does not add up to the simulated ambient concentration for all emission sources.

<sup>b</sup> Confidence intervals are based only on the uncertainty distribution from the GBD concentration estimates and were calculated as described in Section 3.5. Specifically, this uncertainty is estimated by sampling 1,000 draws of a distribution for each grid cell based on the model output mean and standard deviation.

<sup>c</sup> Anthropogenic dust refers to anthropogenic fugitive, combustion, industrial dust.

<sup>d</sup> Total dust includes anthropogenic dust and windblown mineral dust.

As discussed in the introduction to this report, this analysis does not assume different levels of toxicity for different PM components or sources. This assumption is consistent with the approach used in the GBD and is based on conclusions by national (e.g., U.S. EPA) and international (e.g., WHO) agencies drawn from the evidence available. Furthermore, crustal material is a typical constituent of urban PM<sub>2.5</sub> throughout the world and thus a component of the PM<sub>2.5</sub> exposures included in many epidemiological studies designed to understand their effects on health. With respect to health impacts related to windblown mineral dust, some current evidence suggests impacts of dust storms on hospitalizations, with emerging evidence also supporting impacts on all-cause, cardiovascular, and

respiratory mortality (Crooks et al. 2016; Kang et al. 2013; Karanasiou et al. 2012; Mallone et al. 2011; Perez et al. 2008; Vodonos et al. 2014, 2015). However, we acknowledge that the differential toxicity of PM of varying composition and from diverse sources remains an area of active research.

These burden estimates attributable to PM<sub>2.5</sub> and the sectoral contributions to them are driven by the estimates for rural populations. Seventy-five percent (815,300 deaths) of the overall burden attributable to PM<sub>2.5</sub> occurs among the rural population, reflecting the large percentage (67%) of the Indian population living in rural areas, as well as differences in underlying mortality rates and age structure found in rural India compared with urban areas.

**Table 4.** Source Sector Contributions to PM<sub>2.5</sub>-Attributable Deaths (95% UI) in India, 2015

| Source Sector                   | All India<br>(95% UI)               | Rural India<br>(95% UI)         | Urban India<br>(95% UI)         |
|---------------------------------|-------------------------------------|---------------------------------|---------------------------------|
| All ambient PM <sub>2.5</sub>   | 1,090,400<br>(939,600 to 1,254,600) | 815,300<br>(693,200 to 944,300) | 275,000<br>(240,800 to 310,900) |
| Residential biomass             | 267,700<br>(230,600 to 309,300)     | 204,800<br>(175,000 to 238,700) | 62,900<br>(54,600 to 71,100)    |
| Total coal                      | 169,300<br>(145,900 to 193,000)     | 124,500<br>(106,100 to 143,300) | 44,800<br>(39,000 to 50,800)    |
| Industrial coal                 | 82,100<br>(70,400 to 93,900)        | 60,200<br>(51,400 to 69,300)    | 21,900<br>(19,000 to 24,900)    |
| Powerplant coal                 | 82,900<br>(71,600 to 94,700)        | 61,400<br>(52,300 to 70,500)    | 21,500<br>(18,700 to 24,500)    |
| Open burning                    | 66,200<br>(56,700 to 76,800)        | 50,500<br>(42,800 to 59,500)    | 15,700<br>(13,700 to 17,700)    |
| Transportation                  | 23,100<br>(19,900 to 26,400)        | 17,400<br>(14,800 to 20,200)    | 5,600<br>(4,900 to 6,400)       |
| Brick production                | 24,100<br>(20,700 to 27,800)        | 18,100<br>(15,500 to 21,100)    | 5,900<br>(5,100 to 6,700)       |
| Distributed diesel              | 20,400<br>(17,600 to 23,800)        | 16,200<br>(13,700 to 19,100)    | 4,200<br>(3,600 to 4,800)       |
| Anthropogenic dust <sup>a</sup> | 99,900<br>(86,500 to 114,400)       | 74,000<br>(63,100 to 85,500)    | 25,900<br>(22,700 to 29,300)    |
| Total dust <sup>b</sup>         | 412,500<br>(353,300 to 474,600)     | 303,700<br>(256,600 to 351,300) | 108,900<br>(94,900 to 123,700)  |

<sup>a</sup> Anthropogenic dust includes only anthropogenic fugitive, combustion, and industrial dust.

<sup>b</sup> Total dust includes anthropogenic dust and windblown mineral dust.

In contrast to the situation in many other countries where urban concentrations are highest, annual average population-weighted PM<sub>2.5</sub> concentrations in rural and urban India were similar (about 70 µg/m<sup>3</sup>).

The source contributions to PM<sub>2.5</sub>-attributable mortality were slightly lower in urban areas than in rural areas for several sources: residential biomass combustion (22.9% versus 25.1% in rural areas), open burning (5.7% versus 6.2%), and distributed diesel (1.5% versus 2.0%). The contributions were somewhat larger in urban than in rural areas from coal combustion (16.3% versus 15.3%) and total dust (39.6% versus 37.2%).

Age-standardized DALY rates (DALYs/100,000) are more useful than deaths for comparing the impacts of sources within India because they control for population sizes and differences in the age structure of rural and urban populations. DALY rates are shown in Table 5 and were higher in rural areas than urban areas for all source

sectors, in part reflecting differences in underlying disease rates between urban and rural areas. However, the magnitude of differences in DALY rates between urban and rural areas differs by source sector. By comparing the percentage differences in rates between rural and urban areas, it is possible to identify where exposures from different source sectors have greater impacts on population health. For example, whereas DALY rates are on average 37% higher in rural areas for all ambient PM<sub>2.5</sub> than in urban areas, the differential is even greater for distributed diesel (78%), residential biomass (52%), and open burning (48%) — indicating the higher exposures to emissions from these source sectors in rural areas. Although DALY rates are still higher in rural areas than in urban areas for coal combustion and dust (total and anthropogenic), the differentials in DALY rates are lower than those for all ambient PM<sub>2.5</sub> or distributed diesel, for example, indicating that exposures from these sectors in urban areas are closer to those in rural areas.

**Table 5.** Source Sector Contributions to PM<sub>2.5</sub>-Attributable Age-Standardized DALY Rates (DALYs/100,000) in 2015, Stratified by All-India, Rural, and Urban Areas

| Source Sector                   | All India<br>(95% UI)     | Rural India<br>(95% UI)   | Urban India<br>(95% UI)   | % Rural – Urban<br>Difference |
|---------------------------------|---------------------------|---------------------------|---------------------------|-------------------------------|
| All ambient PM <sub>2.5</sub>   | 2,922<br>(2,528 to 3,323) | 3,172<br>(2,730 to 3,632) | 2,308<br>(2,027 to 2,607) | 27                            |
| Residential biomass             | 724<br>(631 to 823)       | 804<br>(692 to 927)       | 529<br>(463 to 599)       | 34                            |
| Total coal                      | 452<br>(393 to 513)       | 484<br>(417 to 552)       | 374<br>(326 to 423)       | 23                            |
| Industrial coal                 | 218<br>(188 to 248)       | 232<br>(200 to 265)       | 182<br>(159 to 207)       | 22                            |
| Powerplant coal                 | 223<br>(194 to 252)       | 240<br>(206 to 273)       | 180<br>(157 to 204)       | 25                            |
| Open burning                    | 178<br>(154 to 205)       | 197<br>(168 to 228)       | 133<br>(116 to 152)       | 32                            |
| Transportation                  | 62<br>(54 to 71)          | 68<br>(59 to 78)          | 47<br>(41 to 53)          | 31                            |
| Brick production                | 65<br>(56 to 74)          | 71<br>(61 to 82)          | 50<br>(43 to 56)          | 30                            |
| Distributed diesel              | 56<br>(48 to 64)          | 64<br>(54 to 75)          | 36<br>(31 to 40)          | 44                            |
| Anthropogenic dust <sup>a</sup> | 268<br>(233 to 304)       | 288<br>(248 to 329)       | 218<br>(191 to 246)       | 24                            |
| Total dust <sup>b</sup>         | 1,099<br>(952 to 1,258)   | 1,173<br>(1,004 to 1,345) | 914<br>(798 to 1,036)     | 22                            |

<sup>a</sup> Anthropogenic dust includes only anthropogenic fugitive, combustion, and industrial dust.

<sup>b</sup> Total dust includes anthropogenic and windblown mineral dust.

## 5.0 ESTIMATION OF THE FUTURE BURDEN OF DISEASE RELATED TO MAJOR AIR POLLUTION SOURCES

### 5.1 CHARACTERIZATION OF FUTURE SCENARIOS

In this work we develop and evaluate three future scenarios for 2030 and 2050 from estimated trends in emissions from all emission sectors. The three scenarios are a reference scenario (REF) and two alternate scenarios (S2 and S3) independent of one another and each with a unique set of evolving technology mixes representing different levels of emissions control and deployment of low-emissions technologies. The three scenarios are described briefly in Table 6. The scenarios represent a range of assumptions about shifts in technology over time in each of the sectors that result in changes in both emissions of PM<sub>2.5</sub> (primary emissions), its components BC and OC, and its gaseous precursors (SO<sub>2</sub>, NO<sub>x</sub>, and NMVOCs).

The primary analysis focused on sector contributions under each of the scenarios for the year 2050. For the year 2030, an interim analysis was conducted to predict total ambient PM<sub>2.5</sub> concentration and associated disease burden for each of the scenarios; sensitivity simulations to assess sectoral contributions were not conducted.

### 5.2 ESTIMATION OF EMISSIONS UNDER FUTURE SCENARIOS

Starting with the base year of 2015, growth rates in sectoral activity were identified in two periods, 2015–2030 and 2030–2050. Projections of sectoral activity growth in each period were based on expected changes in demand and services from sectoral reports (see Appendix E, Table E.1, available on the HEI website, for details). The sectoral activity was then apportioned to various technologies based on the technology-mix identified and assumed from published literature (Table E.2). Technology-based energy demand per unit activity (Table E.3) and specific fuel

**Table 6.** Future Scenarios of Energy and Emissions Control Policies

**REF, or Reference Scenario**

Where the sectoral energy demand is met through sectoral technology-mix evolution at rates corresponding to changes observed during 2005–2015.

**S2, or Ambitious Scenario**

Assumes that the technology mix will reflect (1) the energy-efficiency targets for thermal power and industry as desired in India’s NDC; (2) the emissions standards in transport as proposed in auto-fuel policy; and (3) the emissions controls expected from an influx of cleaner technologies in residential, brick production, and informal industry sectors.

**S3, or Aspirational Scenario**

Aimed at more profound energy efficiency targets, represented by published high-efficiency–low-carbon-growth pathways in industrial, electricity-generation, and transport sectors; high rates of shifting away from traditional biomass technologies (residential and informal industry); and including a complete end to agricultural field burning.

consumption and fuel properties were used to estimate fuel demand (Table E.4). Technology-linked emission factors for PM<sub>2.5</sub> and its precursors (Table E.5) were used to calculate emissions. The schematic of the overall methodology is illustrated in Figure 18.

**5.2.1 Growth in Sectoral Activity Demand**

Analysis of published sectoral demand projections or growth targets for 2015–2030 and 2030–2050, along with past sectoral growth during 2005–2015 from government reports (Pandey et al. 2014; Sadavarte and Venkataraman 2014), was used to arrive at mean sectoral growth rates during the two periods (Table E.1). Electricity generation comprises fossil-fuel–based sources (coal-, oil-, and gas-fired thermal power plants) and non-fossil-fuel–based sources. Electricity generation through coal-fired thermal power plants, referred to as “thermal power” in Appendix E text and Tables E.3 and E.5, is the only source of emissions, whereas renewable sources (e.g., hydroelectric generation) are assumed to have zero emissions. Published growth rates in electricity demand were analyzed (Dharmadhikary and Dixit 2011; India Energy Security Scenarios [IESS] NITI Aayog 2015) to arrive at annual growth rates of 6.3% in 2015–2030 and 6.7% in 2030–2050,

resulting in installed capacity rising from 245 gigawatts (GW) in 2015 to an estimated 1,080 GW in 2050.

Sectoral demand projections in heavy industry (cement, iron and steel, fertilizers, and non-ferrous materials) and light industry from available reports (IEA 2009; IESS NITI Aayog 2015; Murthy 2014; PNGRB 2013) were used to estimate the industry growth rates in the two periods (Table E.1, Row 2). For example, present-day production of cement increased from 215 MT/yr to an estimated 957 MT/yr, and production of iron and steel increased from 88 MT/yr to 280 MT/yr in 2050. The growth in the fertilizer sector was reported to be lower than other sectors, reaching saturation by 2030 (PNGRB 2013), growing from present-day production of 190 MT/yr to an estimated 271 MT/yr in 2050.

The transport sector comprises (1) passenger vehicles, including private-passenger vehicles (two-stroke and four-stroke two- and three-wheelers and four-wheeler petrol vehicles), and public passenger vehicles (four-wheeler diesel vehicles and buses); and (2) freight including light-duty diesel vehicles (LDDVs) and heavy-duty diesel vehicles (HDDVs) (Pandey and Venkataraman 2014). For transport, growth in demand was estimated under the categories of passenger and freight (Table E.1), respectively, as 5.78% and 3.61% in 2015–2030, and 2.89% and 1.8% in 2030–2050 (Guttikunda and Mohan 2014; IESS NITI Aayog 2015). The present-day passenger activity of 9,997 billion passenger-km and freight activity of 2,084 billion ton-km rose to an estimated 41,057 billion passenger-km and 5,073 billion ton-km in 2050, respectively.

Population growth (UN 2005), at annual growth rates of 1.25% in 2015–2030 and 0.53% in 2030–2050, was assumed to drive energy demand in residential and dispersed diesel (linked to residential use of diesel electric generators). Building construction was estimated to grow annually at 6.6% (2015–2030) (Maithel et al. 2012), although it was adjusted downward to 3.37% 2030–2050, using a factor of decrease in cement production, during the latter period. Thus, the assumed national brick demand of 250 billion bricks in 2015 is expected to rise to 1,265 billion bricks in 2050. Growth rates for informal industry, including food and agricultural product processing, were assumed to be the same as for the agricultural sector resulting in an increase of estimated wood consumption from 28 MT/yr in 2015 to 41 MT/yr in 2050.

To estimate growth in agricultural production and related burning of residues for field clearing as well as agricultural use of tractors and pumps, a growth rate of 1.02% (Ray et al. 2013) was computed for agricultural production during both 2015–2030 and 2030–2050, from increases in food demand. This resulted in the growth of agricultural

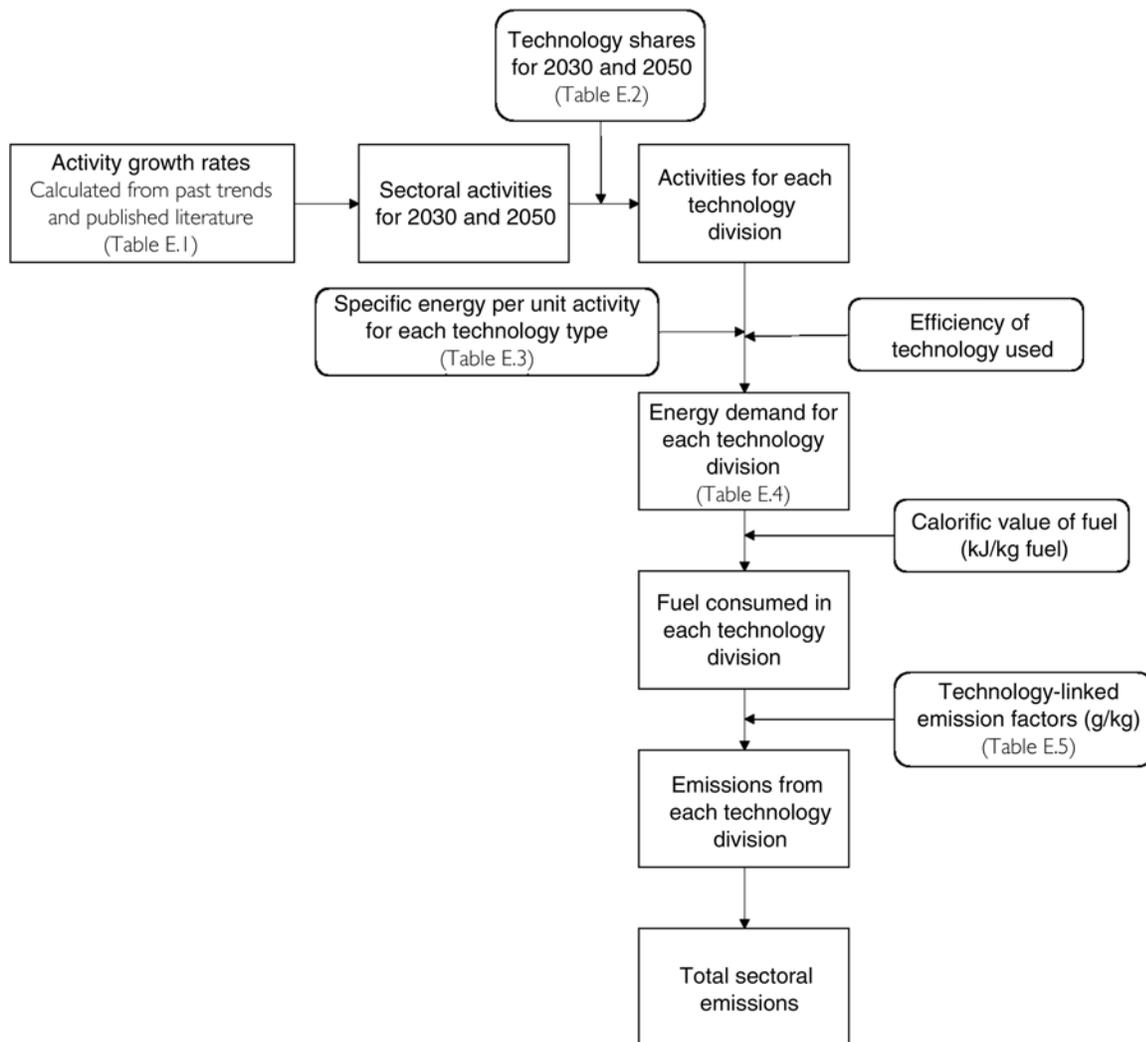


Figure 18. Methodological flow diagram for projection of future emissions. (See Appendix E, available on HEI website, for Tables E.1–E.5.)

open burning from an estimated 147 MT/y in 2015 to 210 Mt/yr in 2050. These growth rates are used to project the energy demand for each sector to 2030 and 2050 and analyze evolution of energy use under different scenarios with different technology mixes.

### 5.2.2 Evolution of Technology Mix

The technology mix assumed under different scenarios for each sector is summarized here with further details in Table E.2 in Appendix E (available on the HEI website). In 2015, power generation was almost entirely from subcritical pressure thermal power plants with an average gross efficiency of 30.5% (IEP 2006; IESS NITI Aayog 2015); a switch to more efficient technologies, such as supercritical,

ultra-supercritical, and integrated gasification combined cycle, is expected in future. For 2030 and 2050, respectively, the non-fossil-fuel shares were assumed to be 30% and 40% in REF, 40% and 60% in S2, and 75% and 80% in S3. The central goal of India's INDC (India's NDC 2015) is to achieve 40% share of electricity generation from non-fossil fuels by 2030, supported by a domestic objective of achieving 175 GW of renewable energy by 2022 — a goal the government is working actively to achieve. The assumed technology mix in S2 follows the INDC's proposed non-fossil-fuel share of 2030. In S3, it is consistent with high efficiency–low carbon growth cases in earlier studies (Anandarajah and Gambhir 2014; IESS Niti Aayog, 2015 [Level 4]; Shukla and Chaturvedi 2012). For thermal

power plants, the transition of sub-critical boiler technology to more efficient technologies, such as super-critical, ultra-super-critical, and integrated gasification combined cycle, is based on published scenarios (IEP 2006; IESS NITI Aayog 2015). In industry, energy efficiency is prescribed using the PAT mechanism (IESS NITI Aayog 2015; MoP 2008). Under the PAT initiative (MoP 2008), PAT penetrations for different heavy industries in 2030 and 2050 were adopted from the Level 2 and Level 4 trajectories of the IESS 2047 scenarios (IESS NITI Aayog, 2015). Their PAT penetrations were assumed to range from 58%–75% in 2030 to 60%–75% in 2050 for the REF scenario, from 62%–79% in 2030 and 69%–84% in 2050 for the S2 scenario, and from 85%–100% across both time periods in the S3 scenario (Appendix E, Table E.2, available on the HEI website).

In the transport sector, current technology shares are 81% private vehicles (two-wheeler, three-wheeler, and cars) and 19% public vehicles (buses and taxis) (Pandey and Venkataraman 2014). The share of private vehicles is projected to increase in the REF scenario until 2030, especially for two-wheelers and cars (Guttikunda and Mohan 2014; NTDP 2013). However, beyond 2030, as gross domestic product stabilizes, no further increase in private vehicle share is assumed, but public transport is assumed to be in greater demand. Therefore, in the S2 scenario, private-vehicle share is assumed to be 75% and 70% in 2030 and 2050, respectively. For the S3 scenario, private-vehicle share is assumed to decrease rapidly to 60% in 2030 and 40% in 2050 to be consistent with Level 2 of IESS (NITI Aayog 2015) (Appendix E, Table E.2). For future emissions, Auto Fuel Policy (Government of India, 2014) recommendations were applied, wherein two- and three-wheelers were proposed to have Bharat Stage (BS)-IV standards from April 1, 2015, and LDDVs and HDDVs to have BS-Va and BS-Vb. As has been discussed in the section on Air Quality Management, there has been a recent proposal to leapfrog directly to BS-VI for all on-road vehicle categories by 2020 (MoRTH 2016). However, scenarios used here do not reflect such a quick change, but have kept the share of BS-VI at modest levels for a number of reasons: potential delays in availability of BS-VI compliant fuels; difficulties in making the technologies adaptive to Indian road conditions as well as cost-effective (ICRA 2016); and the likely continued use of non-BS-VI compliant vehicles in peri-urban and rural areas.

In the brick sector, currently 76% of total bricks are produced by Bull's trench kilns and 21% by clamp kilns. Clamp kilns are highly polluting, with sun-dried bricks stacked alternately with layers of powdered fuel and allowed to smolder until the bricks are baked. The demand

for non-fired-brick walling materials is currently negligible, but is expected to rise with the availability of hollow-block technology and the governmental incentives for fly-ash bricks (MoEF 2017). For fired bricks, cleaner technologies include a retrofit to existing Bull's trench kilns, called zig-zag firing, or to vertical shaft brick kilns, which are significantly more efficient, but capital intensive. For small clamp kilns, where regulation may not be effective, a constant activity level, but a decreasing share was assumed in future, with new cleaner technologies filling growing demand (personal communication, S. Maitel, 2015). Evolution of technologies in informal industry from traditional wood furnaces presently supplying all energy requirements to gasified and liquefied petroleum gas (LPG)-based technologies is assumed to increase to 20% and 35% in 2030 and 2050, respectively, for S2 and to 65% and 80% in S3 (Appendix E, Table E.2, available on the HEI website).

