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Global Burden of Disease from Major Air Pollution Sources (GBD MAPS): A Global Approach

Erin McDuffie, Randall Martin, Hao Yin, and Michael Brauer

Includes a Commentary by the Institute's Special Review Panel

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CONTENTS

Research Report 210

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; Bloomberg Philanthropies contributed the primary support for the GBD MAPS Global project. HEI has funded more than 340 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 2,500 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. The Research Committee solicits input from HEI sponsors and other stakeholders and works with scientific staff to develop a Five-Year Strategic Plan, select research projects for funding, and oversee their conduct. The Review Committee, which has no role in selecting or overseeing studies, works with staff to evaluate and interpret the results of funded studies and related research.

All project results and accompanying comments by the Review Committee (or, in this case, the HEI Special Review Panel) are widely disseminated through HEI's website (*www.healtheffects.org*), printed reports, newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.

ABOUT THIS REPORT

Research Report 210, *Global Burden of Disease from Major Air Pollution Sources (GBD MAPS): A Global Approach,* presents a research project funded by Bloomberg Philanthropies and conducted by Dr. Erin McDuffie of Washington University in St. Louis, Missouri, and her colleagues. The report contains three main sections.

The HEI Statement, prepared by staff at HEI, is a brief, nontechnical summary of the study and its findings; it also briefly describes the HEI Special Review Panel's comments on the study.

The Investigators' Report, prepared by McDuffie and colleagues, describes the scientific background, aims, methods, results, and conclusions of the study.

The Commentary, prepared by the HEI Special Review Panel with the assistance of HEI staff, places the study in a broader scientific context, points out its strengths and limitations, and discusses remaining uncertainties and implications of the study's findings for public health and future research.

This report has gone through HEI's rigorous review process. When an HEI-funded study is completed, the investigators submit a draft final report presenting the background and results of the study. This draft report is first examined by outside technical reviewers and a biostatistician. The report and the reviewers' comments are then evaluated by members of an independent Special Review Panel of distinguished scientists who are not involved in selecting or overseeing HEI studies. During the review process, the investigators have an opportunity to exchange comments with the Special Review Panel and, as necessary, to revise their report. The Commentary reflects the information provided in the final version of the report.

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HEI STATEMENT

Synopsis of Research Report 210

A Global Assessment of Burden of Disease from Exposure to Major Air Pollution Sources

INTRODUCTION

Exposure to air pollution has long been associated with mortality and shortened life expectancy and has been acknowledged as one of the main risk factors that affect people's health worldwide. Among all air pollutants, fine particulate matter ($PM_{2.5}$) has been identified as a substantial public health concern. The Global Burden of Disease (GBD) Study and similar assessments provide information on the impacts of outdoor $PM_{2.5}$ and other air pollutants on air quality and health, but they have not provided detailed information on which sources of air pollution are the biggest contributors to health burden.

HEI initiated the Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project to determine which air pollutant sources or fuels — including coal combustion, residential fuel burning, windblown dust, and waste combustion — contribute most to the outdoor $PM_{2.5}$ concentrations and their associated health burden. The first two GBD MAPS reports examined this question in China and India.

The current report conducted by Dr. Erin McDuffie and Dr. Randall Martin of Washington University in St. Louis, Missouri, Dr. Michael Brauer at The University of British Columbia in Canada, and colleagues, contains a global analysis of estimated source contributions to outdoor air pollution and related health effects using updated emissions inventories, satellite and air quality modeling, and relationships between air quality and health at global, regional, country, and metropolitan-area scales. The intent was to incorporate the data into annual updates to annual State of Global Air reports on global air quality and associated health effects in a joint project of HEI and the Institute for Health Metrics and Evaluation) (*www.stateofglobalair.org*) and to help identify priorities for source-specific policies and interventions.

What This Study Adds

- The study provides the first comprehensive estimates of source contributions to $PM_{2.5}$ levels and cause-specific disease burden at global, regional, and national scales to help inform policy.
- It used updated emissions inventories categorized by sector and fuel, satellite data and air quality modeling, and the most recent estimates of relationships between air quality and health.
- Major sources of $PM_{2.5}$ varied substantially by country, with notable contributions from energy generation, industry, transportation, windblown dust, and agriculture sectors in certain locations.
- Combustion of fossil fuels (coal, oil, and natural gas) contributed to an estimated one million deaths globally (27.3% of all mortality); 800,000 of those deaths were in South Asia or East Asia (32.5% of air pollution related deaths in those regions).
- The results are valuable additions to our understanding of how various sources of air pollution contribute to exposure and health burdens.
- All input data and results have been made publicly available to support the active development of finer scale air quality management strategies that focus on specific source sectors.