India's rural population largely depends on biomass fuels for cooking, water heating, and lighting (Venkataraman et al. 2010). Although India has introduced improved biomass cookstoves to improve fuel efficiency and to reduce exposures to smoke by using chimneys or combustion improvements, further technological improvements or alternatives are required to reach the LPG-like emission levels necessary to reduce disease risk from residential biomass burning. The REF scenario assumes an increasing penetration rate of LPG and piped natural gas typical of 1995–2015 (Pandey et al. 2014). The S2 and S3 scenarios assumed a future switch in residential energy to use of liquefied or piped natural gas or low-emission biomass gasifier stoves and biogas, an assumption consistent with energy efficiency increases proposed in Levels 2 and 4 of the IESS (NITI Aayog 2015). We used lower rates of clean technology adoption in the residential sector in both the REF and S2 scenarios because no current legislation or standards target this sector. However in the S3 scenario, we assumed a complete switch away from traditional biomass fuels. For residential lighting, 37% is provided by highly polluting kerosene wick lamps and lanterns, which emit large amounts of black carbon (Lam et al. 2012). The balance is provided by electricity, with less than 1% provided by solar lamps. Residential lighting is assumed to shift completely from the modest present-day dependence on kerosene to electricity and solar lamps in 2030 and 2050 (National Solar Mission 2010), a change expected with a national promotion of renewable energy.

The analysis for the agricultural sector assumes that residues of cereal and sugarcane are burned in the field, based on satellite observations of active fire cycles in agricultural land-use areas (Venkataraman et al. 2006). Gupta (2014)

indicated greater mechanization of agriculture, with a decrease in amounts of residue, but an increase in incidence of field burning to clear the rubble consisting of 6–12-inch stalks, before sowing. Mulching technology was reported to allow sowing even through the rubble and loosely spread residue, thus avoiding burning for field clearing. The present work assumes different levels of mulching, replacing field burning, in future years (Appendix E, Table E.2, available on the HEI website).

Different technology mixes for each source or sector are matched with corresponding specific energy (in petajoules [PJ], equal to  $10^{15}$  joules) per unit activity related to each technology type included (Appendix E, Table E.3). In technology evolution, a given technology may improve in efficiency with time or may be replaced with higher efficiency–lower emissions technology at greater rates with time. Both these possibilities are captured in the assumptions, with no efficiency improvement with time characterizing REF, but with increasing efficiency improvements with time (in 2030 and 2050) characterizing S2 and S3 scenarios (Appendix E, Table E.3). Thus, in scenarios with high-efficiency energy technologies, there is a reduction of total energy consumption despite increase in activity. In the transport sector (Government of India 2014), engine efficiency improvements are not foreseen to have significant increases across technologies (e.g., across BS-III to BS-VI); however, emission decreases are envisaged from control technologies, as described in Table E.5 in Appendix E, available on the HEI website.

The projected energy demand in the three scenarios, respectively, in 2030 and 2050 are, 57 EJ (an exajoule [EJ] is equal to  $10^{18}$  joules) and 111 EJ in REF, 50 EJ and 85 EJ in S2, and 41 EJ and 65 EJ in S3 (Appendix E, Table E.4). These estimates are broadly consistent with energy scenarios from exogenous energy economic models (Anandarajah and Gambhir 2014; Chaturvedi and Shukla 2014; Parikh 2012; Shukla and Chaturvedi 2012) for reference and high efficiency–low carbon growth cases, which are widely accepted to represent growth trajectories for India. Typically future energy demand is projected in 2050 to be within a range of 95–110 EJ for reference scenarios (Parikh 2012; Shukla and Chaturvedi et al. 2012) and 45–55 EJ for low carbon pathways (Anandarajah and Gambhir 2014; Chaturvedi and Shukla 2014). Further, emissions of  $\text{CO}_2$  estimated under these scenarios (not shown) were evaluated with published literature. Estimated emissions of  $\text{CO}_2$  in 2030 and 2050, respectively, were 3,400 Tg/yr and 7,200 Tg/yr in the REF scenario, and 2,500 Tg/yr and 2,000 Tg/yr in the S3, or high efficiency and clean technology adoption scenario. These estimates are broadly consistent with published 2050 emissions of 7,200–7,800 Tg/yr  $\text{CO}_2$  for

reference cases, and 2,500–3,400 Tg/yr  $\text{CO}_2$  under different low carbon scenarios (Anandarajah and Gambhir 2014; Shukla et al. 2009). These assessments helped establish consistency of energy demand with top-down economic models among sectors and sub-sectors, before the analysis moved on to estimate emissions of  $\text{PM}_{2.5}$  and its precursors.

In each technology division the energy demand was converted to fuel consumption and matched with corresponding emission factors described in Appendix E, Table E.5 (available on the HEI website) to arrive at emissions.

### 5.2.3 Evolution of Emissions for Future Scenarios

Figure 19 compares the projected emissions of each air pollutant from the various sectors under the three scenarios for 2030 and 2050 with the baseline year 2015. Emissions of  $\text{PM}_{2.5}$  evolve from present-day levels of 9.1 MT/yr to 2050 levels of 18.5, 11.6, and 3.0 MT/yr, respectively, in the three scenarios (Figure 19A). In all future scenarios, there is faster growth of industry and electricity generation than of residential energy demand, with 60–70% of future emissions arising from the industrial sector. These scenarios assume immediate actions to curb residential and agricultural emissions, with future controls largely effected by shifts to 75%–80% non-coal thermal power generation in 2050.

Future reductions in BC (Figure 19B) and OC (Figure 19C) emissions result from a number of actions in residential and informal industry sectors and from agricultural activities related to these sectors. These include actions that enable a shift to cleaner residential energy solutions, a shift away from fired-brick walling materials toward greater use of clean brick production technologies, and a shift away from agricultural field burning through the introduction of mulching practices (assumed in S3). Future increases in transport demand could lead to increased BC emissions from diesel-powered public transport, thus providing an important decision lever in favor of the introduction of CNG or electric-powered public transport (in S3).

Under both REF and S2 scenarios (Figure 19D), emission growth of  $\text{SO}_2$  is driven by growth in electricity demand and industrial production, while reduction is driven by a shift to non-carbon power generation (nuclear, hydro, solar, and wind) and modest adoption of flue gas desulfurization technology. These scenarios assume low rates of flue-gas desulfurization-technology adoption because of the absence of current regulation and current implementation of this technology.

Emissions of  $\text{NO}_x$  increase in 2050 (Figure 19E) to 31.7 MT/yr under REF and 18.4 MT/yr under S2, but stabilize at 10.5 MT/yr under S3. The emissions shares are dominated by thermal power and the transport sector, and grow with

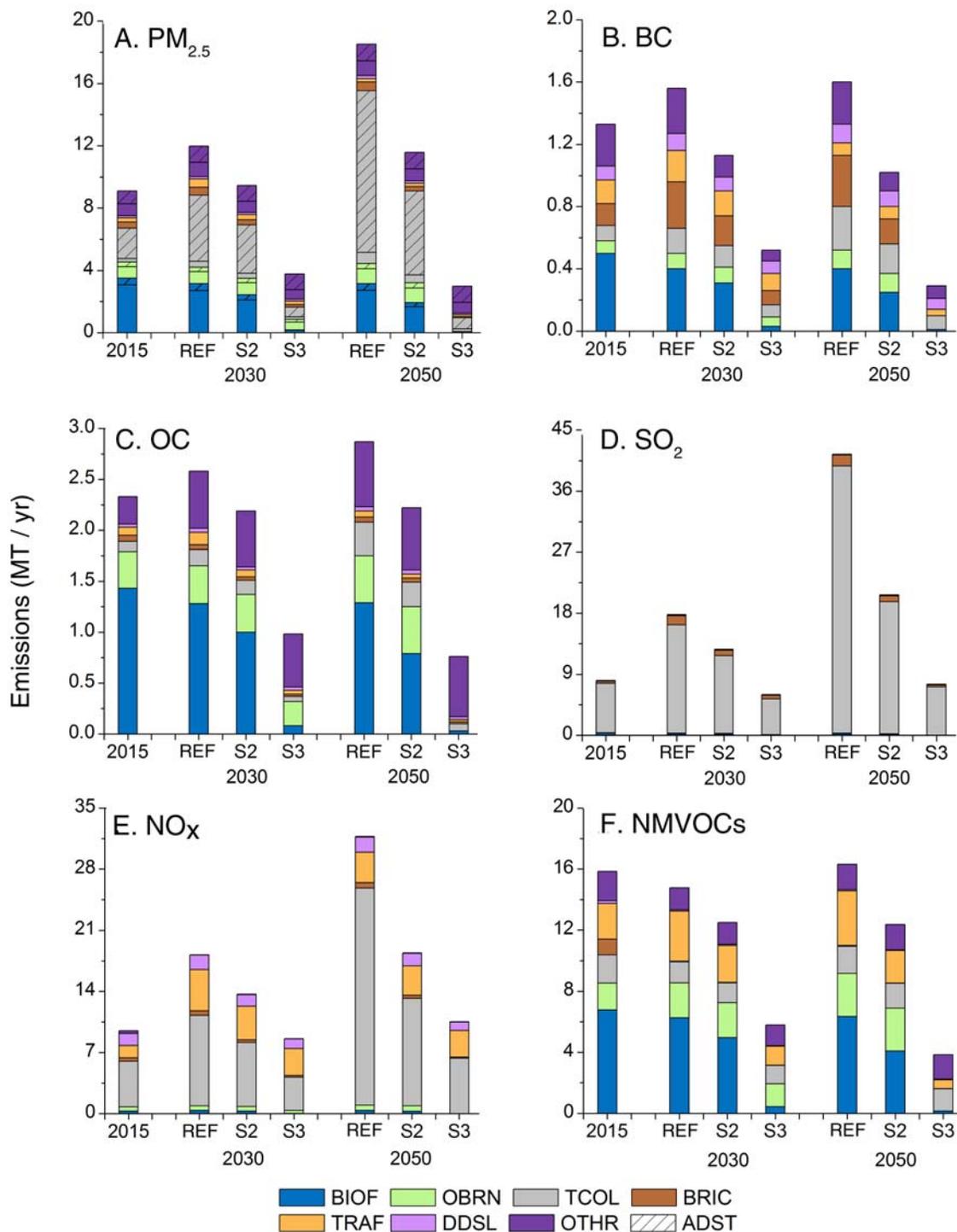


Figure 19. Projected emissions of major air pollutants in India during 2015–2050 under future scenarios REF, S2, and S3: (A) PM<sub>2.5</sub>, (B) BC, (C) OC, (D) SO<sub>2</sub>, (E) NO<sub>x</sub>, and (F) NMVOCs. BIOF, biomass fuel (residential cooking, lighting, and heating); OBRN, open burning (agricultural residue and forest); TCOL, total coal (electricity generation, heavy and light industry); BRIC, fired-brick production (predominantly in traditional brick kilns); TRAF, transportation (on-road and off-road transport — diesel/gasoline/CNG vehicles and trains); DDSL, distributed diesel (agricultural pumps, agricultural tractors, and electric generator sets); OTHR, other sources, not individually treated (residential lighting, cooking with gas/kerosene, informal industry in food and agricultural product processing); ADST, anthropogenic dust (designated by hatchmarks within major emitting source categories: coal fly-ash and mineral-based pollution particles).

sectoral growth under the first two scenarios. Under the S3 scenario, shifts to tighter emission standards for vehicles, to a greater share of CNG in public transport, and to non-fossil-fuel power generation all reduce NO<sub>x</sub> emissions. A non-negligible — approximately 20% — share of NO<sub>x</sub> emissions is from residential, agricultural field burning, and brick production sectors, which are reduced in magnitude by the adoption of mitigation efforts based largely on cleaner combustion technologies.

Emissions of NMVOCs increase in 2050 to 16.3 MT/yr under the REF scenario, but decrease to about 3.8 MT/yr under S3 (Figure 19F). In the S3 scenario, mitigation of emissions from residential biomass, energy extraction (coal mining and oil exploration), and open burning leads to an offset of more than two-thirds of present-day NMVOC emissions. However, a shift to public transport based on CNG drives the increase in NMVOC emissions from the transport sector. Therefore, alternate modes and technologies in the transport sector need further attention.

As discussed in Sections 3.1 and 4.2, anthropogenic dust emissions (Philip et al. 2017) correspond to mineral-based pollution particles, including coal fly ash, and contribute about 40% of Indian PM<sub>2.5</sub> emissions in the base year 2015. In future scenarios REF and S2, respectively, anthropogenic dust contributed 6.0 and 4.6 MT/yr in 2030 and 12.0 and 6.8 MT/yr in 2050, arising primarily (60%–85%) from coal fly ash, with the balance from fugitive on-road dust and waste burning. In the highest-control S3 scenario, anthropogenic dust emissions were reduced to about 1.8 MT/yr in both 2030 and 2050. This reduction stems from the assumed significant shift to 80%–85% non-coal thermal power generation, leading to large reductions in coal fly ash emissions. Thus, in the S3 scenario anthropogenic dust emissions arose largely from on-road fugitive dust and waste burning (over 50%), with a lower contribution from coal fly-ash (35–40%).

The net effect of these assumptions is that under the REF scenario, emissions are projected to increase steadily over time. Under the S2 scenario, they are also projected to increase but at a slower rate. Only under the aspirational scenario, S3, are appreciable reductions in emissions of the various air pollutants expected.

#### 5.2.4 Evaluation of Emissions Projections (2015–2050)

As a final evaluation, the emission projections for each of our scenarios were compared with those for India included in the four representative concentration pathways (RCP) scenarios adopted by the Intergovernmental Panel on Climate Change as a common basis for modeling future climate change (Clarke et al. 2007; Fujino et al.

2006; Hijioka et al. 2008; Riahi et al. 2007; van Vuuren et al. 2007). The RCP scenarios were designed to represent a range of possible future climate outcomes in terms of radiative forcing watts per square meter (W/m<sup>2</sup>) values (2.6, 4.5, 6.0, and 8.5) in 2100 relative to pre-industrial levels. They incorporate globally consistent assumptions about changes in industry, transport, residential, and agricultural practices; associated emissions; and related energy use. RCP2.6 assumes net negative CO<sub>2</sub> emissions after around 2070. RCP4.5 and RCP6.0 aim for a smooth stabilization of concentrations by 2150 and RCP8.5 stabilizes concentrations only by 2250. However, RCP scenarios are not tied to any specific socioeconomic and technology evolution pathway, which makes any direct comparison of underlying assumptions difficult yet permits comparison of gross emission magnitudes.

Figure 20 compares the projected India emissions in the RCP scenarios with those from this study for the years 2030 and 2050. The sectors used in the RCP scenarios corresponded to ones used in this study; they included energy (power plants, energy conversion, extraction, and distribution), domestic (residential and commercial), industry (combustion and processing), surface transportation, and agricultural waste burning in fields. Because RCP scenarios address climate-relevant emissions, projections were not available for primary PM<sub>2.5</sub>, but were available for precursor gases, SO<sub>2</sub>, NO<sub>x</sub>, and NMVOCs, and for PM<sub>2.5</sub> constituents, BC and OC.

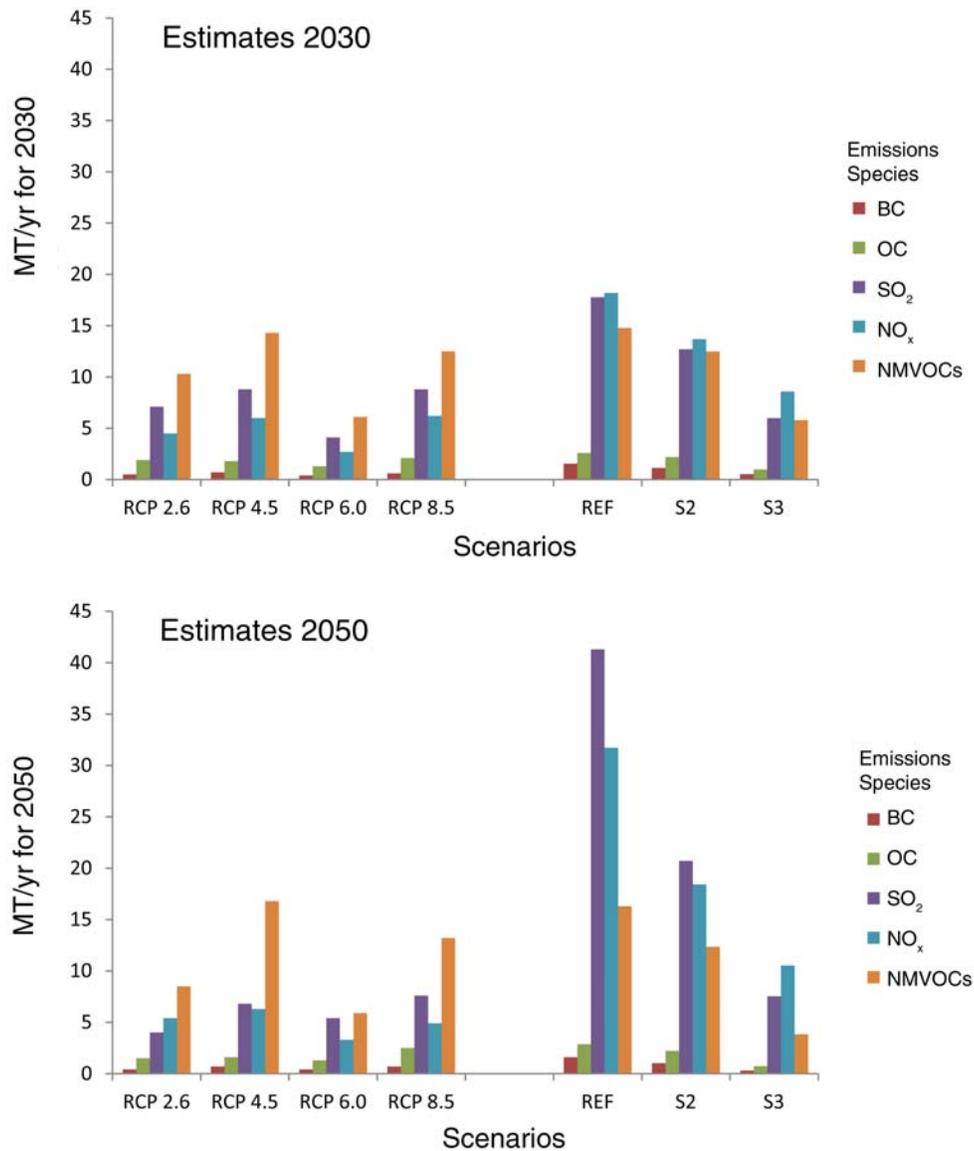
With some notable exceptions, the projected emissions for the scenarios from this study, in particular S3, were broadly in line with those of the RCPs. They are greater agreement with some RCP scenarios than others. For example, the emissions estimated for this study were in agreement with those in RCP scenarios for SO<sub>2</sub> (between S3 and RCP8.5), for BC (between S3 and RCP2.6), and for OC (between S2 and RCP8.5). For NMVOC, emissions in REF, S2, and S3, agreed well with those from with RCP4.5, RCP8.5, and RCP6.0, respectively. However, SO<sub>2</sub>, NO<sub>x</sub>, and BC emissions in the REF and S2 scenarios were substantially higher than those estimated for all of the RCP scenarios in 2030 and 2050. The larger SO<sub>2</sub> emissions estimates in those scenarios result from assumptions of low rates of flue gas desulfurization technology deployment (maximum of 25%), based on present-day and proposed legislation in the thermal power sector. Emissions of BC in the REF and S2 scenarios exceeded those of most RCPs by factors of 1.5 to 3, from inclusion of new sources like residential lighting (with kerosene wick lamps) and water and space heating (with biomass fuels).

**5.3 SIMULATED FUTURE AMBIENT PM<sub>2.5</sub> CONCENTRATIONS AND SECTOR CONTRIBUTIONS UNDER ALTERNATIVE SCENARIOS**

The same methods described in Section 3.2 for the baseline year 2015 were used to simulate the PM<sub>2.5</sub> concentrations and the fractional contributions from each sector under each of the three future scenarios. Figure 21 shows

the simulated total ambient PM<sub>2.5</sub> concentrations in each future scenario (REF, S2, and S3) for both 2030 and 2050 to illustrate the different spatial patterns under each scenario. In the REF scenario, the total PM<sub>2.5</sub> concentrations are projected to remain elevated in the north and northeast regions in 2030 with an expanded area of high concentrations in 2050. Under the S2 scenario, although simulated

**Representative Control Pathway versus Global Burden of Disease**



**Figure 20. Comparisons between the representative concentration pathways (RCP) scenario and Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) India scenario emissions in 2030 and 2050.** RCP scenarios are based on an assumption of future stabilization of radiative forcing (W/m<sup>2</sup>) in 2100; RCP2.6 assumes net negative CO<sub>2</sub> emissions after about 2070; RCP4.5 and RCP6.0 aim for a smooth stabilization of concentrations by 2150; and RCP8.5 stabilizes concentrations only by 2250. REF, or reference, is a scenario where technology-mix changes reflect current legislation and current technology-diffusion rates. For the GBD MAPS scenario descriptions, see Table 6.

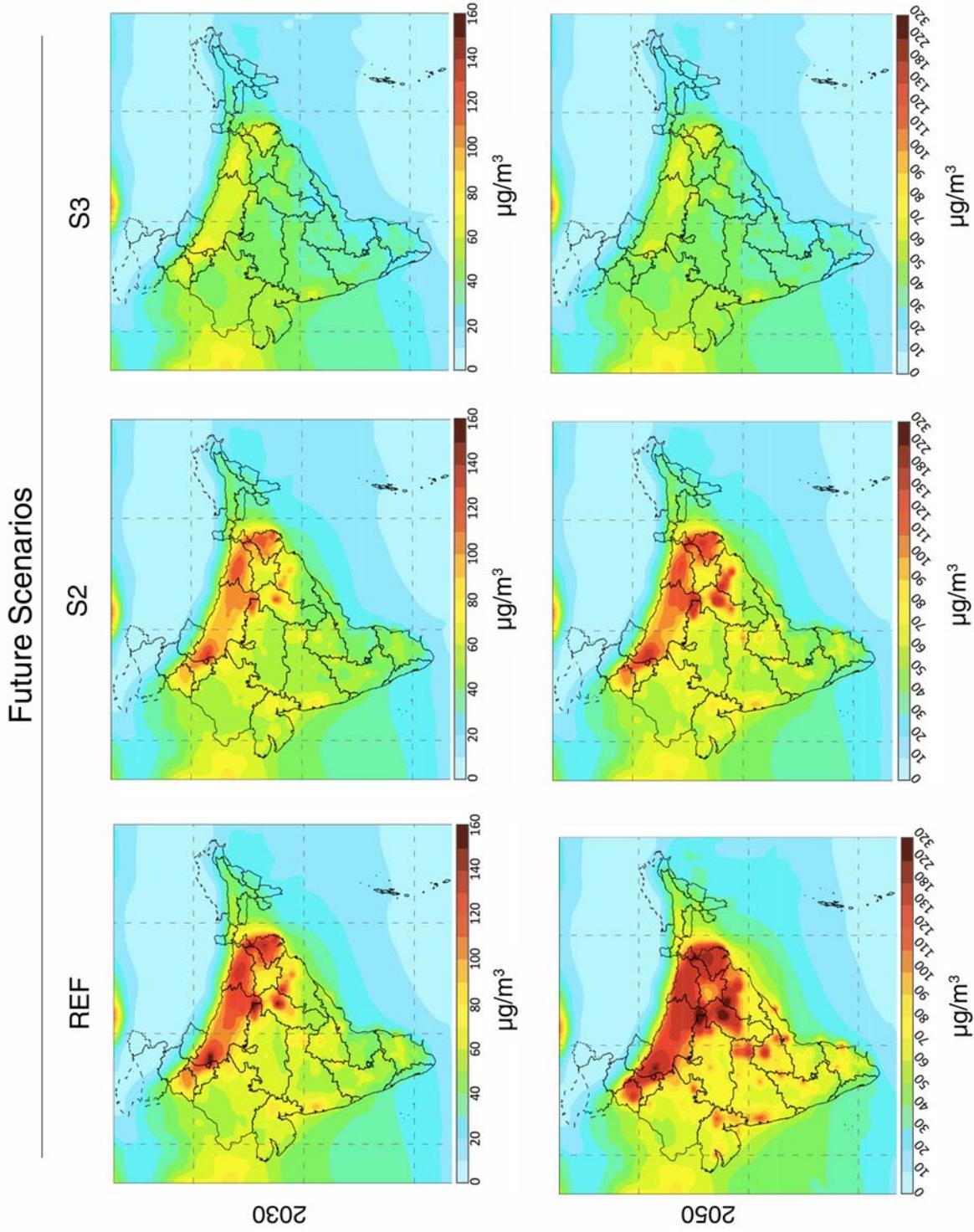


Figure 21. Simulated total ambient PM<sub>2.5</sub> concentrations in 2030 and 2050 under the REF, S2, and S3 scenarios.

concentrations are projected to improve relative to REF, the spatial patterns are very similar, with the north and northeast regions remaining as the most polluted areas. Promoting a total shift away from traditional biomass technologies (S3 scenario) both reduces overall concentrations and leads to a reduction in spatial variability within India.