APPROACH

The GBD MAPS Global project was designed to assess potential health benefits that could result from air quality strategies targeted towards specific sector and fuel combinations. The approach was built on the existing GBD Study and GBD MAPS framework. The investigators applied globally consistent data and methods to inform policy to enable inclusion of results into future iterations of the GBD Study and State of Global Air reports.

McDuffie and colleagues started by expanding and updating the only publicly available global emissions inventory to generate monthly emissions data for 1970 to 2017 for seven key atmospheric pollutants (nitrogen

This Statement, prepared by the Health Effects Institute, summarizes a research project funded by HEI and conducted by Dr. Erin McDuffie (project lead) and Dr. Randall Martin (co-PI) of Washington University in St. Louis, Missouri, Dr. Michael Brauer (co-PI) at The University of British Columbia in Canada, and colleagues. Research Report 210 contains both the detailed Investigators' Report and a Commentary on the study prepared by an HEI Special Review Panel.

oxides, carbon monoxide, sulfur dioxide, ammonia, nonmethane volatile organic compounds, black carbon, and organic carbon), 11 anthropogenic sectors (including agriculture, energy, industry, and transportation), and four fuel categories (coal, biofuel, liquid fuel, and a remaining category that included such industrial processes as fugitive emissions).

The investigators used the emissions data in an updated global air quality model and combined those results with satellite data to model outdoor $PM_{2.5}$ at a final spatial resolution of 0.01° × 0.01° (about 1 km × 1 km at the equator). They compared the modeled concentrations of outdoor $PM_{2.5}$ with measurements made at many stations in different countries to confirm that the model gave realistic values. They then calculated average exposures to outdoor $PM_{2.5}$ for all the people living in different countries and world regions for the source sectors and fuel categories. To find the contributions of each sector or fuel in 2017, they looked at the changes in modeled outdoor $PM_{2.5}$ concentrations when they omitted that sector or fuel from the analysis. Finally, the investigators applied relationships between air pollution and health at different ages to calculate the numbers of deaths that were related to the outdoor $PM_{2.5}$ sources. They calculated historical impacts by assuming that the percentage contributions of the various source sectors and fuels had not changed.

KEY RESULTS

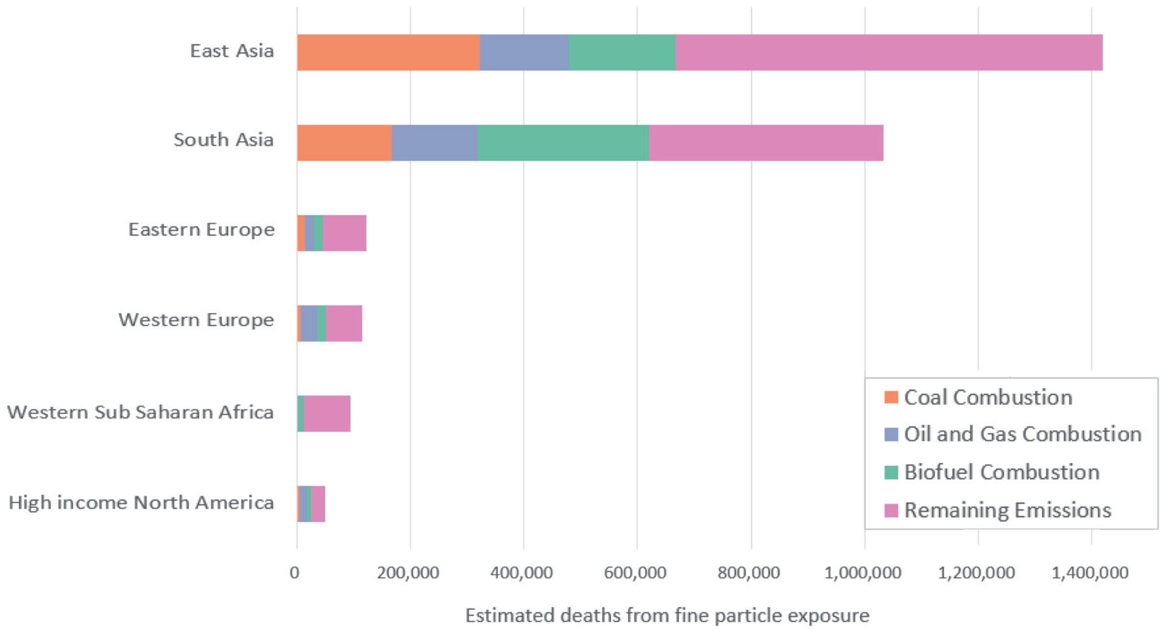
McDuffie and colleagues provide the first comprehensive estimates of source contributions to exposure to $PM_{2.5}$ and cause-specific disease burden at global, regional, and national scales. The investigators used detailed publicly available emissions inventories and found that the major sources of $PM_{2.5}$ varied substantially by country. Energy generation (including both electricity and residential cooking and heating was the largest source sector. Energy generation (including both electricity and fuel production) and industry were important source sectors in many countries. Windblown dust was the source sector that had the most variation; it accounted for 1.5% of deaths related to exposure to outdoor $PM_{2.5}$ in Bangladesh and 70.6% in Nigeria. Agriculture was an important contributor to health burdens from exposure to outdoor $PM_{2.5}$ in some regions because of emissions of ammonia, which is a precursor to $PM_{2.5}$. Combustion of fossil fuels (coal, oil, and natural gas) contributed to an estimated one million deaths globally (27.3% of all mortality); 800,000 of those deaths were in South Asia or East Asia (32.5% of deaths in those regions) (Statement Figure). Of the fossil fuels, coal contributed the highest emissions and related deaths. International shipping and agriculture sectors had higher impacts than are widely recognized. Biofuel and remaining emissions from fossil fuels and other sources also had substantial contributions that exceeded those of fossil fuels in some places.