Figures 22, 23, and 24 show simulated percentage contributions of major emission sectors to  $PM_{2.5}$  in 2050 under the REF, S2, and S3 scenarios, respectively. As in the baseline case, residential biomass burning contributes most to ambient  $PM_{2.5}$  concentrations in north India. In the future scenarios, the contribution of residential

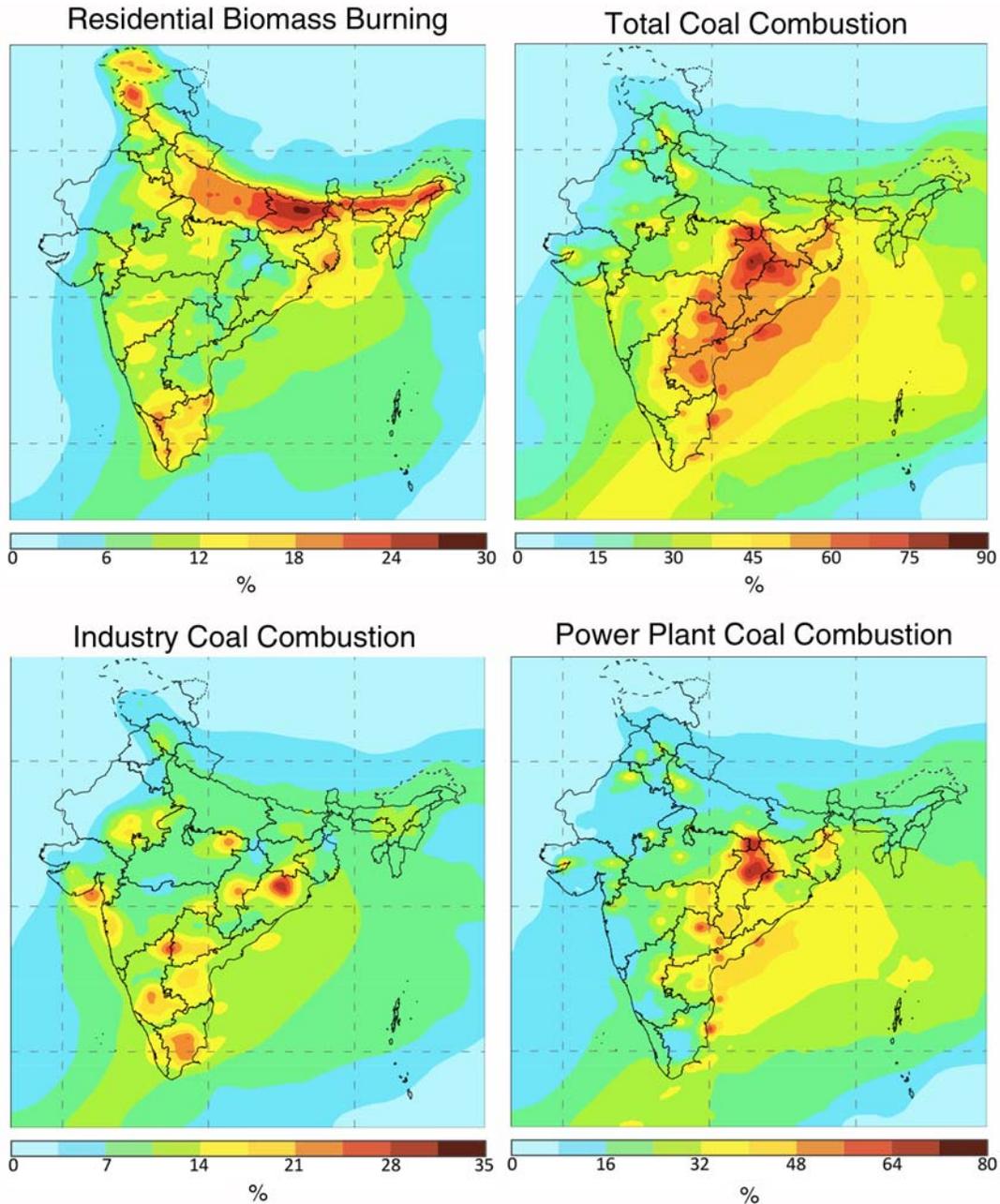


Figure 22. Simulated percentage contributions by sector to  $PM_{2.5}$  in REF scenario (2050). (Figure continues next page.)

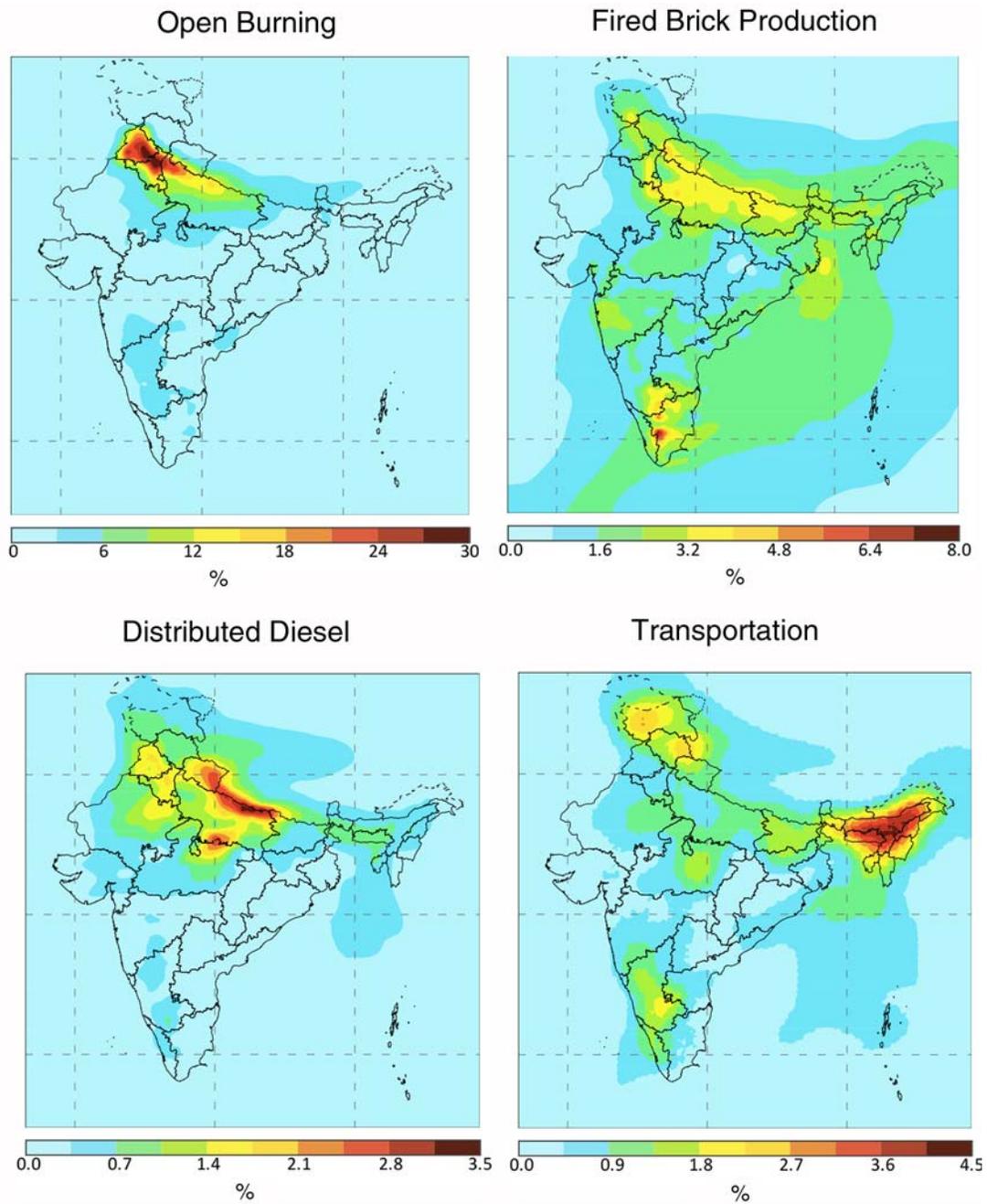


Figure 22. (Continued.)

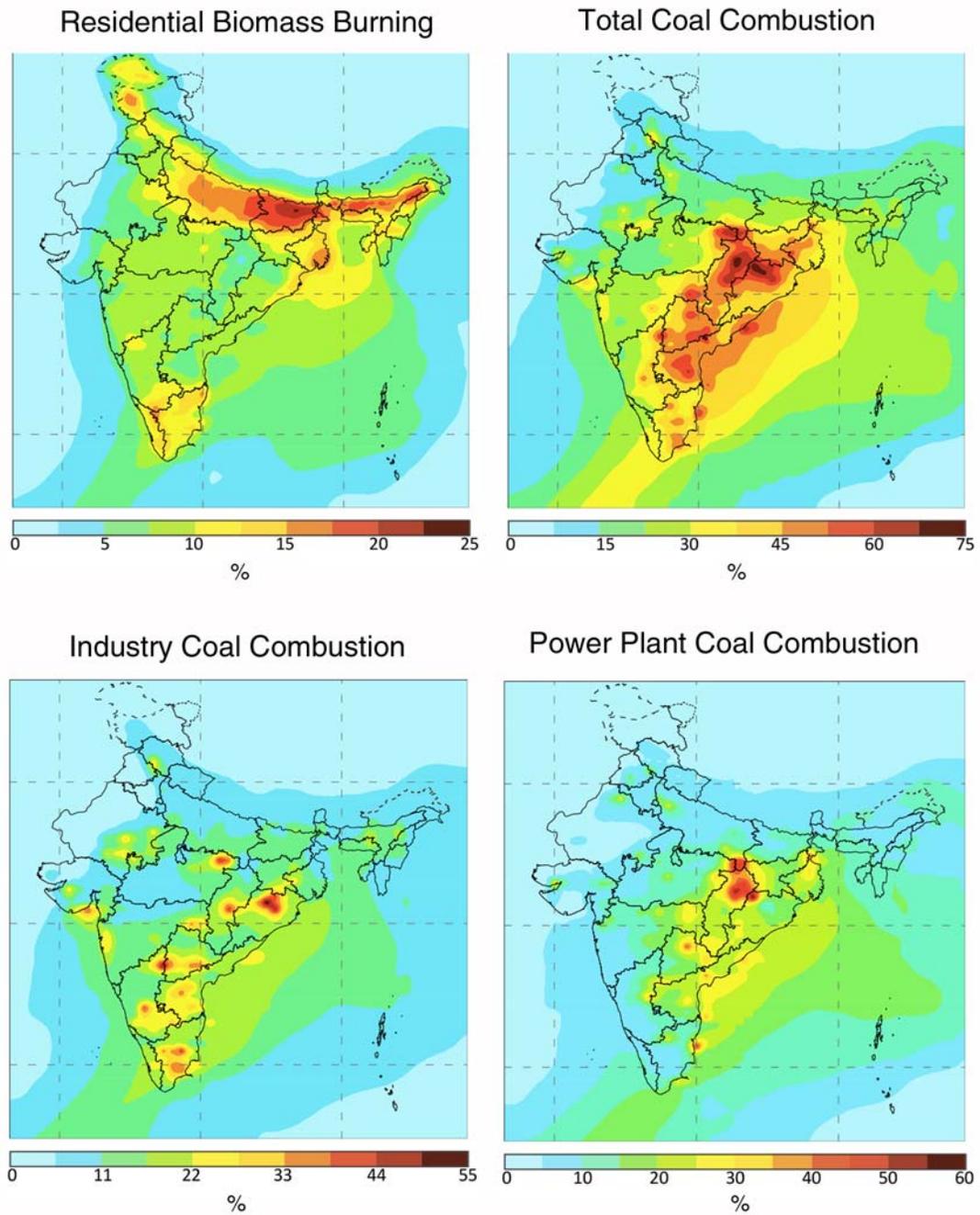


Figure 23. Simulated percentage contributions by sector to PM<sub>2.5</sub> in the S2 scenario (2050). (Figure continues next page.)

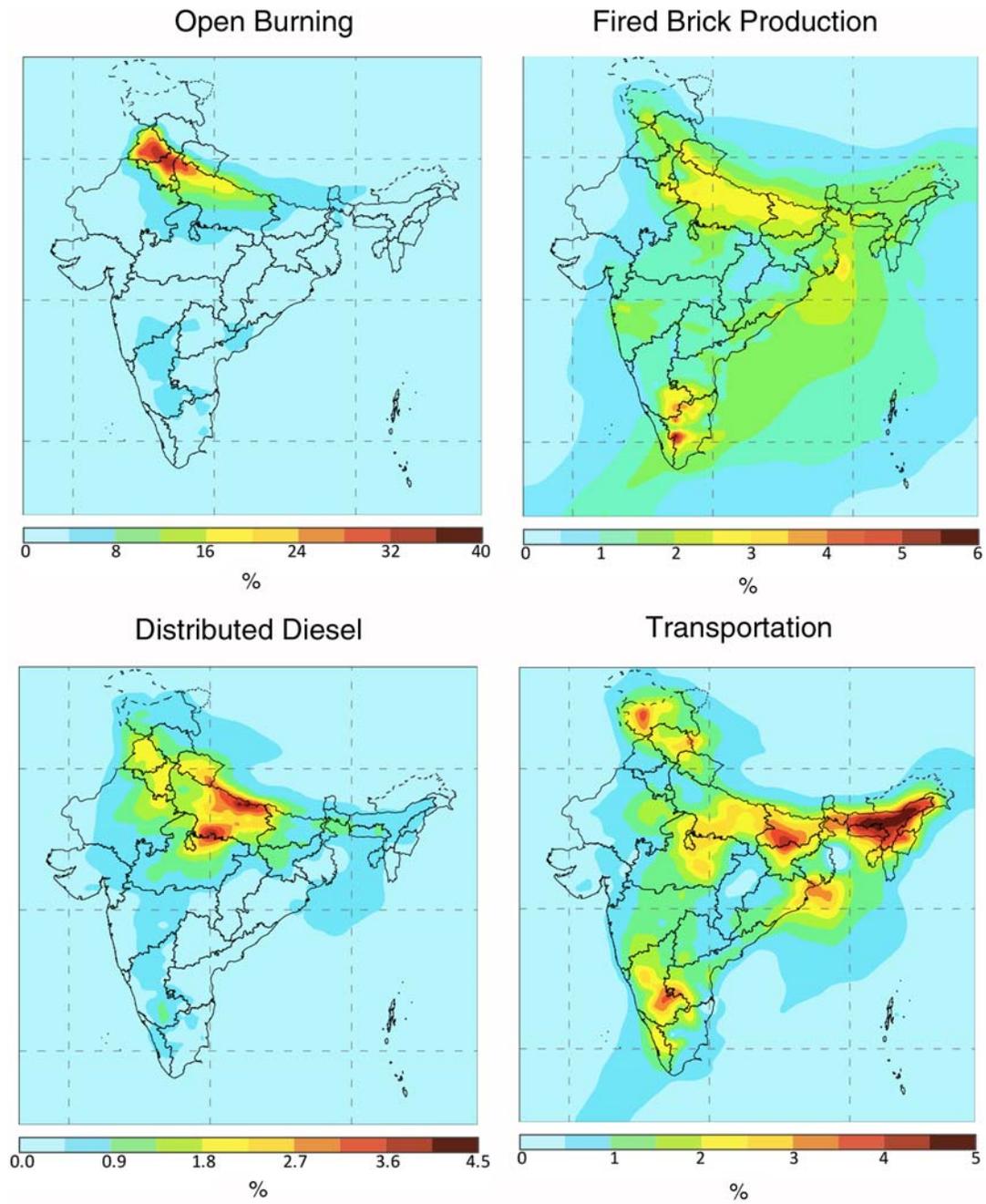


Figure 23. (Continued.)

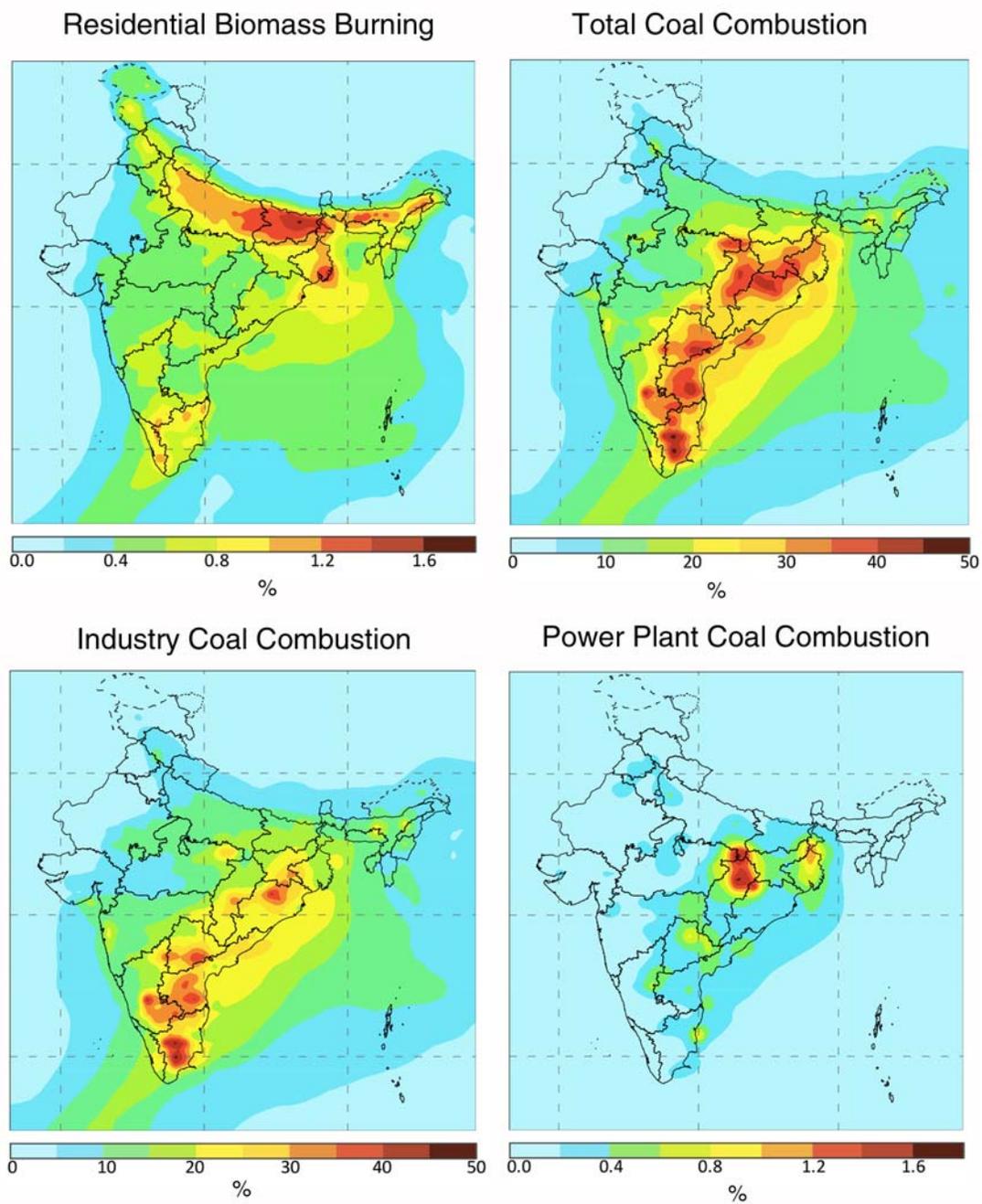


Figure 24. Simulated percentage contributions by sector to PM<sub>2.5</sub> in S3 scenario (2050). (Figure continues next page.)

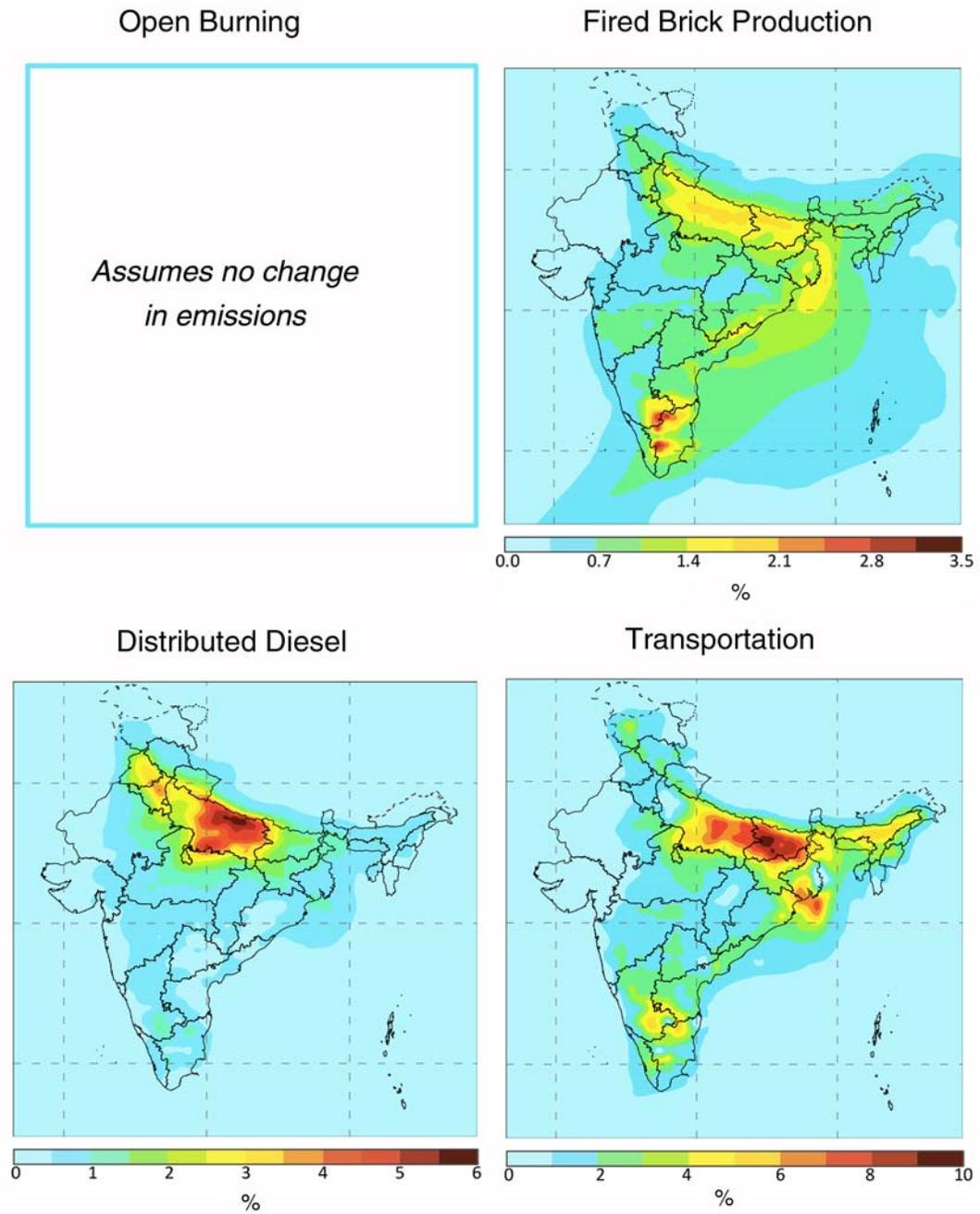


Figure 24. (Continued.)

biomass burning to  $PM_{2.5}$  concentration decreases as more control measures are put into effect. In the S3 scenario, residential biomass burning has the least influence on ambient concentrations (less than 1.8%) (Figure 24).

Coal combustion contributions to  $PM_{2.5}$  have similar spatial distributions in all future scenarios. In all scenarios, coal combustion becomes the largest contributor to ambient  $PM_{2.5}$ . In the REF scenario, the contribution of coal burning is projected to account for 50%–90% of the  $PM_{2.5}$  concentrations in southeast India, an increase that is mainly attributable to coal combustion for electrical power generation. In the two stricter scenarios, which assume power generation using more efficient technologies, the percentage reductions in the contributions of power plant coal combustion to ambient  $PM_{2.5}$  ranged from 45% to 75% in S2 and by a further 20% to 50% in S3.

In the REF and S2 scenarios, the contribution of open burning to  $PM_{2.5}$  in 2050 is similar to that in the base scenario. The S3 scenario assumes no further emissions from open burning. Emissions from fired-brick production, distributed diesel, and traffic also have similar contributions to  $PM_{2.5}$  in the future scenarios compared with the baseline, with percentage contributions of less than 10%. The contributions of brick production and distributed diesel decrease slightly, whereas that of transportation increases slightly in the future.

#### 5.4 METHODS FOR ESTIMATING FUTURE $PM_{2.5}$ CONCENTRATIONS AND DISEASE BURDEN ATTRIBUTABLE TO INDIVIDUAL SECTORS

To estimate the future burden for each of the three scenarios in 2050, it is first necessary to estimate both future population-weighted concentrations (which are used to calculate the PAF) and future mortality.

Recall that to calculate the population-attributable fraction ( $PAF_{PM_{2.5}}$ ) in 2015 we used the gridded surface of (total) ambient  $PM_{2.5}$  concentrations that was developed for GBD 2015 ( $PM_{2.5}^{GBD2015}$ ) together with the sector contributions estimated from GEOS-Chem, as described in Section 3.3.

Calculating  $PAF_{PM_{2.5}}$  for other years (i.e., 2050) requires estimating both  $f_{sector}$  and total ambient  $PM_{2.5}$ . The  $f_{sector}$  is calculated from additional year 2050 GEOS-Chem simulations described above, which necessarily also simulate total ambient  $PM_{2.5}$  ( $PM_{2.5}^{GChem2050}$ ), the standard simulation (i.e., STD). In order to account for changes in the levels of total ambient  $PM_{2.5}$  between 2015 and 2050, we scaled  $PM_{2.5}^{GBD2015}$  by the change in total ambient  $PM_{2.5}$  simulated by GEOS-Chem between 2015 and 2050:

$$PM_{2.5}^{GBD2050} = \frac{PM_{2.5}^{GChem2050}}{PM_{2.5}^{GChem2015}} \times PM_{2.5}^{GBD2015} \quad (4)$$

Note that for each of the different future scenarios (REF, S2, and S3), a different STD simulation, specific to each scenario, was used to estimate  $PM_{2.5}^{GChem2050}$ .

To calculate the future burden of disease from mortality and DALYs for the three future scenarios (in years 2030 and 2050), we use mortality and DALY estimates, the annual rate of change from 2000/2010 to 2015, and the attributable fraction for 2000/2010 and 2015. As we are imposing specific scenarios related to air pollution and as air pollution is a known risk for mortality, we first isolated the expected mortality not attributable to air pollution for 2050. The mortality not attributable to air pollution was calculated as:

$$Mort_{U(year)} = Mort_{(year)} \times \left(1 - PAF_{PM_{2.5}(year)}\right) \quad (5)$$

where  $Mort$  = mortality rate,  $Mort_U$  = mortality rate unattributable to air pollution,  $PAF_{PM_{2.5}}$  = population attributable fraction due to ambient air pollution, and  $year$  = future year to estimate.

Next, we calculated the annualized rate of change (AROC) in mortality between 2000 and 2015 as:

$$AROC = \frac{\ln\left(\frac{Mort_{U(2015)}}{Mort_{U(2000)}}\right)}{(2015 - 2000)} \quad (6)$$

This step is then repeated for 2010–2015, and we used the most conservative AROC as determined by the absolute minimum value, in order to prevent overextrapolation.

Using the above AROC and year 2015 mortality, we then estimate the mortality that is not attributable to air pollution for future years:

$$Mort_{U(year)} = Mort_{(2015)} \times \exp\left(AROC \times [year - 2015]\right) \quad (7)$$

We then calculate the PAF attributable to air pollution in future years based on the current level and the future scenarios as described above. Using the PAFs, we then calculate the total mortality in the future as:

$$Mort_{(year)} = \frac{Mort_{U(year)}}{\left(1 - PAF_{PM_{2.5}(year)}\right)} \quad (8)$$

All of the aforementioned calculations are done with rates (that is, numbers of outcomes/number of population). In order to convert these results back to number of outcomes in the future, projections of population in 2030 or

2050 are required. For this project, we used the UN World Population Prospects data (United Nations 2017), after splitting them into GBD age groups using the 2015 composition proportions for those groups. These projections were not developed for the states and urban/rural breakdowns of India. As such, we also split the projections to these locations using the proportion of that age/sex group in a given urban/rural state location breakdown to the total population in that age/sex group for all of India, multiplied by the total population in that age/sex group for all of India in 2030 as:

$$\begin{aligned} & \text{Population}_{\text{Location, Age, Sex, 2030}} \\ &= \frac{\text{Population}_{\text{State, Age, Sex, 2015}}}{\text{Population}_{\sum_{i=\text{Location}}^n \text{Age, Sex, 2015}}} \quad (9) \\ & \times \text{Population}_{\sum_{i=\text{Location}}^n \text{Age, Sex, 2030}} \end{aligned}$$

A similar projection was then made for 2050 using the same methodology.

### 5.5 FUTURE POPULATION-WEIGHTED $\text{PM}_{2.5}$ CONCENTRATIONS AND CONTRIBUTIONS BY INDIVIDUAL SECTORS UNDER ALTERNATIVE SCENARIOS

Projected population-weighted ambient  $\text{PM}_{2.5}$  concentrations and sector contributions for each of the three future scenarios are provided in Figures 25 and 26 with additional details in Table 7. Under REF the population-weighted  $\text{PM}_{2.5}$  concentration is projected to increase relative to 2015 14% by 2030 and 43% by 2050, whereas in the aspirational scenario S3, there are 30%–35% decreases in 2030–2050. In scenario S2, a 1% increase in concentration is predicted for 2030, and a 10% increase is projected for 2050 (Figure 25 and Table 7).

Sector contributions are affected differently depending on the specific scenario, although in most cases percent contributions increase in scenarios REF and S2 compared with the year 2015 estimates, with decreases only realized under scenario S3 (Figure 26 and Table 7). Two exceptions are dust and residential biomass. Total and anthropogenic dust concentrations are projected to increase, whereas residential biomass contribution decreases under all scenarios. Dust from anthropogenic activities (anthropogenic dust) is a larger contributor to total dust in REF (53% of total dust, compared with 26% in 2015) and S2 (39% of total dust), whereas its contributions in S3 (14%) are low. Overall, in S3, total dust (in this scenario dominated by windblown mineral dust) is the largest contributor to ambient  $\text{PM}_{2.5}$ , as a result of the dramatic reductions in

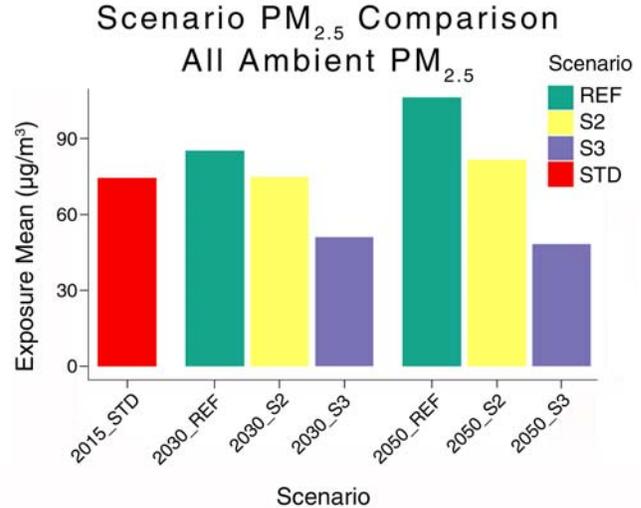


Figure 25. Population-weighted mean total ambient  $\text{PM}_{2.5}$  concentrations in India for 2015 (STD) and for the three scenarios in the years 2030 and 2050.

emissions projected for all of the other sectors (including anthropogenic dust) in this aspirational scenario. Industrial coal contributions increase in 2050 compared with 2015, even under S3, although this increase is offset by a decrease in coal-fired power plant contributions, leading to a net 21% decrease in the total coal contribution to ambient  $\text{PM}_{2.5}$  concentrations.

The concentration from transportation sources remains low ( $<2 \mu\text{g}/\text{m}^3$ ) under all scenarios but does not decrease in the aspirational scenario. That the transportation contribution decreases in REF but increases in S3 relative to 2015 reflects competing trends from 2015 to 2050 in which emissions per vehicle generally decrease but vehicle-km driven increases. Specifically, passenger vehicle-km increase about fourfold from 2015 to 2050 accompanied by reductions of 15% to 55% in primary  $\text{PM}_{2.5}$  emissions, but with increases in transport-related  $\text{SO}_2$  (27% to 73%) and  $\text{NO}_x$  (93% to 121%) emissions, depending on the scenario. Further, emissions from transportation may be affected by reductions in emissions from other sectors and nonlinear atmospheric chemistry (e.g., reductions in other combustion sources leaving more ammonia available to react with transportation combustion products to form secondary PM). Indeed, evaluation of simulation results indicates that the sensitivity of nitrate to transportation sources in scenario S2 is larger than the nitrate sensitivity in the REF scenario (see Appendix F, available on the HEI website). This analysis suggests that increased available ammonia in S2, resulting from reductions in emissions from other sectors, leads

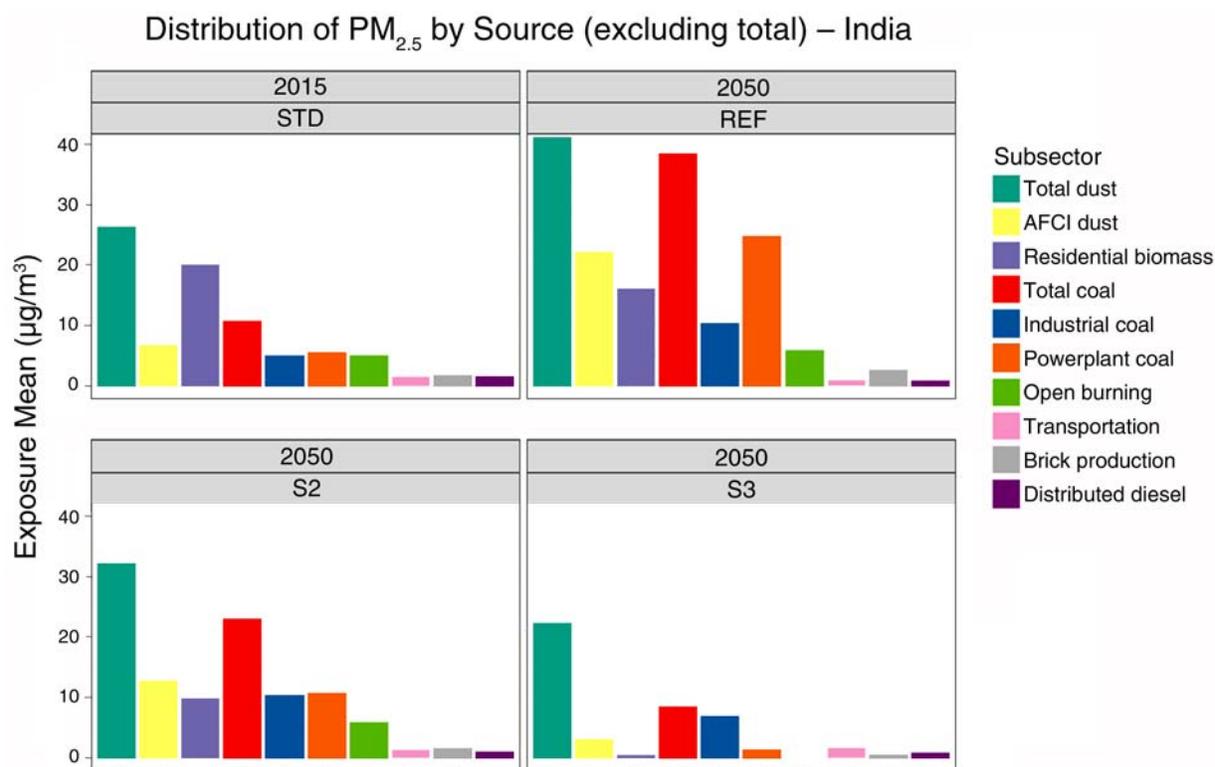


Figure 26. Population-weighted means of PM<sub>2.5</sub> concentrations in India from all sectors for 2015 (STD) and for each of the three scenarios in 2050.

to increased particulate ammonium nitrate formation associated with transportation emissions, relative to the REF scenario. Furthermore, for a number of reasons — because we are estimating sectoral contributions to ambient PM<sub>2.5</sub> based on the fractional contribution from each sector, because transportation is small relative to the other sectors, and because the spatial pattern of the fraction of transport emissions varies between scenarios — it is possible that the decrease in REF, followed by increases in S2 and S3, is an artifact attributable to increasing fractional contributions from transport relative to other sectors where the decreases are much more dramatic.

For the different scenarios, the urban and rural differences in exposures remained small and reflected the differences seen in 2015 (see Table 7).

### 5.6 ESTIMATES OF FUTURE DISEASE BURDEN ATTRIBUTABLE TO INDIVIDUAL SECTORS

Using the methods described in the previous section, we estimated PM<sub>2.5</sub>-attributable mortality for total ambient

PM<sub>2.5</sub> in 2030 and 2050 and for PM<sub>2.5</sub> mortality attributable to individual sectors for 2050, under all three future scenarios.

Mean population-weighted exposures increased in 2030 for the REF scenario, were unchanged for scenario S2, and decreased for the aspirational S3 scenario (Figure 27). Given the larger population trends described above, the mortality burden for all three scenarios grows substantially in 2030, and especially in 2050 despite the exposure decrease in scenario S3 (as well as the other two scenarios). As exposures for scenario S2 were similar to those in 2015, the magnitude of the impacts of demographic changes from 2015 to 2030 is reflected in the difference in the numbers of attributable deaths between these two time periods, or approximately 500,000.

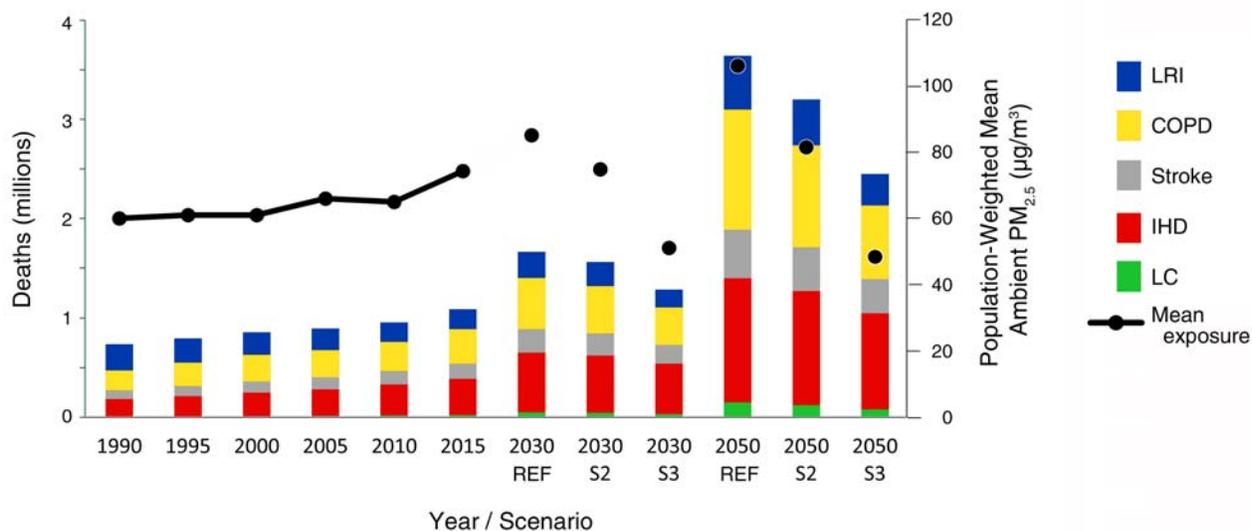
These estimates for each scenario and year are provided in Table 8 along with the baseline (STD) estimates for 2015 for comparison. The table lists the number of deaths attributable to PM<sub>2.5</sub> for all of India. (PM<sub>2.5</sub>-attributable DALYs were also estimated as were the details for urban and rural areas; these results are provided in Appendix G, available on the HEI website.) Approximately 100,000 attributable

**Table 7.** Population-Weighted Ambient PM<sub>2.5</sub> Concentration and Percentage Contribution to Ambient PM<sub>2.5</sub> Attributable to Different Source Sectors by Region (Rural vs. Urban) in 2015 and 2050 for Three Future Scenarios (and in 2030 for All Ambient PM<sub>2.5</sub> Only)

| Source Sector                   | Year | Scenario | All India                              |                | India Rural                            |                | India Urban                            |                |
|---------------------------------|------|----------|--|----------------|--|----------------|--|----------------|
|                                 |      |          | PM <sub>2.5</sub> (µg/m <sup>3</sup> ) | % Contribution | PM <sub>2.5</sub> (µg/m <sup>3</sup> ) | % Contribution | PM <sub>2.5</sub> (µg/m <sup>3</sup> ) | % Contribution |
| All ambient PM <sub>2.5</sub>   | 2015 | STD      | 74.3                                   | —              | 74.4                                   | —              | 73.2                                   | —              |
|                                 | 2030 | REF      | 85.2                                   | —              | 85.2                                   | —              | 84.7                                   | —              |
|                                 | 2030 | S2       | 74.9                                   | —              | 74.8                                   | —              | 74.6                                   | —              |
|                                 | 2030 | S3       | 51.1                                   | —              | 51.0                                   | —              | 51.3                                   | —              |
|                                 | 2050 | REF      | 106.3                                  | —              | 106.1                                  | —              | 107.2                                  | —              |
|                                 | 2050 | S2       | 81.7                                   | —              | 81.5                                   | —              | 82.0                                   | —              |
|                                 | 2050 | S3       | 48.5                                   | —              | 48.5                                   | —              | 48.5                                   | —              |
| Residential biomass             | 2015 | STD      | 20.0                                   | 24.0           | 20.3                                   | 24.2           | 17.9                                   | 22.1           |
|                                 | 2050 | REF      | 16.1                                   | 13.9           | 16.3                                   | 14.1           | 14.7                                   | 13.0           |
|                                 | 2050 | S2       | 9.9                                    | 11.0           | 10.0                                   | 11.1           | 9.0                                    | 10.4           |
|                                 | 2050 | S3       | 0.4                                    | 0.8            | 0.4                                    | 0.8            | 0.4                                    | 0.7            |
| Total coal                      | 2015 | STD      | 10.7                                   | 15.7           | 10.6                                   | 15.5           | 11.5                                   | 17.1           |
|                                 | 2050 | REF      | 38.4                                   | 36.1           | 38.0                                   | 35.7           | 40.5                                   | 38.0           |
|                                 | 2050 | S2       | 22.9                                   | 28.8           | 22.7                                   | 28.5           | 24.0                                   | 30.5           |
|                                 | 2050 | S3       | 8.5                                    | 18.3           | 8.4                                    | 18.1           | 8.8                                    | 19.4           |
| Industrial coal                 | 2015 | STD      | 4.9                                    | 7.7            | 4.9                                    | 7.6            | 5.2                                    | 8.5            |
|                                 | 2050 | REF      | 10.5                                   | 10.5           | 10.4                                   | 10.3           | 11.0                                   | 11.5           |
|                                 | 2050 | S2       | 10.4                                   | 13.6           | 10.3                                   | 13.5           | 10.8                                   | 14.7           |
|                                 | 2050 | S3       | 6.9                                    | 15.2           | 6.8                                    | 15.0           | 7.0                                    | 16.0           |
| Powerplant coal                 | 2015 | STD      | 5.5                                    | 7.6            | 5.4                                    | 7.6            | 5.9                                    | 8.0            |
|                                 | 2050 | REF      | 24.7                                   | 22.6           | 24.5                                   | 22.5           | 26.3                                   | 23.5           |
|                                 | 2050 | S2       | 10.7                                   | 12.9           | 10.6                                   | 12.9           | 11.3                                   | 13.4           |
|                                 | 2050 | S3       | 1.4                                    | 2.7            | 1.3                                    | 2.6            | 1.5                                    | 2.9            |
| Open burning                    | 2015 | STD      | 5.0                                    | 5.5            | 4.9                                    | 5.5            | 5.4                                    | 5.6            |
|                                 | 2050 | REF      | 5.8                                    | 4.6            | 5.7                                    | 4.6            | 6.4                                    | 4.5            |
|                                 | 2050 | S2       | 5.8                                    | 5.8            | 5.7                                    | 5.8            | 6.3                                    | 5.8            |
|                                 | 2050 | S3       | 0.0                                    | 0.0            | 0.0                                    | 0.0            | 0.0                                    | 0.0            |
| Transportation                  | 2015 | STD      | 1.6                                    | 2.1            | 1.6                                    | 2.1            | 1.5                                    | 2.1            |
|                                 | 2050 | REF      | 1.0                                    | 0.9            | 1.0                                    | 1.0            | 0.8                                    | 0.8            |
|                                 | 2050 | S2       | 1.4                                    | 1.6            | 1.4                                    | 1.7            | 1.1                                    | 1.3            |
|                                 | 2050 | S3       | 1.6                                    | 3.0            | 1.7                                    | 3.0            | 1.2                                    | 2.3            |
| Brick production                | 2015 | STD      | 1.7                                    | 2.2            | 1.8                                    | 2.1            | 1.7                                    | 2.2            |
|                                 | 2050 | REF      | 2.6                                    | 2.3            | 2.6                                    | 2.3            | 2.5                                    | 2.2            |
|                                 | 2050 | S2       | 1.6                                    | 1.8            | 1.6                                    | 1.8            | 1.5                                    | 1.7            |
|                                 | 2050 | S3       | 0.5                                    | 1.0            | 0.5                                    | 1.0            | 0.5                                    | 1.0            |
| Distributed diesel              | 2015 | STD      | 1.6                                    | 1.8            | 1.7                                    | 1.8            | 1.2                                    | 1.4            |
|                                 | 2050 | REF      | 0.9                                    | 0.7            | 0.9                                    | 0.7            | 0.7                                    | 0.5            |
|                                 | 2050 | S2       | 1.0                                    | 1.0            | 1.0                                    | 1.0            | 0.8                                    | 0.8            |
|                                 | 2050 | S3       | 0.9                                    | 1.5            | 0.9                                    | 1.6            | 0.7                                    | 1.2            |
| Anthropogenic dust <sup>a</sup> | 2015 | STD      | 6.8                                    | 8.9            | 6.7                                    | 8.8            | 7.5                                    | 9.6            |
|                                 | 2050 | REF      | 22.2                                   | 19.6           | 21.8                                   | 19.3           | 24.7                                   | 21.1           |
|                                 | 2050 | S2       | 12.7                                   | 15.1           | 12.5                                   | 14.9           | 14.0                                   | 16.2           |
|                                 | 2050 | S3       | 3.1                                    | 6.3            | 3.1                                    | 6.2            | 3.4                                    | 6.7            |
| Total dust <sup>b</sup>         | 2015 | STD      | 26.3                                   | 38.8           | 26.2                                   | 38.7           | 27.1                                   | 39.5           |
|                                 | 2050 | REF      | 41.9                                   | 41.4           | 41.4                                   | 41.3           | 44.7                                   | 42.6           |
|                                 | 2050 | S2       | 32.2                                   | 42.0           | 32.0                                   | 41.9           | 33.8                                   | 42.7           |
|                                 | 2050 | S3       | 22.3                                   | 47.3           | 22.2                                   | 47.4           | 22.8                                   | 47.0           |

<sup>a</sup> Anthropogenic dust includes only anthropogenic fugitive, combustion, and industrial dust.