When comparing their findings to the earlier studies in China and India, the investigators reported that the mix of air pollutant sources had remained similar in India between 2015 and 2017 but that emissions from combustion of coal and biofuels in China were reduced between 2014 and 2017. The patterns in the results were generally the same as in previous studies, although there were some variations because different relationships between air quality and health, emissions inventories, and air quality models were used. The research team has made all datasets, code, and visualizations publicly available to allow for future extensions and comparisons by other researchers (*gbdmaps.med.ubc.ca*).

EVALUATION AND CONCLUSIONS

In its independent review of the report, the ad hoc Special Review Panel identified as strengths of the study the global perspective, the application of standardized methods across countries, and the availability of data and code. The report includes a new contemporary and comprehensive global emissions inventory categorized by sector and fuel and new high-resolution $PM_{2.5}$ exposure estimates. The Panel commended the investigators for their work and observed that the rich data generated by this study will be a valuable resource to mine for additional details for years to come. Strengths of the approach are that it used (1) the most recent updated emissions data available, (2) current methods for modeling air pollution sources and combining the models with observations to assess and improve model performance, and (3) methods consistent with GBD methods to allow comparisons with previous GBD MAPS research.

The Panel concurred with the investigators that there were several sources of uncertainty that likely vary in magnitude by location and source sector that warrant further investigation: (1) the assumption that all particle mixtures have equal effects on mortality, (2) the quality and quantity of emissions and air quality data in different regions, and (3) the method to exclude emissions from source sectors one by one. The assumption that all particles are equally toxic in particular could have important implications for policy given that natural sources with high uncertainty in emissions estimates appear to dominate anthropogenic sources in several regions (e.g., windblown dust in the western sub-Saharan Africa region).



Statement Figure. Estimated deaths for selected regions resulting from exposure to fine particles from combustion of coal, liquid oil and natural gas, biofuel, and remaining emissions that could not be cleanly allocated to combustion of one of those fuels (e.g., fugitive emissions, windblown dust, or industry sources that use multiple fuels).

Having said that, the Panel found that overall, the major conclusions of the analysis, especially at the global scale, are valuable additions to our understanding of how the range of different sources of air pollution contribute to exposure and health burdens. This report provides information on air pollutant source sectors and fuel types that contribute to mortality associated with outdoor concentrations of $PM_{2.5}$ in various countries and regions and will have important implications for the prioritization of which air pollution source sectors to address with policies given the profound differences in source contributions across locations. The results and new datasets will support the active development of finer scale air quality management strategies that focus on specific source sectors and be incorporated in future GBD assessments and the associated State of Global Air communications.

INVESTIGATORS' REPORT

Global Burden of Disease from Major Air Pollution Sources (GBD MAPS): A Global Approach

Erin McDuffie[1], Randall Martin[1,†], Hao Yin[2], and Michael Brauer[2,†]

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ABSTRACT

Ambient fine particulate matter (particles <2.5 µm in aerodynamic diameter [$PM_{2.5}$*]) is the world's leading environmental health risk factor. Reducing the $PM_{2.5}$ disease burden requires specific strategies that target dominant sources across multiple spatial scales. The Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project provides a contemporary and comprehensive evaluation of contributions to the ambient $PM_{2.5}$ disease burden from source sectors and fuels across 21 regions, 204 countries, and 200 subnational areas. We first derived quantitative contributions from 24 emission sensitivity simulations using an updated global atmospheric chemistry-transport model, input with a newly developed detailed anthropogenic emissions dataset that includes emissions specific to source sector and fuels. These simulation results were integrated with newly available high-resolution satellite-derived $PM_{2.5}$ exposure estimates and disease-specific concentration–response relationships consistent with the GBD project to quantify contributions of specific source sector and fuel to the ambient $PM_{2.5}$ disease burden across all regions, countries, and subnational areas. To improve the transparency and reproducibility of this and future work, we publicly provided the global atmospheric chemistry-transport model source code, emissions dataset and emissions model source code, analysis scripts, and source sensitivity results, and further described the emissions dataset and source contribution results in two publications.