<sup>b</sup> Total dust includes anthropogenic and windblown mineral dust.



**Figure 27.** Population-weighted mean exposure to ambient PM<sub>2.5</sub> and attributable deaths in India 1990–2050 by year and by cause under three future scenarios. LC, lung cancer; IHD, ischemic heart disease; COPD, chronic obstructive pulmonary disease; LRI, lower-respiratory infections.

deaths are due to the increased exposure in REF in 2030 compared with 2015. The exposure decrease for scenario S3 results in about 270,000 fewer deaths, which are offset by the increase of approximately 500,000 due to demographic factors, resulting in a net increase of about 200,000 deaths in 2030 for S3 compared with 2015. As expected, the same general patterns are evident in 2050 with more substantial increases in exposure and attributable burden — a total of 3.6 million deaths under the REF scenario. In all scenarios, including the aspirational S3 scenario, attributable burden is increased compared with 2015 even as exposure is expected to decrease. For each of the scenarios, more than 2 million attributable deaths are projected for India in 2050.

Comparison of the age-adjusted DALY rates is more appropriate for reflecting the value of reducing exposures under the different scenarios because they control for differences in age and population size among populations. Figure 28 compares PM<sub>2.5</sub>-attributable DALY rates by cause of death in rural and urban areas of India for 2015 and for the three future scenarios in 2030 and in 2050. Note that even as DALY rates increase in 2050 for the REF scenario for rural areas, the rates for S2 are lower than those in REF in 2030 and 2050, and the rates for S3 are lower than the rates under the current 2015 scenario, reflecting in part the benefit of more aggressive reductions in exposure to ambient PM<sub>2.5</sub>.

Figure 29 compares the impacts on PM<sub>2.5</sub>-related mortality from different source sectors for the base year 2015 (STD) and for each of the scenarios, as well as for urban and rural areas. Among the sectors, coal emerges as one of the more important sectoral contributors to burden in REF, surpassing the impact of residential biomass. The importance of the coal contribution is projected to decrease somewhat in S2 and more so in S3, although in both cases it is the second largest contributor to PM<sub>2.5</sub>-related disease burden after that of total dust. These decreases in the contribution of coal in S2 and S3 relative to REF are primarily driven by decreases in the burning of coal in power plants; for example, in scenarios S2 and S3, 60% and 80%, respectively, of thermal power is projected to be generated from non-coal sources, compared with 40% in the REF scenario. Given these projected reductions in power plant coal burning, the relative contribution of industrial coal to the burden of disease from all coal burning (total coal) increases from REF to S2 to S3.

Residential biomass combustion also continues to be an important contributor to the disease burden attributable to ambient PM<sub>2.5</sub> under the REF (over 500,000 deaths) and S2 (over 300,000 deaths) scenarios in 2050 (Table 8 and Figure 29). Though not included in these estimates, residential biomass combustion has a further — and more substantial — impact on disease burden in India via its contribution to household air pollution (977,000 deaths in

**Table 8.** Total Numbers of Deaths Attributable to Ambient PM<sub>2.5</sub> Overall and from Individual Source Sectors in 2015 and 2050 (in 2030, only for All Ambient PM<sub>2.5</sub>) for Three Future Scenarios

| Source Sector                   | Year | Scenario | All India |
|---------------------------------|------|----------|-----------|
| All ambient PM <sub>2.5</sub>   | 2015 | STD      | 1,090,400 |
|                                 | 2030 | REF      | 1,662,500 |
|                                 | 2030 | S2       | 1,560,100 |
|                                 | 2030 | S3       | 1,287,600 |
|                                 | 2050 | REF      | 3,642,400 |
|                                 | 2050 | S2       | 3,200,500 |
| Residential biomass             | 2015 | STD      | 267,700   |
|                                 | 2050 | REF      | 526,400   |
|                                 | 2050 | S2       | 366,800   |
| Total coal                      | 2015 | STD      | 169,300   |
|                                 | 2050 | REF      | 1,299,300 |
|                                 | 2050 | S2       | 894,700   |
| Industrial coal                 | 2015 | STD      | 82,100    |
|                                 | 2050 | REF      | 365,500   |
|                                 | 2050 | S2       | 413,400   |
| Powerplant coal                 | 2015 | STD      | 82,900    |
|                                 | 2050 | REF      | 828,800   |
|                                 | 2050 | S2       | 410,900   |
| Open burning                    | 2015 | STD      | 66,200    |
|                                 | 2050 | REF      | 203,400   |
|                                 | 2050 | S2       | 229,600   |
| Transportation                  | 2015 | STD      | 23,100    |
|                                 | 2050 | REF      | 33,500    |
|                                 | 2050 | S2       | 52,500    |
| Brick production                | 2015 | STD      | 24,100    |
|                                 | 2050 | REF      | 87,600    |
|                                 | 2050 | S2       | 59,900    |
| Distributed diesel              | 2015 | STD      | 20,400    |
|                                 | 2050 | REF      | 31,000    |
|                                 | 2050 | S2       | 39,300    |
| Anthropogenic dust <sup>a</sup> | 2015 | STD      | 99,900    |
|                                 | 2050 | REF      | 742,800   |
|                                 | 2050 | S2       | 496,000   |
| Total dust <sup>b</sup>         | 2015 | STD      | 412,500   |
|                                 | 2050 | REF      | 1,479,600 |
|                                 | 2050 | S2       | 1,310,900 |
|                                 | 2050 | S3       | 1,156,200 |

<sup>a</sup> Anthropogenic dust includes only anthropogenic fugitive, combustion, and industrial dust.

<sup>b</sup> Total dust includes anthropogenic and windblown mineral dust.

2015). Reductions in emissions from residential biomass combustion, such as those envisioned for scenario S3, should be a high priority. They would not only have a large potential to reduce disease burden, but would also have the added benefit of reducing climate-forcing emissions (Lacey et al. 2017).

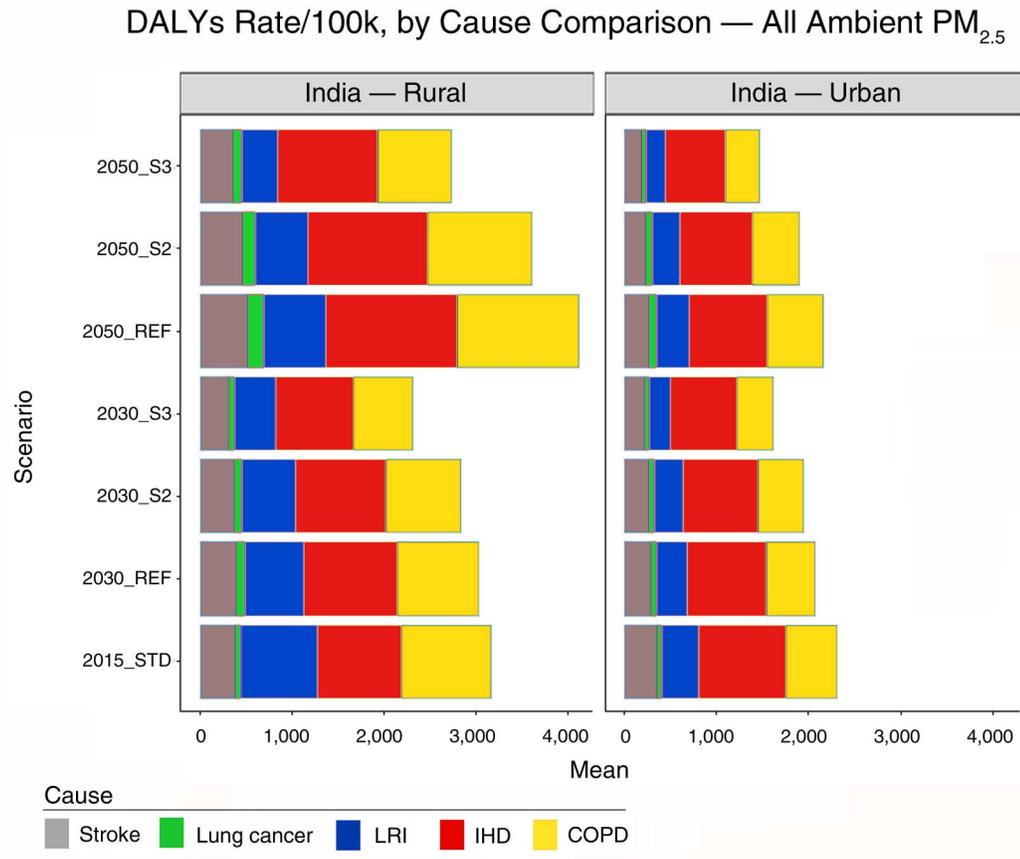
In 2015, as well as in each of the future scenarios, dust is a major contributor to disease burden. Although a portion of this dust arises from windblown mineral dust, including that which may originate outside of India, a large proportion (23% in 2015 and 47% in the REF scenario) originates from anthropogenic activities. Indeed, in each of the future scenarios the increases in population-weighted dust concentrations (e.g., from 26.3 µg/m<sup>3</sup> in 2015 to 41.9 µg/m<sup>3</sup> in 2050 in the REF scenario) are entirely attributable to changes in the anthropogenic component. Left unchecked, as in the REF scenario, anthropogenic dust emissions are projected to be responsible for 740,000 attributable deaths; attributable disease burden is projected to increase compared with 2015 levels in each of the scenarios. Given these projections, our analysis suggests more attention should be directed toward reductions in anthropogenic dust emissions especially. Specifically, dust from anthropogenic activities is a major contributor in the REF and S2 scenarios. In the S3 scenario, however, total dust, made up mostly from windblown mineral dust, is the largest remaining contributor to disease burden. This relative increase in contribution to burden from this source is caused by the aggressive reductions in emissions from the other sectors assumed in this scenario.

In each of the future scenarios, open burning associated with agriculture was scaled for population growth, given population's role in driving food consumption, food production, and the generation of residue that needs to be disposed of. Accordingly, the REF and S2 scenarios project increases in exposure and disease burden associated with open burning (from 66,000 in 2015 to more than 200,000 attributable deaths in 2050). These findings suggest a need for alternative approaches to combustion for this material, for example, to achieve the reductions in burden that would be realized by elimination of such burning, as is assumed under scenario S3.

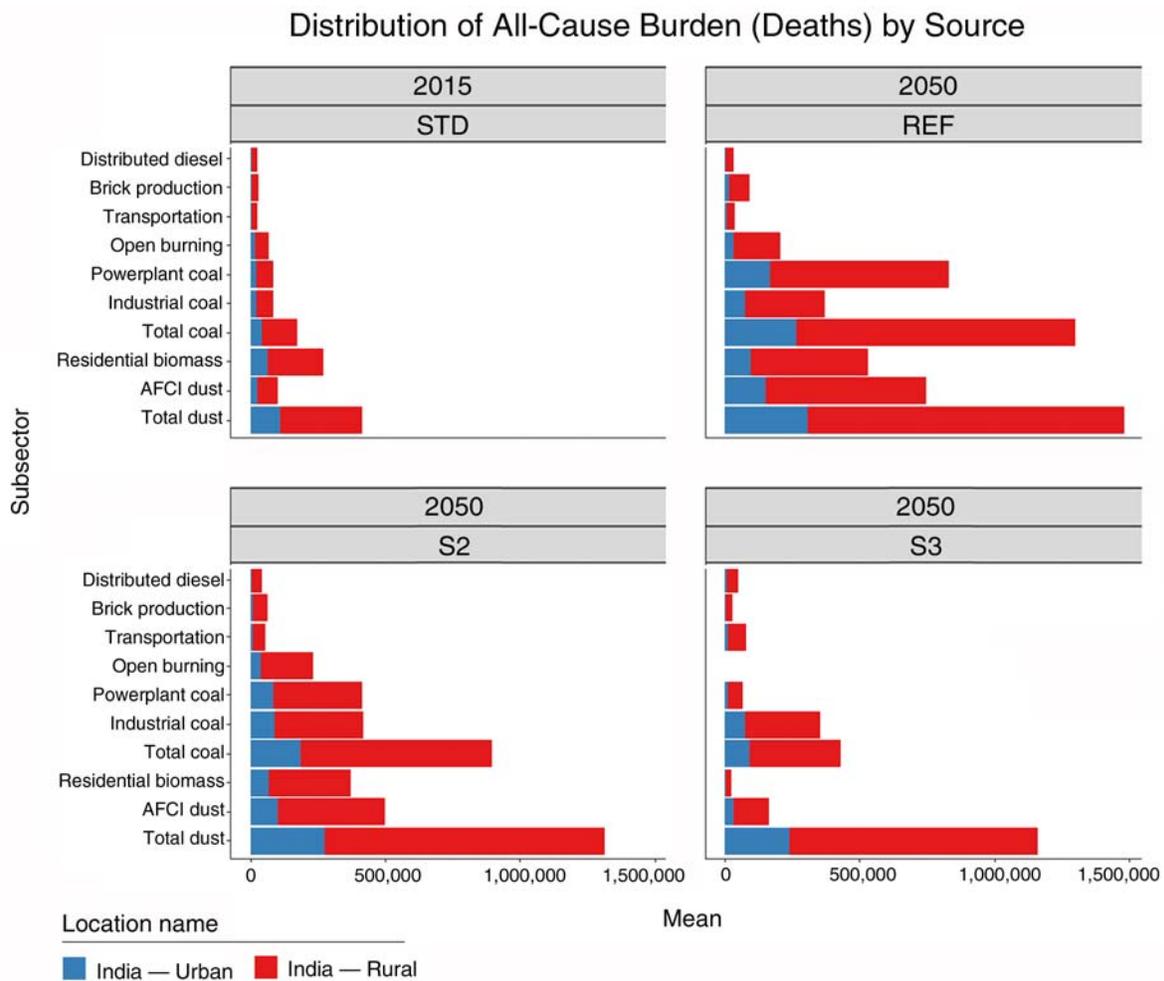
Although the impacts of distributed diesel sources and transportation contributions to disease burden are small relative to the other source sectors, their contributions are projected to increase under all of the future scenarios. These increases in disease burden occur despite reductions in emissions anticipated by technology improvements and structural changes because of the demographic trends (population growth, aging, and rates of disease) that impact the numbers of people affected by air pollution exposures. For transportation, gains from decreased

emissions are partially offset by increases in vehicle use and likely from continued NO<sub>x</sub> emissions under BS-VI standards. The vehicle growth and continued NO<sub>x</sub> emissions are expected to contribute more substantially to PM formation in the future years. Brick production is projected to have increased impacts on disease burden under the REF and S2 scenarios, whereas under scenario S3

impacts are projected to be similar to those in 2015, reflecting a combination of emissions reduction and the impact of demographic trends. Plots with cause-specific mortality data for individual source sectors, for each of the scenarios can be found in Appendix H. Comparable plots can be found for DALY rates in Appendix I. Appendices H and I are available on the HEI website.



**Figure 28. Comparison of DALY rates (DALYs/100,000 population) by cause of death attributable to ambient PM<sub>2.5</sub> for different scenarios in rural and urban India.** LRI, lower-respiratory infection; IHD, ischemic heart disease; COPD, chronic obstructive pulmonary disease.



**Figure 29.** Distribution of mortality attributable to specific sources of  $PM_{2.5}$  in urban and rural areas of India in 2015 (STD) and for each of the three future scenarios in 2030 and 2050. AFCI dust, dust from anthropogenic fugitive, combustion, and industrial activities.

## 6.0 SUMMARY AND CONCLUSIONS

Ambient  $PM_{2.5}$  is a major contributor to mortality and disease burden in India, estimated to have been responsible for 1.09 million deaths and 29.6 million DALYs in 2015, making it the third leading risk factor for mortality in India. This report estimates the contributions to that burden that are attributable to major sources of  $PM_{2.5}$  air pollution and projects future mortality and disease burden in 2030 and 2050 under alternative emission scenarios. Specific source sectors that were examined include residential biomass, coal (industrial and power generation), transportation, open burning, distributed diesel sources, and brick production, as well as anthropogenic and wind-blown mineral dust.

Three future scenarios of energy use and air pollution control were then developed: REF, a “reference” scenario where current practices remain unchanged, and two alternative sets of emission reduction measures for major sources, referred to as scenarios S2 (ambitious) and S3 (aspirational). These scenarios were used for analysis of mortality and disease burden projections for all sources of  $PM_{2.5}$  in the years 2030 and 2050. For 2050, we also estimated the major source contributions to ambient  $PM_{2.5}$  and their associated disease burdens under each of the future scenarios considering both future mortality projections and future emissions scenarios. Simulation of the impact of different air pollution source sectors on ambient pollution concentrations with a high-resolution chemical transport model incorporates complex and nonlinear relationships between

emissions and ambient concentrations and allows for spatial disaggregation at a resolution appropriate for health impact analysis. Importantly, this analysis is unique, being based on highly resolved state-level estimates of underlying cause-specific mortality rates, which allow disease burden estimates to be reported for urban and rural areas within India using nonlinear relationships between exposure and mortality.

### 6.1 CURRENT AND FUTURE EXPOSURE AND BURDEN

The levels of ambient  $PM_{2.5}$  have been climbing steadily in India over the last 25 years. In 2015, annual average population-weighted  $PM_{2.5}$  concentration for India as a whole reached  $74.3 \mu\text{g}/\text{m}^3$ , with even higher concentrations experienced in various states. The vast majority (99.9%) of the Indian population lives with  $PM_{2.5}$  levels that exceed the WHO's Air Quality Guideline level ( $10 \mu\text{g}/\text{m}^3$  annual average) and nearly 90% live in areas exceeding the WHO Interim Target-1 of  $35 \mu\text{g}/\text{m}^3$ .

The analysis of different control scenarios shows that the actions taken to reduce emissions have profound implications for both the exposures to and disease burden from ambient  $PM_{2.5}$ . Not surprisingly, the REF scenario approach leads to the largest increases in the mean population-weighted exposures to  $PM_{2.5}$  in both 2030 and in 2050 relative to current levels (Figure 22). Even the S2 scenario, an ambitious scenario that will require major commitments to emissions reductions in the face of continued economic growth, is projected just to hold  $PM_{2.5}$  to current levels by 2030, and to a more modest increase (10%) by 2050. Only under the most active reductions envisioned in the aspirational S3 scenario are exposures projected to be reduced substantially by 2030 and 2050 compared with current levels. The 2050 population-weighted mean exposure for the S3 scenario, even excluding any impact from windblown mineral dust, is estimated to be nearly three times higher than the WHO Air Quality Guideline.

The burden of disease, in terms of the numbers of deaths attributable to all  $PM_{2.5}$ , is substantial and expected to grow in the future despite the projected exposure decreases in both the S2 and S3 scenarios. Compared with 1.09 million deaths in 2015, ambient  $PM_{2.5}$  was projected to be responsible for 1.7 million, 1.6 million, and 1.3 million deaths in 2030 and rising to 3.6 million, 3.2 million, and 2.5 million deaths in 2050 for REF, S2, and S3, respectively. However, the scenario analysis suggests that the number of deaths attributable to  $PM_{2.5}$  was consistently lower in the more aggressive S2 and S3 scenarios than in the REF scenario. Nearly 100,000 to 400,000 deaths could be avoided in 2030 and as many as 340,000 to nearly

1.2 million deaths avoided if the more aggressive measures described in scenarios S2 and S3 were implemented.

The projected increases in mortality despite the decreases in exposure to  $PM_{2.5}$  illustrate the importance of population dynamics in determining temporal trends in mortality attributable to ambient  $PM_{2.5}$ . Under all scenarios, the projected increase in mortality attributable to a larger and older population and increased numbers of deaths from IHD, stroke, COPD, and LC leads to net increases in the number of deaths attributable to exposure to ambient  $PM_{2.5}$ . By 2050, DALY rates were lower in both S2 and S3 scenarios than for the REF scenario; in addition, the DALY rates in the S3 scenario were lower than in 2015. We note, however, that our estimates of future mortality are based on extrapolating trends in cause-specific mortality from 2000–2015, which may change between 2015 and 2050.

### 6.2 KEY ROLE OF RURAL EXPOSURES IN BURDEN ESTIMATES

Rural and urban areas experience markedly different disease burdens, as shown in Figure 29. The burden estimates for the entire country of India, and the sectoral contributions to them, are driven largely by estimates for the rural population. Seventy-five percent (75%) of deaths attributable to  $PM_{2.5}$  (815,300 attributable deaths) occurred among the rural population in 2015. This finding reflects the high percentage of the Indian population that lives in rural areas (67%), as well as differences in underlying mortality rates, age structures, and, as discussed above, the exposures experienced by the urban and rural Indian populations. Unlike the situation in many countries, exposure levels in rural and urban areas in India are similar. Urban areas had slightly lower contributions to attributable mortality from residential biomass combustion (22.9% in urban areas compared with 25.1% in rural areas), open burning (5.7% compared with 6.2%), and distributed diesel (1.5% compared with 2.0%), and somewhat larger contributions from coal combustion (16.3% compared with 15.3%) and dust (39.6% compared with 37.2%).

Age-standardized DALY rates, which control for differences in population size and age structure, were higher in rural areas compared with urban areas, in part reflecting differences in underlying disease rates (Table 5). However, because they control for population size and age structure, they are also more appropriate for reflecting differences in exposure. For example, age-standardized DALY rates are on average 37% higher in rural areas for all ambient  $PM_{2.5}$  than in urban areas and are even higher for certain source sectors — distributed diesel, residential biomass, and open

burning — reflecting the higher exposures to these source sectors in rural areas. The percentage differences in age-standardized DALY rates between rural and urban areas are lower for coal combustion and dust than for all ambient PM<sub>2.5</sub>, indicating the importance of exposures from these source sectors in urban areas.

### 6.3 CURRENT AND FUTURE BURDENS FROM SPECIFIC SOURCES

The major motivation for this study was to provide insights to the contributions different sources or sectors make both to ambient air pollution and the burden of disease attributable to it. These analyses combined with the scenarios for reducing emissions from these sectors help identify the kinds of actions that are necessary to make substantial improvements in air quality and health.

#### 6.3.1 Residential Biomass and Open Burning

Residential biomass was the single largest human activity sectoral contributor to disease burden in 2015, responsible for 267,700 deaths (24.5% of the total attributable to ambient PM<sub>2.5</sub>). These burdens do not include the additional substantial burden from indoor exposure to biomass burning in the home. Left unaddressed, the burden from the contribution of residential biomass to outdoor air pollution could grow to more than 500,000 annual deaths in 2050. There is, however, substantial opportunity to reduce these exposures and effects, especially through a major shift in fuel use to cleaner fuels.

Open burning was responsible for fewer deaths (66,200 [6.1%] PM<sub>2.5</sub>-attributable deaths) than residential biomass combustion in 2015. However, without major controls, the contribution of open burning to health burden is expected to double in the future. Future estimates of emissions from open burning from agriculture are scaled for population growth given needs for increased food consumption, production, and the generation and disposal of residue. Assuming current practices in agriculture and no legislative interventions to limit agricultural field burning in REF and S2, open burning leads to more than 200,000 projected attributable deaths in both scenarios. These impacts strongly suggest a need for alternative approaches to this agricultural practice, ideally leading to its elimination, the benefits of which are estimated under scenario S3.

#### 6.3.2 The Growing Importance of Coal

Coal combustion, roughly evenly split between industrial sources and thermal power plant combustion, was responsible for 169,300 deaths (15.5%) in 2015. In all future scenarios, however, coal is expected to replace residential

biomass as a leading important contributor to health burden. Under the REF scenario, the absolute attributable burden increases considerably — to nearly 1.3 million annual deaths in 2050. Relative to other sectors, coal also emerges as one of the more important contributors to burden, surpassing the impact of residential biomass in all three future scenarios. However, aggressive emissions control measures, such as those incorporated into scenarios S2 and S3 for coal-burning thermal-power plants and industries, could help avoid between 400,000 and 850,000 coal-attributable deaths in 2050.

#### 6.3.3 Transportation, Brick Kilns, and Distributed Diesel

Compared with other source sectors in this nationwide analysis, transportation, brick kilns, and distributed diesel have relatively small impacts on current health burden, but their impacts are expected to grow under future scenarios. Although emissions from vehicular transportation is frequently mentioned in public discourse as a major contributor to air pollution, especially in Indian cities, our broad analysis of air pollution in rural as well as urban areas shows relatively smaller contributions from transportation on a national basis and even in urban areas relative to other sectors in 2015 (<2 µg/m<sup>3</sup> to population-weighted concentrations and <2.5% to disease burden). However, transportation and distributed diesel sources typically operate in closer proximity to populations than do large stationary sources; the approaches to estimating exposure in this study at a relatively larger scale therefore may somewhat underestimate the actual exposures, and the related disease burden attributable to these sources.

Although small in comparison to other source sectors, the impacts of transportation and distributed diesel sources are projected to increase substantially under all of the future scenarios. These increases are due both to competing factors affecting emissions and to the growth and aging of the population, as discussed for other sectors. For transportation, the future scenarios reflect a complex interplay. This analysis assumes decreased per-vehicle emissions because of implementation of BS VI/6, albeit not as significantly for NO<sub>x</sub>, which increases in future scenarios and which also contributes to formation of PM<sub>2.5</sub>. The per-vehicle improvements, however, may be offset by increases in the numbers of vehicles and vehicle use. The analysis also assumes changes in transportation modes, especially in S2 and S3, which involves, for example, shifts to CNG and electric-bus fleets in urban areas, but continued reliance on diesel in rural areas.

Brick production is projected to have increased impacts on disease burden under the REF and S2 scenarios. Under the most ambitious control scenario, S3, the impacts on

mortality have remained at levels similar to those estimated for 2015, reflecting a balance between the impacts of reductions in emissions and the impact of demographic trends on mortality.

### 6.3.4 Anthropogenic and Windblown Dusts

In 2015, dust arising from anthropogenic activities, including combustion (e.g., coal fly ash) and resuspended road dust and windblown mineral dust, which largely originates outside of India, were also major contributors to ambient PM<sub>2.5</sub> in India, responsible for 39% of population-weighted PM<sub>2.5</sub>. Dust arising from anthropogenic activities alone was responsible for about 9% of population-weighted PM<sub>2.5</sub> in 2015.

The present and future impacts of dust, both anthropogenic and windblown, on disease burden are very large. Of the total 1.09 million deaths attributable to PM<sub>2.5</sub> in 2015 in India, 412,500 deaths (38%) are attributable to total dust; of these, approximately 99,900 deaths are attributable to dust from anthropogenic activities. In each of the future scenarios, the increases in population-weighted dust concentrations are entirely attributable to changes in the anthropogenic component. For example, under the REF scenario, the anthropogenic component of dust more than tripled from 6.8 µg/m<sup>3</sup> in 2015 to 22.2 µg/m<sup>3</sup> in 2050. Specifically, road dust emissions are projected nearly to double between 2015 and 2030 and to stabilize, but not decrease, from 2030 to 2050, as emissions reductions from improvements to road quality are offset by those from increased vehicle use. Left unchecked, as in the REF scenario, dust emissions from anthropogenic activities are projected to be responsible for 743,000 attributable deaths. Given the focus of this report on emissions related to human activities, these projections from our analysis suggest that more attention should be directed toward reductions in anthropogenic dust emissions. However, the magnitude of the potential burden from windblown mineral dust suggests the need for further attention to mitigation strategies for these sources as well.

### 6.4 COMPARISON WITH OTHER ESTIMATES

No studies exist whose methods are truly comparable to those used in this study; some recent peer-reviewed studies provide more limited assessments using different data and methods, but have estimated quite similar sectoral impacts on disease burden. For example, as part of a global analysis for the year 2010, Lelieveld and colleagues (2015) estimated that approximately 50% of the disease burden attributable to air pollution in India originated with residential biofuel combustion (compared with 25% in this analysis), 14% from power plant combustion

(compared with 8% in this analysis), 11% from “natural sources” (not estimated in this analysis), 6.5% from industry (7.5% from industrial coal combustion in this analysis), 6% from open burning (about 6% in this analysis), and 5% (compared with 2% in this analysis) from transportation. Guttikunda and Jawahar (2014) estimated that coal-fired power plants were responsible for 80,000–115,000 deaths in India in 2010 (compared with 83,000 in this analysis).

The other, and often better known, category of studies that offer estimates of sectoral contributions to air pollution levels are source apportionment analyses, which use very different methods to apportion measured concentrations of PM to source categories based on chemical composition. Review of the receptor modeling studies in India shows that they reach a wide range of conclusions, even for the same city, suggesting methodological weaknesses related to application of specific chemical constituents as source tracers, limited availability of locally derived emissions source profiles, and limited use of organic molecular markers (Pant and Harrison 2012). Qualitatively, our estimates of sectoral contributions to ambient PM<sub>2.5</sub> were similar to findings in the limited number of source apportionment studies using receptor modeling that have been conducted for major Indian cities. For example, Banerjee and colleagues (2015) summarized multiple receptor modeling analyses and reported on the importance of crustal and road dust resuspension sources, along with vehicular, residential biofuel, and industrial emissions. Similarly, Singh and colleagues (2017) summarized PM<sub>2.5</sub> urban receptor modeling analyses from throughout South Asia and over all sites; their study highlighted the percentage contributions of vehicular emissions (mean ± SD: 37 ± 20%), followed by industrial emissions (23 ± 16%), secondary aerosols (22 ± 12%), and natural sources (20 ± 15%), with approximately 15% contributions from biofuel combustion. In a study of source contributions to air pollution in Delhi, investigators at the Indian Institute of Technology at Kanpur found seasonal differences in transportation contributions to PM<sub>2.5</sub> levels, ranging from 9% in the summer and 25% in the winter using data from 2013–2014. The larger contributions of vehicular emissions in their analysis are due to the fact that these studies were conducted in urban areas and often based on monitoring sites that were impacted by nearby roads, while at the same time, as noted above, the larger grid scale in this study may have underestimated the transport contributions to exposure and burden within cities. In addition, although the majority of studies that were considered included vehicle emissions and natural sources (crustal material and sea salt) as source terms, fewer than half of

the studies included source terms for residential biofuels or industrial emissions so that the relative contribution of vehicle emissions appears larger.

This report provides the first comprehensive assessment of the current and predicted burdens of disease attributable to major sources in India. In particular, this assessment incorporates updated, locally derived, and spatially disaggregated emissions estimates that are combined with high-resolution concentration estimates that include satellite observations and a large number of available ground measurements from India. Furthermore, the integrated exposure–response relationship applied in this analysis incorporates recent concentration–response functions from an increasing number of large cohort studies. In addition we incorporate state-level variation in underlying disease burden estimates that are stratified by urban and rural populations and the evaluation of multiple future scenarios. Despite the strengths described above, as in most analyses of future health burden and pollution impacts, this analysis is not without limitations. For example, in this report we focus our assessment on only PM<sub>2.5</sub>, given that in the GBD 2015 report, the burden attributable to PM<sub>2.5</sub> vastly exceeded that attributable to ozone in India. Recent research has suggested both a greater risk from ozone exposure (hazard ratio of 1.14 per 10 ppb increase in long term ozone exposure [Turner et al. 2016] compared with a hazard ratio of 1.03 used in GBD 2015) and the potential for increases in exposure in the future (Silva et al. 2016), which suggest a more significant role for ozone in future air pollution–related disease burden assessments. The IER function, while necessary to estimate disease burden from PM<sub>2.5</sub> exposure at the levels typical throughout much of India, has been developed primarily from studies conducted at lower concentrations in North American and Europe as similar long term cohort studies from India are lacking. In addition, although the differential toxicity of PM of varying composition and from diverse sources remains an area of active research, consistent with current evidence as synthesized by the U.S. EPA (2009) and the World Health Organization’s REVIHAAP assessment (WHO 2013) and following the Global Burden of Disease and other assessments, we assume that all airborne particles smaller than 2.5 µm in aerodynamic diameter are equally toxic. This assumption is of particular relevance given the important role of windblown mineral dust and dust arising from anthropogenic activities in this analysis. As in any assessment of future emissions, our projections of pollution under future scenarios in 2030 and 2050 are based upon a range of planned initiatives and expected

growth and development as well as reasonable and feasible policies and technology changes. The extent to which these will be realized or perhaps replaced by as yet unknown disruptive technologies and trends is unknown. As such these scenarios are best used to bound (between the reference scenario and the more aspirational S3 scenario) the likely path of emissions in India.

Similarly, our mortality projections are based on a straightforward but rather simple annual rate of change metric and likely differ from more sophisticated mortality-forecasting algorithms. In addition, although the simulations do incorporate emissions originating outside of India, our analysis of contributions of sectors besides windblown mineral dust is focused only on emissions that originate in India and their impact on disease burden within India. Our estimates also do not quantify the impact of Indian emissions on disease burden in other countries as has been done in other analyses (Q Zhang et al. 2017).

## 6.5 CONCLUSION

The analyses conducted in this study have shown that multiple air pollution sources present a significant health burden attributable to ambient air pollution in India today. They also pose major challenges for air quality management and for the reduction of air-pollution-related health burden in the future. As is the case for all countries that are growing and aging in ways that make them more susceptible to the effects of air pollution, future mortality attributable to air pollution in India is expected to grow even with reduction in air pollution levels. In India, given expected growth in economic activity and population, our estimates predict that future exposures to ambient PM<sub>2.5</sub> will increase by 2050 under the REF scenario and even under the ambitious S2 scenario. Reductions in exposure are projected in 2030 and 2050 only under S3, the most aspirational air pollution control scenario. When combined with the changes in population demographics, these future exposures are predicted to increase the future levels of mortality attributable to air pollution in India. However, our estimates also indicate that there are significant opportunities in both urban and rural India to avoid hundreds of thousands to more than a million deaths by 2050 if the active emission control measures described in scenarios S2 and S3 are implemented. Ultimately, aggressive implementation of air quality management, such as that simulated for our aspirational S3 scenario, will be required to lead India to a reduction of disease burden and protection of public health from air pollution in the future.

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### 8.0 REFERENCES

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- Akagi SK, Yokelson RJ, Wiedinmyer C, Alvarado MJ, Reid JS, Karl T, et al. 2011. Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmos Chem Phys* 11:4039–4072; doi:10.5194/acp-11-4039-2011 [Online 3 May 2011].
- Alexander B, Allman DJ, Amos HM, Fairlie TD, Dachs J, Hegg DA, et al. 2012. Isotopic constraints on the formation pathways of sulfate aerosol in the marine boundary layer of the subtropical northeast Atlantic Ocean. *J Geophys Res-Atmos* 117(D6):304; doi:10.1029/2011JD016773 [Online 27 March 2012].
- Alexander B, Park RJ, Jacob DJ, Li QB, Yantosca RM, J Savarino, et al. 2005. Sulfate formation in sea-salt aerosols: constraints from oxygen isotopes. *J Geophys Res-Atmos* 110(D10); doi:10.1029/2004JD005659 [Online 25 May 2005].
- Anandarajah G, Gambhir A. 2014. India's CO<sub>2</sub> emission pathways to 2050: What role can renewables play? *Appl Energy* 131:79–86. Available: <https://doi.org/10.1016/j.apenergy.2014.06.026>.
- Andreae MO, Merlet P. 2001. Emission of trace gases and aerosols from biomass burning. *Global Biogeochem Cycles* 15(4):955–966.
- Awasthi A, Singh N, Mittal S, Gupta PK, Agarwal R. 2010. Effects of agriculture crop residue burning on children and young on PFTs in North West India. *Sci Total Environ* 408(20):4440–4445.
- Badrinath S, Sharma T, Biswas J, Srinivas V. 1996. A case control study of senile cataract in a hospital based population. *Indian J Ophthalmol* 44(4):213–217.
- Baidya S, Borken-Kleefeld J. 2009. Atmospheric emissions from road transportation in India. *Energy Policy* 37: 3812–3822. Available: <http://dx.doi.org/10.1016/J.Enpol.2009.07.010>.
- Balakrishnan K, Cohen A, Smith KR. 2014. Addressing the burden of disease attributable to air pollution in India: The need to integrate across household and ambient air pollution exposures. *Environ Health Perspect* 122:A6–A7.
- Balakrishnan K, Ganguli B, Ghosh S, Sankar S, Thanasekaran V, Rayudu VN, et al. 2011a. Part 1. Short-term effects of air pollution on mortality: results from a time-series analysis in Chennai, India. In: *Public Health and Air Pollution in Asia (PAPA): Coordinated Studies of Short-Term Exposure to Air Pollution and Daily Mortality in Two Indian Cities*. Research Report 157. Boston, MA:Health Effects Institute.
- Balakrishnan K, Ramaswamy P, Sambandam S, Thangavel G, Ghosh S, Johnson P, et al. 2011b. Air pollution from household solid fuel combustion in India: An overview of exposure and health related information to inform health research priorities. *Global Health Action*; doi:10.3402/gha.v4i0.5638 [Online 4 October 2011].
- Balakrishnan K, Sambandam S, Ramaswamy P, Ghosh S, Venkatesan V, Thangavel G, et al. 2015. Establishing integrated rural-urban cohorts to assess air pollution-related health effects in pregnant women, children and adults in southern India: An overview of objectives, design and methods in the Tamil Nadu Air Pollution and Health Effects (TAPHE) study. *BMJ Open*; doi:10.1136/bmjopen-2015-008090.
- Banerjee T, Murari M, Kumar M, Raju MP. 2015. Source apportionment of airborne particulates through receptor modeling: Indian scenario. *Atmos Res* 164–165:167–187.
- Basu C, Ray M, Lahiri T. 2001. Traffic-related air pollution in Calcutta associated with increased respiratory symptoms and impaired alveolar macrophage activity. *J Environ Poll* 8:187–195.
- Behera D. 1997. An analysis of effect of common domestic fuels on respiratory function. *Indian J Chest Dis Allied Sci*. 39(4):235–243.
- Bhalla K, Shotten M, Cohen A, Brauer M, Shahraz S, Burnett R, et al. 2014. *Transport for health: the global burden of disease from motorized road transport*. Washington, DC:W.B. Group.
- Bhushan C, Kanchan SK, Bahel K. 2016. A report on the survey of implementation of the continuous emissions monitoring system in India. New Delhi, India:Centre for Science and Environment. Available: <http://cseindia.org/userfiles/cems-implementation-survey-report.pdf> [accessed 11 August 2017].

- Bladen WA. 1983. Relationship between acute respiratory illness and air pollution in an Indian industrial city. *J Air Pollut Control Assoc* 33:226–227.
- Boys BL, Martin RV, van Donkelaar A, MacDonell RJ, HsuNC, Cooper MJ, et al. 2014. Fifteen-year global time series of satellite-derived fine particulate matter. *Environ Sci Technol* 48(19): 11109–11118.
- Brauer M, Amann M, Burnett R, Cohen A, Dentener F, Ezzati M, et al. 2012. Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. *Environ Sci Technol* 46(2):652–660; doi:10.1021/es2025752 [Online 8 December 2011].
- Brauer M, Freedman G, Frostad J, van Donkelaar A, Martin RV, Dentener F, et al. 2016. Ambient air pollution exposure estimation for the global burden of disease 2013. *Environ Sci Technol* 50:79–88; doi:10.1021/acs.est.5b03709 [Online 23 November 2015].
- Brook RD, Rajagopalan S, Pope CA III, Brook JR, Bhatnagar A, Diez-Roux AV, et al. 2010. Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation* 121(21):2331–2378; doi:10.1161/CIR.0b013e3181d8e1 [Online 1 June 2010].
- Burnett RT, Pope CA III, Ezzati M, Olives C, Lim SS, Mehta S, et al. 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ Health Perspect* 122(4):397–403.
- Cao G, Zhang X, Gong S, An X, Wang Y. 2011. Emission inventories of primary particles and pollutant gases for China. *Chin Sci Bull* 56(8):781–788.
- CEA (Central Electricity Authority). 2010. Annual Report 2010-2011. New Delhi, India:Central Electricity Authority, Ministry of Power, Government of India. Available: [www.cea.nic.in/reports/annual/annualreports/annual\\_report-2010.pdf](http://www.cea.nic.in/reports/annual/annualreports/annual_report-2010.pdf) [accessed 11 August 2017].
- Census. 2011. Houselisting and Housing Census Data – 2011. Ministry of Home Affairs, Government of India. Available: [http://censusindia.gov.in/2011census/hlo/hlo\\_highlights.html](http://censusindia.gov.in/2011census/hlo/hlo_highlights.html) [accessed 15 August 2017].
- Centre for Science and Environment (CSE). 2016a. Reinventing Air Quality Monitoring — Potential of Low Cost Alternative Monitoring Methods. Available: [www.cseindia.org/userfiles/reinventing-air-quality-monitoring-potential-of-low-cost-dec27.pdf](http://www.cseindia.org/userfiles/reinventing-air-quality-monitoring-potential-of-low-cost-dec27.pdf) [accessed 11 August 2017].
- Centre for Science and Environment (CSE). 2016b. Towards a Clean Air Action Plan: Lesson from Delhi. Available: [www.cseindia.org/userfiles/delhi-clean-air-action-plan-dec27.pdf](http://www.cseindia.org/userfiles/delhi-clean-air-action-plan-dec27.pdf) [accessed 11 August 2017].
- Chafe ZA, Brauer M, Klimont Z, Van Dingenen R, Mehta S, Rao S, et al. 2014. Household cooking with solid fuels contributes to ambient PM<sub>2.5</sub> air pollution and the burden of disease. *Environ Health Perspect* 122(12):1314–1320.
- Chaturvedi PR, Shukla V. 2014. Role of energy efficiency in climate change mitigation policy for India: Assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change* 123(3–4).
- Clarke L, Edmonds J, Jacoby H, Pitcher H, Reilly J, Richels R. 2007. Scenarios of greenhouse gas emissions and atmospheric concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC:Department of Energy, Office of Biological & Environmental Research.
- Climate Action Tracker. 2017. Country Assessment for India. Available: <http://climateactiontracker.org/countries/india.html> [accessed 11 August 2017].
- CMA (Cement Manufacturers Association). 2007a. Basic Data – Indian Cement Industry: CMA Annual Publication. New Delhi, India:Cement Manufacturers' Association.
- CMA (Cement Manufacturers Association). 2007b. Annual Cement Statistics. New Delhi, India:Cement Manufacturers' Association.
- CMA (Cement Manufacturers Association). 2012. Annual Report 2011-12. Cement Manufacturers' Association, New Delhi. Available: [www.cmaindia.org/mc-admin/assets/images/listfiles/mc-list11457661552040369881.pdf](http://www.cmaindia.org/mc-admin/assets/images/listfiles/mc-list11457661552040369881.pdf) [accessed 11 August 2017].
- CMIE (Centre for Monitoring of Indian Economy). 2010. Economic Intelligence Service: Energy 2010. New Delhi, India:Centre for Monitoring of Indian Economy.
- Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, et al. 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 389:1907–1918. Available: [http://dx.doi.org/10.1016/S0140-6736\(17\)30505-6](http://dx.doi.org/10.1016/S0140-6736(17)30505-6) [Online 10 April 2017].
- CPCB (Central Pollution Control Board). 2004. Highlights 2004. Available: [http://cpcb.nic.in/Highlights/highlights\\_2004.pdf](http://cpcb.nic.in/Highlights/highlights_2004.pdf) [accessed 11 August 2017].

- CPCB (Central Pollution Control Board). 2010. Status of the Vehicular Pollution Control Programme in India. Delhi, India:Ministry of Environment & Forests. Available: [www.cpcb.nic.in/upload/NewItems/NewItem\\_157\\_VPC\\_REPORT.pdf](http://www.cpcb.nic.in/upload/NewItems/NewItem_157_VPC_REPORT.pdf) [accessed 11 August 2017].
- Crooks JL, Cascio WE, Percy MS, Reyes J, Neas LM, Hilborn ED. 2016. The association between dust storms and daily non-accidental mortality in the United States, 1993-2005. *Environ Health Perspect* 124(11):1735–1743.
- Cropper ML, Simon NB, Alberini A, Arora S, Sharma PK. 1997. The health benefits of air pollution control in Delhi. *Amer J Agri Econ* 79(5): 1625–1629.
- Das N, Baral SS, Sahoo SK, Mohapatra RK, Ramulu TS, Das SN, et al. 2009. Aerosol physical characteristics at Bhubaneswar, East Coast of India. *Atmos Res* 93(4):897–901.
- Dhadse S, Kumari P, Bhagia LJ. 2008. Fly ash characterization, utilization and government initiatives in India — A review. *J Sci Ind Res* 67:11–18.
- Dharmadhikary S, Dixit S, 2011. Thermal power plants on The Anvil: Implications and need for rationalisation. Prayas Energy Group, Pune Available: [www.prayaspune.org/peg/publications/item/164-thermal-power-plants-on-the-anvil-implications-and-need-for-rationalisation.html](http://www.prayaspune.org/peg/publications/item/164-thermal-power-plants-on-the-anvil-implications-and-need-for-rationalisation.html) [accessed 15 August 2017].
- Dholakia HH, Bhadra D, Garg A. 2014. Short term association between ambient air pollution and mortality and modification by temperature in five Indian cities. *Atmos Environ* 99:168–174.
- Dutt D, Srinivasa D, Rotti S, Sahai A, Konar D. 1996. Effect of indoor air pollution on the respiratory system of women using different fuels for cooking in an urban slum of Pondicherry. *Nat Medical J India* 9(3):113–117.
- Dutta A, Ray MR, Banerjee A. 2012. Systemic inflammatory changes and increased oxidative stress in rural Indian women cooking with biomass fuels. *Toxicol Appl Pharmacol* 261(3):255–262.
- EPCA (Environment Protection, Prevention and Control Authority). 2017. Comprehensive Action Plan for air pollution control with the objective to meet ambient air quality standards in the National Capital Territory of Delhi and National Capital Region, including states of Haryana, Rajasthan and Uttar Pradesh (Report No. 71). Available: [www.epca.org.in/EPCA-Reports1999-1917/Final-EPCA-Report-71-CAP-for-Delhi-NCR.pdf](http://www.epca.org.in/EPCA-Reports1999-1917/Final-EPCA-Report-71-CAP-for-Delhi-NCR.pdf) [accessed 11 August 2017].
- Eze IC, Hemkens LG, Bucher HC, Hoffmann B, Schindler C, Kunzli N, et al. 2015. Association between ambient air pollution and diabetes mellitus in Europe and North America: systematic review and meta-analysis. *Environ Health Perspect* 123(5):381–389.
- FAI (Fertilizer Association of India). 2010. Fertilizer Statistics 2010-2011. New Delhi, India:Fertilizer Association of India.
- Fairlie TD, Jacob DJ, Dibb JE, Alexander B, Avery MA, van Donkelaar A, et al. 2010. Impact of mineral dust on nitrate, sulfate, and ozone in transpacific Asian pollution plumes. *Atmos Chem Phys* 10:3999–4012.
- Fairlie TD, Jacob DJ, Park RJ. 2007. The impact of transpacific transport of mineral dust in the United States. *Atmos Environ* 41(6):1251–1266.
- Fountoukis C, Nenes A. 2007. ISORROPIA II: A computationally efficient thermodynamic equilibrium model for  $K^+ - Ca^{2+} - Mg^{2+} - NH_4^+ - Na^+ - SO_4^{2-} - NO_3^- - Cl^- - H_2O$  aerosols. *Atmos Chem Phys* 7:4639–4659.
- Fujino J, Nair R, Kainuma M, Masui T, Matsuoka T. 2006. Multi-gas mitigation analysis on stabilization scenarios using AIM global model. *Ener J* 27:343–353.
- Fulton L, Eads G. 2004. IEA/SMP Model Documentation and Reference Case Projection. Available: [www.wbcsd.org](http://www.wbcsd.org) [accessed 15 August 2017].
- Garg A, Shukla PR, Kapshe M. 2006. The sectoral trends of multigas emissions inventory of India. *Atmos Environ* 40(24):4608–4620. Available: <http://dx.doi.org/10.1016/j.atmosenv.2006.03.045> [accessed 14 August 2017].
- GBD MAPS Working Group. 2016. Burden of disease attributable to coal-burning and other major sources of air pollution in China. Boston, MA:Health Effects Institute. Available: [www.healtheffects.org/publication/burden-disease-attributable-coal-burning-and-other-air-pollution-sources-china](http://www.healtheffects.org/publication/burden-disease-attributable-coal-burning-and-other-air-pollution-sources-china) [accessed 11 August 2017].
- GBD 2015 Risk Factor Collaborators. 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2015: A systematic analysis for the Global Burden of Disease study 2015. *Lancet* 388:1659–1724.
- Ghude SD, Pfister GG, Jena C, van der A, RJ, Emmons LK, Kumar R. 2013. Satellite constraints of nitrogen oxide ( $NO_x$ ) emissions from India based on OMI observations and WRF-Chem simulations. *Geophys Res Lett* Available: <http://dx.doi.org/10.1029/2012GL053926> [accessed 11 August 2017].

- Giglio L, Randerson JT, van der Werf GR. 2013. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *J Geophys Res Biogeosciences* 118(1):317–328.
- Government of India. 2014. Auto Fuel Vision and Policy 2025: Report of the Expert Committee. Available: [www.petroleum.nic.in/sites/default/files/autopol.pdf](http://www.petroleum.nic.in/sites/default/files/autopol.pdf) [accessed 11 August 2017].
- Goyal S. 2016. Sangrur tops state in use of happy seeder machines. *Tribune of India*, 15 March. Available: [www.tribuneindia.com/news/punjab/community/sangrur-tops-state-in-use-of-happy-seeder-machines/208994.html](http://www.tribuneindia.com/news/punjab/community/sangrur-tops-state-in-use-of-happy-seeder-machines/208994.html) [accessed 11 August 2017].
- Guarnieri M, Balmes JR. 2014. Outdoor air pollution and asthma. *Lancet* 383(9928):1581–1592.
- Gupta D, Boffetta P, Gaborieau V, Jindal S. 2001. Risk factors of lung cancer in Chandigarh, India. *Ind J Med Res* 113:142–150.
- Gupta R. 2014. Essays on Air Pollution, Global Warming and Agricultural Productivity [PhD dissertation]. Delhi, India:Indian Statistical Institute.
- Gupta S, Agarwal R, Mittal SK. 2016. Respiratory health concerns in children at some strategic locations from high PM levels during crop residue burning episodes. *Atmos Environ* 137:127–134.
- Guttikunda SK, Goel R, Pant P. 2014. Nature of air pollution, emission sources, and management in the Indian cities. *Atmos Environ* 95:501–510. Available: <https://doi.org/10.1016/j.atmosenv.2014.07.006>.
- Guttikunda SK, Jawahar P. 2014. Atmospheric emissions and pollution from the coal-fired thermal power plants in India. *Atmos Environ* 92:449–460.
- Guttikunda SK, Mohan D. 2014. Re-fueling road transport for better air quality in India. *Energy Policy* 68:556–561.
- Heald CL, Collett JL Jr., Lee T, Benedict KB, Schwandner FM, Li Y, et al. 2012. Atmospheric ammonia and particulate inorganic nitrogen over the United States. *Atmos Chem Phys* 12:10295–10312.
- HEI International Scientific Oversight Committee (ISOC). 2010. Outdoor Air Pollution and Health in the Developing Countries of Asia: A Comprehensive Review. Special Report 18. Boston, MA:Health Effects Institute.
- HEI NPACT Review Panel. 2013. Executive Summary. HEI's National Particle Component Toxicity (NPACT) Initiative. Boston, MA:Health Effects Institute.
- Henze DK, Seinfeld JH. 2006. Global secondary organic aerosol from isoprene oxidation. *Geophys Res Lett* 33: L09812; doi:10.1029/2006GL025976 [Online 11 May 2006].
- Henze DK, Seinfeld JH, Ng NL, Kroll JH, Fu T-M, Jacob DJ, et al. 2008. Global modeling of secondary organic aerosol formation from aromatic hydrocarbons: High- vs. low-yield pathways. *Atmos Chem Phys* 8:2405–2420.
- Hijioka Y, Matsuoka Y, Nishimoto H, Masui M, Kainuma M. 2008. Global GHG emissions scenarios under GHG concentration stabilization targets. *J Global Environ Eng* 13:97–108.
- ICRA. 2016. Indian Automobile Industry: Proposed BS-VI Emission Standards. ICRA Limited, New Delhi. Available: <http://www.theicct.org/sites/default/files/publications/India%20BS%20VI%20Policy%20Update%20vF.pdf> [accessed 6 September 2017].
- IEA (International Energy Agency). 2009. Cement Technology Roadmap. International Energy Agency and World Business Council for Sustainable Development. Available: [www.iea.org/publications/freepublications/publication/Cement.pdf](http://www.iea.org/publications/freepublications/publication/Cement.pdf) [accessed 14 August 2017].
- IEP (Integrated Energy Policy). 2006. Integrated Energy Policy: Report of the Expert Committee. New Delhi, India:Government of India Planning Commission. Available: [http://planningcommission.gov.in/reports/genrep/rep\\_intengy.pdf](http://planningcommission.gov.in/reports/genrep/rep_intengy.pdf) [accessed 14 August 2017].
- IESS (India Energy Security Scenarios), NITI Aayog. 2015. India Energy Security Scenarios, 2047, NITI Aayog, Govt of India, 2015. Available: <http://iess2047.gov.in/> [accessed 1 April 2015].
- India Green House Gas Program. 2015. Available: [http://indiaghgp.org/sites/default/files/IndiaGHG-Aug15\\_0.pdf](http://indiaghgp.org/sites/default/files/IndiaGHG-Aug15_0.pdf) [accessed 11 August 2017].
- India's INDC. 2015. India's Intended Nationally Determined Contribution: Working Towards Climate Justice 2015 Report – UNFCCC. Available: <http://www4.unfccc.int/ndcregistry/PublishedDocuments/India%20First/INDIA%20INDC%20TO%20UNFCCC.pdf> [accessed 6 September 2017].
- Jaeglé L, Quinn PK, Bates T, Alexander B, Lin J-T. 2011. Global distribution of sea salt aerosols: New constraints from in situ and remote sensing observations. *Atmos Chem Phys* 11:3137–3157; doi:10.5194/acp-11-3137-2011 [Online 4 April 2011].
- Jawaharlal Nehru National Urban Renewal Mission Overview. 2012. Available: <http://jnnurm.nic.in/wp-content/uploads/2011/01/PMSpeechOverviewE.pdf> [accessed 14 August 2017].

- Jindal S, Aggarwal A, Chaudhry K, Chhabra SK, D'Souza GA, Gupta D, et al. 2006. A multicentric study on epidemiology of chronic obstructive pulmonary disease and its relationship with tobacco smoking and environmental tobacco smoke exposure. *Indian J Chest Dis Allied Sci* 48(1):23–29.
- Kang JH, Liu TC, Keller J, Lin HC. 2013. Asian dust storm events are associated with an acute increase in stroke hospitalisation. *J Epidemiol Comm Health* 67(2):125–131.
- Karanasiou A, Moreno N, Moreno T, Viana M, de Leeuw F, Querol X. 2012. Health effects from Sahara dust episodes in Europe: Literature review and research gaps. *Environ Int* 47:107–114.
- Katsouyanni K, Samet JM, Anderson HR, Atkinson R, Le Tertre A, Medina S, et al. 2009. Air pollution and health: A European and North American approach (APHENA). *Res Rep Health Eff Inst* 142:5–90.
- Kharol SK, Martin RV, Philip S, Vogel S, Henze DK, Chen D, et al. 2013. Persistent sensitivity of Asian aerosol to emissions of nitrogen oxides. *Geophys Res Lett* 40(5):1021–1026; doi:10.1002/grl.50234.
- Klimont Z, Cofala J, Xing J, Wei W, Zhang C, Wang S, et al. 2009. Projections of SO<sub>2</sub>, NO<sub>x</sub> and carbonaceous aerosols emissions in Asia. *Tellus B* 61(4):602–617.
- Kolappan C, Subramani R. 2009. Association between biomass fuel and pulmonary tuberculosis: A nested case-control study. *Thorax* 64(8):705–708.
- Kumar R, Nagar JK, Kumar H, Kushwah AS, Meena M, Kumar P, et al. 2007. Association of indoor and outdoor air pollutant level with respiratory problems among children in an industrial area of Delhi, India. *Arch Environ Occup Health* 62(2):75–80.
- Kumar R, Sharma SK, Thakur JS, Lakshmi PV, Sharma MK, Singh T. 2010. Association of air pollution and mortality in the Ludhiana city of India: A time-series study. *Indian J Public Health* 54(2):98–103.
- Kumar S. 2017. PM Narendra Modi's free LPG scheme PMUY achieves goal, PDS kerosene sales dip 20%. *Financial Express*, 30 May. Available: [www.financialexpress.com/economy/pm-narendra-modis-free-lpg-scheme-pmuy-achieves-goal-pds-kerosene-sales-dip-20/692125/](http://www.financialexpress.com/economy/pm-narendra-modis-free-lpg-scheme-pmuy-achieves-goal-pds-kerosene-sales-dip-20/692125/) [accessed 11 August 2017].
- Kumar S, Sunder Raman R. 2016. Inorganic ions in ambient fine particles over a National Park in central India: Seasonality, dependencies between SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, and NH<sub>4</sub><sup>+</sup>, and neutralization of aerosol acidity. *Atmos Environ* 143:152–163.
- Lacey FG, Henze DK, Lee CJ, van Donkelaar A, Martin RV. 2017. Transient climate and ambient health impacts due to national solid fuel cookstove emissions. *Proc Natl Acad Sci U S A* 114(6):1269–1274; doi 10.1073/pnas.1612430114 [Online 23 Jan 2017].
- Lahiri T, Ray M, Lahiri P. 2008. Epidemiological Study on Effect of Air Pollution on Human Health (Adults) in Delhi. New Delhi:Central Pollution Control Board. Available: [http://cpcb.nic.in/upload/NewItems/NewItem\\_161\\_Adult.pdf](http://cpcb.nic.in/upload/NewItems/NewItem_161_Adult.pdf) [accessed 15 September 2017].
- Lakshmi PV, Viridi NK, Thakur JS, Smith KR, Bates MN, Kumar R. 2012. Biomass fuel and risk of tuberculosis: A case-control study from northern India. *J Epidemiol Comm Health* 66(5):457–461.
- Lalchandani D, Maithel S. 2013. Towards Cleaner Brick Kilns in India. New Delhi, India:Shakti Sustainable Energy Foundation. Available: [www.gkspl.in/reports/energy\\_efficiency/Towards%20Cleaner%20Brick%20Kilns%20in%20India.pdf](http://www.gkspl.in/reports/energy_efficiency/Towards%20Cleaner%20Brick%20Kilns%20in%20India.pdf) [accessed 11 August 2017].
- Lam NL, Chen Y, Weyant C, Venkataraman C, Sadavarte P, Johnson MA, et al. 2012. Household light makes global heat: High black carbon emissions from kerosene wick lamps. *Environ Sci Technol* 46(24):13531–13538.
- Lee JT, Kim H, Hong YC, Kwon HJ, Schwartz J, Christiani DC. 2000. Air pollution and daily mortality in seven major cities of Korea, 1991–1997. *Environ Res* 84:247–254.
- Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A. 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525:367–371.
- Li M, Zhang Q, Kurokawa J, Woo J, He K, Lu Z, et al. 2017. MIX: A mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP[J]. *Atmos Chem Phys* 17(2):935–963.
- Liao H, Henze DK, Seinfeld JH, Wu S, Mickley LJ. 2007. Biogenic secondary organic aerosol over the United States: Comparison of climatological simulations with observations. *J Geophys Res* 112(D6):201; doi:10.1029/2006JD007813 [Online 16 March 2007].
- Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 380:2224–2260.

- Loomis D, Grosse Y, Lauby-Secretan B, El Ghissassi F, Bouvard V, Benbrahim-Tallaa L, et al. 2013. The carcinogenicity of outdoor air pollution. *Lancet Oncol* 14:1262–1263.
- Lu Z, Zhang Q, Streets DG. 2011. Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010. *Atmos Chem Phys* 11:9839–9864.
- Maithel S, Uma R, Bond T, Baum E, Thao VTK. 2012. Brick kilns performance assessment, emissions measurements, & a roadmap for cleaner brick production in India. Study report prepared by Green Knowledge Solutions, New Delhi, India. Available: [www.ccacoalition.org/en/resources/brick-kilns-performance-assessment-roadmap-cleaner-brick-production-india](http://www.ccacoalition.org/en/resources/brick-kilns-performance-assessment-roadmap-cleaner-brick-production-india) [accessed 11 August 2017].
- Maji S, Ahmed S, Siddiqui WA, Ghosh S. 2017. Short term effects of criteria air pollutants on daily mortality in Delhi, India. *Atmos Environ* 150:210–219.
- Mallone S, Stafoggia M, Faustini A, Gobbi GP, Marconi A, Forastiere F. 2011. Saharan dust and associations between particulate matter and daily mortality in Rome, Italy. *Environ Health Perspect* 119(10):1409–1414.
- Mavalankar D, Trivedi C, Gray R. 1991. Levels and risk factors for perinatal mortality in Ahmedabad, India. *Bull World Health Organ* 69:435–442.
- Mishra V. 2003. Effect of indoor air pollution from biomass combustion on prevalence of asthma in the elderly. *Environ Health Perspect* 111:71–78.
- Mishra V, Retherford RD. 1997. Cooking smoke increases the risk of acute respiratory infection in children. *Nat Fam Health Surv Bull* (8):1–4.
- Mishra VK, Retherford RD, Smith KR. 1999. Biomass cooking fuels and prevalence of tuberculosis in India. *Int J Infect Dis* 3:119–129.
- Mishra V, Smith KR, Retherford RD. 2005. Effects of cooking smoke and environmental tobacco smoke on acute respiratory infections in young Indian children. *Pop Environ* 26:375–396.
- MoC (Ministry of Coal). 2007. Coal Directory of India, 2006-07. Kolkata, India: Coal Controller's Organisation, Ministry of Coal, Government of India.
- MoEF (Ministry of Environment and Forest). 1981. The Air (Prevention and Control) Act, 1981. Available: [www.moef.nic.in/legis/air/air1.html](http://www.moef.nic.in/legis/air/air1.html) [accessed 11 August 2017].
- MoEF (Ministry of Environment and Forest). 2000. Municipal Solid Wastes (Management and Handling) Rules. Available: [www.moef.nic.in/legis/hsm/mswmhr.html](http://www.moef.nic.in/legis/hsm/mswmhr.html) [accessed 11 August 2017].
- MoEF (Ministry of Environment and Forest). 2015. Environment Standards for Thermal Power Plants along with the Corrigendum. Available: [www.moef.gov.in/sites/default/files/Thermal%20plant%20gazette%20scan.pdf](http://www.moef.gov.in/sites/default/files/Thermal%20plant%20gazette%20scan.pdf) [accessed 11 August 2017].
- MoEF (Ministry of Environment and Forest). 2017. Energy efficiency improvements in the Indian brick industry. Available: [www.resourceefficientbricks.org](http://www.resourceefficientbricks.org) [accessed 7 November 2017].
- Mohan M, Sperduto RD, Angra SK, Milton RC, Mathur RL, Underwood BA, et al. 1989. India–US case-control study of age-related cataracts. India–US Case-Control Study Group. *Arch Ophthalmology* 107:670–676.
- MoHFW (Ministry of Health and Family Welfare). 2015. Report of the Steering Committee on Air Pollution and Health-Related Issues. New Delhi, India: Ministry of Health and Family Welfare, Government of India. Available: <http://ehsdiv.sph.berkeley.edu/krsmith/publications/2015/MoHFW%20AP%20Steering%20Com.pdf> [accessed 11 August 2017].
- MoP (Ministry of Power), Bureau of Energy Efficiency. 2008. Perform, Achieve and Trade (PAT). Available: <https://www.beeindia.gov.in/content/pat-3> [accessed 28 September 2017].
- MoP (Ministry of Power). 2015. Energy Efficient Norms for Power Plants. Press Information Bureau. Government of India. Available: <http://pib.nic.in/newsite/PrintRelease.aspx?relid=117384> [accessed 11 August 2017].
- MoP (Ministry of Power). 2016. Draft National Electric Plan (Volume 1) Generation. Available: [www.cea.nic.in/reports/committee/nep/nep\\_dec.pdf](http://www.cea.nic.in/reports/committee/nep/nep_dec.pdf) [accessed 11 August 2017].
- MoPNG (Ministry of Petroleum and Natural Gas). 2012. Indian Petroleum and Natural Gas Statistics 2011–12. New Delhi, India: Ministry of Petroleum and Natural Gas, Government of India.
- MoPNG (Ministry of Petroleum & Natural Gas). 2016. Pradhan Mantri Ujjwala Yojana. Press Information Bureau. Available: <http://pib.nic.in/newsite/PrintRelease.aspx?relid=155686> [accessed 11 August 2017].
- MoPNG (Ministry of Petroleum and Natural Gas). 2017. Annual Report 2016–2017. Available: [www.petroleum.nic.in/sites/default/files/AR16-17.pdf](http://www.petroleum.nic.in/sites/default/files/AR16-17.pdf) [accessed 11 August 2017].
- MoRTH (Ministry of Road Transportation and Highways). 2016a. Press release. Government of India. Available:

<http://pib.nic.in/newsite/PrintRelease.aspx?relid=134232> [accessed 6 September 2017].

MoRTH (Ministry of Road Transport and Highways). 2016b. Notification. Available: <http://egazette.nic.in/WriteReadData/2016/168300.pdf> [accessed 11 August 2017] (see page 22 for English).

MoWR (Ministry of Water Resources, Government of India). 2006–2007. Minor Irrigation Census. Available: <http://micensus.gov.in/intnat.html> [accessed 11 August 2017].

Murthy, KSS. 2014. Indian Aluminium Demand to Grow 5 Times by 2030: Prof. K.S.S. Murthy, Gen. Secretary, Aluminium Association of India. Available: <http://metalworld.co.in/newsletter/2014/Apr14/FacetoFace0414.pdf> [accessed 14 August 2017].

National Sample Survey Organization (NSSO). 2012. Household Consumption of Various Goods and Services in India. Report 541. New Delhi, India: MOSPI, Government of India.

National Solar Mission. 2010. Indian Solar Radiation Atlas: Phase II. Ministry of New and Renewable Energy, Govt. of India. Available: [www.mnre.gov.in/solar-mission/jnnsim/introduction-2/](http://www.mnre.gov.in/solar-mission/jnnsim/introduction-2/) [accessed 11 August 2017].

Newby DE, Mannucci PM, Tell GS, Baccarelli AA, Brook RD, Donaldson K, et al. 2015. Expert position paper on air pollution and cardiovascular disease. *Eur Heart J* 36:83–93b; doi: 0.1093/eurheartj/ehu458 [Online 11 August 2017].

NITI Aayog. 2017. India Leaps ahead. Available: [http://niti.gov.in/writereaddata/files/document\\_publication/RMI\\_India\\_Report\\_web.pdf](http://niti.gov.in/writereaddata/files/document_publication/RMI_India_Report_web.pdf) [accessed 11 August 2017].

NTDPC (National Transport Development Policy Committee). 2013. Moving India to 2032, India transport report, Government of India, National Transport Development Policy Committee, India, New Delhi. Available: [http://planningcommission.nic.in/reports/genrep/NTDPC\\_Vol\\_01.pdf](http://planningcommission.nic.in/reports/genrep/NTDPC_Vol_01.pdf). [accessed 1 April 2016].

Olivier JG, Bouwman AF, Berdowski JJM, Veld, C, Bloos JPJ, Visschedijk AJH, et al. 1996. Description of EDGAR Version 2.0: A set of global emission inventories of greenhouse gases and ozone-depleting substances for all anthropogenic and most natural sources on a per country basis and on 1 degree × 1 degree grid. Available: [https://inis.iaea.org/Search/search.aspx?orig\\_q=RN:29006635](https://inis.iaea.org/Search/search.aspx?orig_q=RN:29006635) [accessed 14 August 2017].

Omori T, Fujimoto G, Yoshimura I, Nitta H, Ono M. 2003. Effects of particulate matter on daily mortality in 13 Japanese cities. *J Epidemiol* 13:314–322.

Pal R, Mahima GA, Singh C, Tripathi A, Singh RB. 2014. The effects of fireworks on ambient air and possible impact on cardiac health, during Deepawali festival in north India. *World Heart J* 5:21–32.

Pande JN, Bhatta N, Biswas D, Pandey RM, Ahluwalia G, Siddaramaiah NH, et al. 2002. Outdoor air pollution and emergency room visits at a hospital in Delhi. *Indian J Chest Diseases Allied Sci* 44:13–19.

Pandey A, Sadavarte P, Rao AB, Venkataraman C. 2014. Trends in multi-pollutant emissions from a technology-linked inventory for India: II. Residential, agricultural and informal industry sectors. *Atmos Environ* 99:341–352. Available: <http://dx.doi.org/10.1016/j.atmosenv.2014.09.080> [accessed 14 August 2017].

Pandey A, Venkataraman C. 2014. Estimating emissions from the Indian transport sector with on-road fleet composition and traffic volume. *Atmos Environ* 98:123–133. Available: <http://dx.doi.org/10.1016/j.atmosenv.2014.08.039> [accessed 14 August 2017].

Pandey MR, Neupane RP, Gautam A, Shrestha IB. 1989. Domestic smoke pollution and acute respiratory infections in a rural community of the hill region of Nepal. *Environ Int* 15:337–340.

Pant P, Harrison RM. 2012. Critical review of receptor modelling for particulate matter: A case study of India. *Atmos Environ* 49:1–12.

Parikh K. 2012. Sustainable Development and Low Carbon Growth Strategy for India. *Energy* 40(1):31–38. Available: <http://dx.doi.org/10.1016/j.energy.2012.01.013>.

Park RJ, Jacob DJ, Chin M, Martin RV. 2003. Sources of carbonaceous aerosols over the United States and implications for natural visibility. *J Geophys Res* 108:4355; doi:10.1029/2002JD003190 [Online 20 June 2003].

Park RJ, Jacob DJ, Field BD, Yantosca RM, Chin M. 2004. Natural and transboundary pollution influences on sulfate-nitrate-ammonium aerosols in the United States: Implications for policy. *J Geophys Res* 109:D15204; doi: 10.1029/2003JD004473 [12 August 2004].

Perez L, Tobias A, Querol X, Künzli N, Pey J, Alastuey A, et al. 2008. Coarse particles from Saharan dust and daily mortality. *Epidemiol* 19(6):800–807.

Philip S, Martin RV, Pierce JR, Jimenez JL, Zhang Q, Canagaratna MR, et al. 2014a. Spatially and seasonally resolved estimate of the ratio of organic mass to organic carbon. *Atmos Environ* 87:34–40.

- Philip S, Martin RV, Snider G, Weagle CL, van Donkelaar A, Brauer M, et al. 2017. Anthropogenic fugitive, combustion and industrial dust is a significant, underrepresented fine particulate matter source in global atmospheric models. *Environ Res Lett*. Available: <http://iopscience.iop.org/article/10.1088/1748-9326/aa65a4> [accessed 14 August 2017].
- Philip S, Martin RV, van Donkelaar A, Lo JW-H, Wang Y, Chen D, et al. 2014b. Global chemical composition of ambient fine particulate matter for exposure assessment. *Environ SciTech* 48(22):13060–13068.
- PNGRB (Petroleum & Natural Gas Regulatory Board). 2013. Vision 2030 Natural Gas Infrastructure in India. Report by Industry Group for Petroleum & Natural Gas Regulatory Board (PNGRB), India. Available: [www.pngrb.gov.in/Hindi-Website/pdf/vision-NGPV-2030-06092013.pdf](http://www.pngrb.gov.in/Hindi-Website/pdf/vision-NGPV-2030-06092013.pdf) [accessed 14 August 2017].
- Pope CA III, Burnett RT, Turner MC, Cohen A, Krewski D, Jerrett M, et al. 2011. Lung cancer and cardiovascular disease mortality associated with ambient air pollution and cigarette smoke: shape of the exposure-response relationships. *Environ Health Perspect* 119(11):1616–1621.
- Purohit P, Amann M, Mathur R, Gupta I, Marwah S, Verma V, et al. 2010. Gains Asia: Scenarios for cost-effective control of air pollution and greenhouse gases in India. Laxenburg, Austria:International Institute for Applied Systems Analysis. Available: <http://pure.iiasa.ac.at/9379/> [accessed 14 August 2017].
- Pye HOT, Chan AWH, Barkley MP, Seinfeld JH. 2010. Global modeling of organic aerosol: The importance of reactive nitrogen (NO<sub>x</sub> and NO<sub>3</sub>). *Atmos Chem Phys* 10:11261–11276; doi:10.5194/acp-10-11261-2010 [Online 30 November 2010].
- Pye HOT, Liao H, Wu S, Mickley LJ, Jacob D, Henze DK, et al. 2009. Effect of changes in climate and emissions on future sulfate-nitrate-ammonium aerosol levels in the United States. *J Geophys Res* 114:D01205; doi:10.1029/2008JD010701 [Online 9 January 2009].
- Qureshi K. 1994. Domestic smoke pollution and prevalence of chronic bronchitis/asthma in a rural area of Kashmir. *Indian J Chest Diseases Allied Sci* 36:61–72.
- Rajaratnam U, Seghal M, Nairy S, Patnayak RC, Chhabra SK, Kilnani, et al. 2011. Part 2. Time-series study on air pollution and mortality in Delhi. In: *Public Health and Air Pollution in Asia (PAPA): Coordinated Studies of Short-Term Exposure to Air Pollution and Daily Mortality in Two Indian Cities*. Research Report 157. Boston, MA:Health Effects Institute.
- Ramachandran S, Kedia S. 2010. Black carbon aerosols over an urban region: Radiative forcing and climate impact. *J Geo Res Atmospheres* 15:D10202; doi:10.1029/2009JD013560 [Online 18 May 2010].
- Ramachandran S, Rajesh TA. 2007. Black carbon aerosol mass concentrations over Ahmedabad, an urban location in western India: Comparison with urban sites in Asia, Europe, Canada, and the United States. *J Geo Res Atmospheres* 112:D06211; doi:10.1029/2006JD007488 [Online 29 March 2007].
- Randerson JT, Chen Y, Werf GR, Rogers BM, Morton DC. 2012. Global burned area and biomass burning emissions from small fires. *J Geo Res Biogeosci* 117(G4). Available: <http://onlinelibrary.wiley.com/doi/10.1029/2012JG002128/abstract> [Online 11 December 2012].
- Ray DK, Mueller ND, West PC, Foley JA. 2013. Yield trends are insufficient to double global crop production by 2050. *PLoS One* 8(6):e66428; doi:10.1371/journal.pone.0066428 [Online 19 June 2013].
- Ray MR, Mukherjee S, Roychoudhury S, Bhattacharya P, Banerjee M, Siddique S, et al. 2006. Platelet activation, upregulation of cd11b/cd18 expression on leukocytes and increase in circulating leukocyte-platelet aggregates in Indian women chronically exposed to biomass smoke. *Human Exp Tox* 25:627–635.
- Riahi K, Gruebler A, Nakicenovic N. 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Tech Forecasting Social Change* 74(7):887–935.
- Roy S, Roy MR, Basu C, Lahiri P, Lahiri T. 2001. Abundance of siderophages in sputum. Indicator of an adverse lung reaction to air pollution. *Acta Cytol* 45:958–964.
- Roychoudhury S, Mondal NK, Mukherjee S, Dutta A, Siddique S, Ray MR. 2012. Activation of protein kinase B (PKB/Akt) and risk of lung cancer among rural women in India who cook with biomass fuel. *Toxicol Appl Pharmacol* 259(1):45–53.
- Sadavarte P, Venkataraman C. 2014. Trends in multi-pollutant emissions from a technology-linked inventory for India: I. Industry and transport sectors. *Atmos Environ* 99: 353–364. Available: <http://dx.doi.org/10.1016/j.atmosenv.2014.09.081> [accessed 15 August 2017].
- Sadavarte P, Venkataraman C, Cherian R, Patil N, Madhavan BL, Gupta T, et al. 2016. Seasonal differences in aerosol abundance and radiative forcing in months of contrasting emissions and rainfall over northern South Asia.

- Atmos Environ 125:512–523. Available: <http://doi.org/10.1016/j.atmosenv.2015.10.092> [accessed 15 August 2017].
- Saha A, Kulkarni P, Shah A, Patel M, Saiyed H. 2005. Ocular morbidity and fuel use: An experience from India. *Occup Environ Med* 62:66–69.
- Sapkota A, Gajalakshmi V, Jetly D, Roychowdhury S, Dikshit R. 2008. Indoor air pollution from solid fuels and risk of hypopharyngeal/laryngeal and lung cancers: A multi-centric case-control study from India. *Int J Epidemiol* 37:321–328.
- Sava F, Carlsten C. 2012. Respiratory health effects of ambient air pollution: An update. *Clin Chest Med* 33:759–769; doi:10.1016/j.ccm.2012.07.003.
- Shaddick G, Thomas M, Jobling A, Brauer M, Donkelaar A, Burnett R. 2016. Data integration model for air quality: A hierarchical approach to the global estimation of exposures to ambient air pollution. Available: <https://arxiv.org/abs/1609.00141> [accessed 15 August 7 2017].
- Shah PS, Balkhair T, Knowledge Synthesis Group on Determinants of Preterm/LBW births. 2011. Air pollution and birth outcomes: A systematic review. *Environ Int* 37:498–516; doi:10.1016/j.envint.2010.10.009 [Online 26 November 2010].
- Sharma S, Goel A, Gupta D, Kumar A, Mishra A, Kundu S, et al. 2015. Emission inventory of non-methane volatile organic compounds from anthropogenic sources in India. *Atmos Environ* 102:209–219. Available: <http://dx.doi.org/10.1016/j.atmosenv.2014.11.070>.
- Shukla PR, Agarwal P, Bazaz AB, Agarwal N, Kainuma M, Matsui T, et al. 2009. Low Carbon Society Vision 2050, India, Indian Institute of Management Ahmedabad, National Institute for Environmental Studies, Kyoto University and Mizuho Information & Research Institute. Available: <http://www.kooperation-international.de/uploads/media/indialcs.pdf>.
- Shukla PR, Chaturvedi V. 2012. Low carbon and clean energy scenarios for India: Analysis of targets approach. *Energy Econ* 34:S487–S495; doi:10.1016/j.eneco.2012.05.002. Available: <http://dx.doi.org/10.1016/j.eneco.2012.05.002>.
- Siddique S, Banerjee M, Ray MR, Lahiri T. 2010. Air pollution and its impact on lung function of children in Delhi, the capital city of India. *Water Air Soil Pollut* 212:89–100.
- Silva RA, West JJ, Lamarque JF, Shindell DT, Collins WJ, Dalsoren S, et al. 2016. The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmos Chem Phys* 16:9847–9862; doi:10.5194/acp-16-9847-2016 [Online 5 August 2016].
- Singh N, Murari V, Kumar M, Barman SC, Banerjee T. 2017. Fine particulates over South Asia: Review and meta-analysis of PM<sub>2.5</sub> source apportionment through receptor model. *Environ Pollut* 223:121–136.
- Snider G, Weagle CL, Murdymootoo KK, Ring A, Ritchie Y, Stone E, et al. 2016. Variation in global chemical composition of PM<sub>2.5</sub>: Emerging results from SPARTAN. *Atmos Chem Phys* 16:9629–9653.
- Sreenivas V, Prabhakar A, Badrinath S, Fernandez T, Roy I, Sharma T, et al. 1999. A rural population based case-control study of senile cataract in India. *J Epidemiol* 9:327–336.
- Steering Committee on Air Pollution and Health Related Issues. 2015. Report of the Steering Committee on Air Pollution and Health Related Issues, Ministry of Health and Family Welfare, Government of India. August 2015. Available: [http://mohfw.nic.in/sites/default/files/5412023661450432724\\_0.pdf](http://mohfw.nic.in/sites/default/files/5412023661450432724_0.pdf) [accessed 11 August 2017].
- Stieb DM, Chen L, Eshoul M, Judek S. 2012. Ambient air pollution, birth weight and preterm birth: A systematic review and meta-analysis. *Environ Res* 117:100–111; doi:10.1016/j.envres.2012.05.007 [Online 21 June 2012].
- Thanikachalam S, Harivanzan V, Mahadevan MV, Murthy JSN, Anbarasi C, Saravanababu CS, et al. 2015. Population study of urban, rural, and semiurban regions for the detection of endovascular disease and prevalence of risk factors and holistic intervention study (purse-his). *Global Heart* 10:281–289.
- Tielsch J, Katz J, Thulasiraj R, Coles C, Sheeladevi S, Yanik EL, et al. 2009. Exposure to indoor biomass fuel and tobacco smoke and risk of adverse reproductive outcomes, mortality, respiratory morbidity and growth among newborn infants in south India. *Int J Epidemiol* 38:1351–1363.
- Times of India. 2017. Why crop burning may continue this year too. *The Times of India* (New Delhi Edition), 22 April. Available: [www.pressreader.com/india/the-times-of-india-new-delhi-edition/20170422/281582355511585](http://www.pressreader.com/india/the-times-of-india-new-delhi-edition/20170422/281582355511585) [accessed 11 August 2017].
- Turner MC, Jerrett M, Pope CA III, Krewski D, Gapstur SM, Diver WR, et al. 2016. Long-term ozone exposure and mortality in a large prospective study. *Am J Respir Crit Care Med* 193(10):1134–1142; doi:10.1164/rccm.201508-1633OC.
- United Nations (UN). Department of Economic and Social Affairs, Population Division. 2017. World Population Prospects: the 2017 Revision, DVD Edition. Available:

[https://esa.un.org/unpd/wpp/Publications/Files/WPP2017\\_KeyFindings.pdf](https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf) [September 2017].

United Nations (UN). 2005. World Population Prospects, The 2004 Revision: Volume III, Analytical Report. New York: UN Department of Economic and Social Affairs, Population Division.

U.S. EPA. 2009. Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2009). EPA/600/R-08/139F. Washington, DC: U.S. EPA.

van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Mu M, Kasibhatla PS, et al. 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos Chem Phys* 10(23):11707–11735.

van Donkelaar A, Martin RV, Brauer M, Boys BL. 2015. Use of satellite observations for long-term exposure assessment of global concentrations of fine particulate matter. *Environ Health Perspect* 123:135–143; doi:10.1289/ehp.1408646.

van Donkelaar A, Martin RV, Brauer M, Hsu NC, Kahn RA, Levy RC, et al. 2016. Global estimates of fine particulate matter using a combined geophysical–statistical method with information from satellites, models, and monitors. *Environ Sci Tech* 50(7):3762–3772.

van Donkelaar A, Martin RV, Brauer M, Kahn R, Levy R, Verduzco C, et al. 2010. Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: Development and application. *Environ Health Perspect* 118(6):847–855; doi:10.1289/ehp.0901623 [Online 16 March 2010].

van Vuuren D, den Elzen M, Lucas P, Eickhout B, Strengers B, van Ruijven B, et al. 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change* 81:119–159; doi:10.1007/s10584-006-9172-9 [Online 13 February 2007].

Venkataraman C, Habib G, Kadamba D, Shrivastava J, Leon J-F, Crouzille B, et al. 2006. Emissions from open biomass burning in India: Integrating the inventory approach with high-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) active-fire and land cover data. *Global Biogeochemical Cycles* 20(2); doi:10.1029/2005GB002547.

Venkataraman C, Sagar AD, Habib G, Lam N, Smith KR. 2010. The Indian national initiative for advanced biomass cookstoves: The benefits of clean combustion. *Energy Sustain Develop* 14(2):63–72, doi:10.1016/j.esd.2010.04.005.

Vodonos A, Friger M, Katra I, Avnon L, Krasnov H, Koutrakis P, et al. 2014. The impact of desert dust exposures on hospitalizations due to exacerbation of chronic obstructive pulmonary disease. *Air Qual Atmos Health* 7(4):433–439.

Vodonos A, Friger M, Katra I, Krasnov H, Zahger D, Schwartz J, et al. 2015. Individual Effect Modifiers of Dust Exposure Effect on Cardiovascular Morbidity. *PLoS One* 10(9):e0137714.

Walker JM, Philip S, Martin RV, Seinfeld H. 2012. Simulation of nitrate, sulfate, and ammonium aerosols over the United States. *Atmos Chem Phys* 12:11213–11227.

Wang Y, Zhang QQ, Jiang J, Zhou W, Wang B, He F, et al. 2014. Enhanced sulfate formation during China's severe winter haze episode in January 2013 missing from current models. *J Geophys Res–Atmos* 119(17):10425–10440; doi:10.1002/2013JD021426 [Online 11 September 2014].

Wong C-M on behalf of the PAPA teams: Bangkok, Hong Kong, Shanghai, and Wuhan. 2010. Part 5. Public Health and Air Pollution in Asia (PAPA): A combined analysis of four studies of air pollution and mortality. In: *Public Health and Air Pollution in Asia (PAPA): Coordinated Studies of Short-Term Exposure to Air Pollution and Daily Mortality in Four Cities*. Research Report 154. Boston, MA: Health Effects Institute.

Wong C-M, Vichit-Vadakan N, Kan H, Qian Z. 2008. Public health and air pollution in Asia (PAPA): A multicity study of short-term effects of air pollution on mortality. *Environ Health Perspect* 116:1195–1202.

World Health Organization (WHO). 2013. Review of Evidence on Health Aspects of Air Pollution – REVIHAAP Project Technical Report. Copenhagen: WHO Regional Office for Europe.

World Health Organization (WHO). 2006. Air quality guidelines—global update 2005. Available: [www.who.int/phe/health\\_topics/outdoorair/outdoorair\\_aqg/en/](http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/) [accessed 15 August 2017].

Zhang L, Jacob DJ, Knipping EM, Kumar N, Munger JW, Carouge CC, et al. 2012. Nitrogen deposition to the United States: Distribution, sources, and processes. *Atmos Chem Phys* 12: 4539–4554.

Zhang Q, Jiang X, Tong D, Davis SJ, Zhao H, Geng G, et al. 2017. Transboundary health impacts of transported global air pollution and international trade. *Nature* 543(7647):705–709; doi:10.1038/nature 21712 [Online 29 March 2017].

Zhang Q, Streets DG, Carmichael GR, He KB, Huo H, Kanari A, et al. 2009. Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos Chem Phys* 9:5131–5153.

Zodpey SP, Ughade SN. 1999. Exposure to cheaper cooking fuels and risk of age-related cataract in women. *Indian J Occup Environ Med* 3:159–161.

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**9.0 MATERIALS AVAILABLE ON THE  
HEI WEBSITE**

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Appendices A through I contain supplemental material not included in the printed report. They are available on the HEI website, [www.healtheffects.org/publications](http://www.healtheffects.org/publications).

Appendix A. Comparisons of Simulated 2015 STD Scenario and GBD 2015 Estimated PM<sub>2.5</sub> Concentrations

Appendix B. Estimated Emissions of PM<sub>2.5</sub>, BC, OC, SO<sub>2</sub>, NO<sub>x</sub>, and NMVOCs at the State Level and by Sector

Appendix C. Population-Weighted Percentage Contribution to Ambient PM<sub>2.5</sub> for Each Future Scenario by State and by Sector

Appendix D. Spatial Patterns of PM<sub>2.5</sub> in Future Scenarios by Sector and State

Appendix E. Assumed Technology Shifts and Growth Rates for Sectoral Activity

Appendix F. Sensitivity of Sulfate, Nitrate, and Ammonium Formation from Transportation Sources under Alternative Future Scenarios REF and S2

Appendix G. Attributable Burden Estimates in Deaths and DALYs by Sector, Scenario, and Urban/Rural Area

Appendix H. Cause-Specific Mortality by Sector and by Urban/Rural Area

Appendix I. Cause-Specific DALYs/100,000 Population by Sector and by Urban/Rural Area

## ABBREVIATIONS AND OTHER TERMS

|           |  |                              |  |
|-----------|--|------------------------------|--|
| AAP       | ambient air pollution  | IESS                         | India Energy Security Scenarios                          |
| ALRI      | acute lower-respiratory infections                                     | IGCC                         | integrated gasification combined cycle                   |
| AOD       | aerosol optical depth  | IHD                          | ischemic heart disease                                   |
| AROC      | annualized rate of change  | IHME                         | Institute for Health Metrics and Evaluation              |
| BC        | black carbon   | INDC                         | Intended National Determined Contributions               |
| BRT       | bus rapid transport  | INTEX-B                      | Intercontinental Chemical Transport Experiment — Phase B |
| BS        | Bharat stage   | ISA                          | Integrated Science Assessment                            |
| CEMS      | Continuous Emission Monitoring System                                  | JNNURM                       | Jawaharlal Nehru National Urban Renewal Mission          |
| CI        | confidence interval  | LC                           | lung cancer  |
| CNG       | compressed natural gas   | LDDVs                        | light-duty diesel vehicles                               |
| COPD      | chronic obstructive pulmonary disease                                  | LRI                          | lower-respiratory infection                              |
| CPCB      | Central Pollution Control Board  | MODIS                        | moderate-resolution imaging spectroradiometer            |
| CPS II    | Cancer Prevention II   | MoEF                         | Ministry of Environment and Forest                       |
| DALY      | disability-adjusted life-year  | MoHFW                        | Ministry of Health and Welfare (Government of India)     |
| DBTL      | Direct Benefit Transfer for LPG program                                | MoP                          | Ministry of Power  |
| DST       | Department of Science and Technology                                   | MoPNG                        | Ministry of Petroleum and Natural Gas                    |
| EPCA      | Environment Protection, Prevention and Control Authority               | MT                           | million tonnes   |
| FAUP      | Fly Ash Utilization Programme  | NITI                         | National Institution for Transforming India              |
| FGD       | flue gas desulfurization   | PAT                          | Perform Achieve and Trade initiative                     |
| GAINS     | Greenhouse gas – Air pollution Interactions and Synergies model        | NAAQS                        | National Ambient Air Quality Standards                   |
| GBD       | Global Burden of Disease   | NAMP                         | National Ambient Air Quality Monitoring Programme        |
| GBD MAPS  | Global Burden of Disease from Major Air Pollution Sources (initiative) | NCR                          | National Capital Region                                  |
| GEOS-Chem | Goddard Earth Observing System Global Chemical Transport Model         | NDC                          | National Determined Contributions                        |
| GFED-4s   | Global Fire Emissions Database, version 4                              | NEP                          | National Electric Plan                                   |
| GIS       | geographic information system  | NGT                          | National Green Tribunal                                  |
| HEI       | Health Effects Institute   | NH <sub>4</sub> <sup>+</sup> | ammonium   |
| HAP       | household air pollution  | NMB                          | normalized mean bias                                     |
| HDDVs     | heavy-duty diesel vehicles   | NMVOC                        | nonmethane volatile organic compound                     |
| IARC      | International Agency for Research on Cancer                            | NO <sub>3</sub> <sup>-</sup> | nitrate  |
| IEA       | International Energy Agency  | NO <sub>x</sub>              | nitrogen oxides  |
| IEP       | Integrated Energy Policy   | OBD                          | on-board diagnostics                                     |
| IER       | integrated exposure–response   | OC                           | organic carbon   |

## ABBREVIATIONS AND OTHER TERMS *(continued)*

|                   |  |                               |   |
|-------------------|--|-------------------------------|---|
| ORVOCs            | other reactive volatile organic compounds                      | SO <sub>4</sub> <sup>2-</sup> | sulfate   |
| PAF               | population attributable fraction                               | STD                           | standard simulation                                       |
| PAT               | Perform, Achieve and Trade initiative                          | SO <sub>2</sub>               | sulfur dioxide  |
| PM                | particulate matter   | TIFAC                         | Technology Information Forecasting and Assessment Council |
| PM <sub>10</sub>  | particulate matter ≤ 10 μm in aerodynamic diameter             | TMREL                         | theoretical minimum risk exposure level                   |
| PM <sub>2.5</sub> | particulate matter ≤ 2.5 μm in aerodynamic diameter            | UI                            | uncertainty interval                                      |
| PMUY              | Pradhan Mantri Ujwala Yojana                                   | UNDP                          | United Nations Development Programme                      |
| RCP               | representative concentration pathways                          | UN                            | United Nations  |
| REF               | Reference scenario   | U.S. EPA                      | U.S. Environmental Protection Agency                      |
| REVIHAAP          | Review of Evidence on Health Aspects of Air Pollution (report) | WHO                           | World Health Organization                                 |

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75 Federal Street, Suite 1400  
Boston, MA 02110, USA  
+1-617-488-2300  
*[www.healtheffects.org](http://www.healtheffects.org)*

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