We found that nearly 1.05 million (95% uncertainty interval [UI]: 0.74–1.36 million) deaths worldwide (27.3% of the total mortality attributable to $PM_{2.5}$) would be avoidable by eliminating fossil fuel combustion, with coal contributing over half of that burden. Residential (19.2%; 736,000 deaths [95% UI: 521,000–955,000]), industrial (11.7%; 448,000 deaths [95% UI: 318,000–582,000]), and energy (10.2%; 391,000 deaths [95% UI: 277,000–507,000]) sector emissions are among the dominant global sources Uncertainty in these estimates reflects those of the input datasets. Regions with the largest anthropogenic contributions generally have the highest numbers of attributable deaths, which clearly demonstrates the importance of reducing these emissions to realize reductions in global air pollution and its disease burden.

This Investigators' Report is one part of Health Effects Institute Research Report 210, which also includes a Commentary by the Special Review Panel and an HEI Statement about the research project. Correspondence concerning the Investigators' Report may be addressed to Dr. Michael Brauer, The University of British Columbia, School of Population and Public Health, 366A – 2206 East Mall, Vancouver, BC V6T1Z3, Canada; e-mail: *michael.brauer@ubc.ca.* No potential conflict of interest was reported by the authors.

Although this document was produced with funding by Bloomberg Philanthropies, the contents of this document have not been reviewed by private party 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.

INTRODUCTION

STUDY RATIONALE

Air pollution, specifically $PM_{2.5}$ in outdoor air, is now recognized as a leading global health risk factor. The State of Global Air (SoGA) reports, on an annual basis, levels and trends in $PM_{2.5}$ exposures and health burden for the more than 200 countries and territories included in the GBD project. Although these analyses and others have put air pollution on the global health agenda, a logical next step toward addressing this risk factor is the identification of important contributing sources and the estimation of their contributions to disease burden.

Multiple previous studies employed global chemical transport modeling as a means to systematically estimate source-specific contributions in specific countries, such as China and India, as well as on a global scale. Two examples of these studies are the previous country-specific GBD MAPS projects. These studies identified coal as the largest contributor to annual population-weighted mean $PM_{2.5}$ mass in China in 2013 and residential emissions as the largest contributor in India in 2015, with an estimated 366,000 and 267,700 attributable deaths, respectively (GBD MAPS Working Group 2016, 2018). In global analyses, Weagle and colleagues (2018) reported residential emissions as the largest source of globally averaged population-weighted mean $PM_{2.5}$ mass in 2014, while Lelieveld and colleagues (2019) reported simulations for 2016 that attributed 3.61 million deaths to all fossil fuel–related sources of ambient air

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

pollution (ozone and $PM_{2.5}$). Although these and other studies provide valuable insight into the major sources of ambient fine particulate matter, they have been limited to specific countries, utilized relatively coarse spatial resolution exposure estimates, and were restricted to a small number of aggregate emission sectors at the global scale that did not capture recent emission trends in populated regions such as China and India.

The GBD MAPS Global project was designed to address many of the above limitations in order to provide comprehensive and contemporary estimates for global $PM_{2.5}$ sources and disease burden estimates with increased relevance for policymakers. These estimates were directly coupled to the broader GBD project to allow for comparability with other risk factors and for future updates. In addition, this analysis provides the first global assessment of $PM_{2.5}$-associated mortality from the combustion of coal, liquid oil and natural gas, and solid biofuel, as well as from specific source–fuel combinations, such as coal use in the energy sector or residential solid biofuel.

STUDY OBJECTIVES

The primary aim of the GBD MAPS Global project was to identify and quantify the dominant sources of ambient $PM_{2.5}$ pollution and their contributions to disease burden at global, national, and subnational scales for all 204 countries and territories included in the GBD 2019 project. To increase the policy relevance of results compared with past studies, the GBD MAPS Global project used the most detailed and contemporary input data to date, provided results across multiple spatial scales, and prioritized both the transparency and reproducibility of this analysis by publicly releasing all input data sources, analysis code, and results.

METHODS

OVERVIEW

The methodology incorporated several distinct sets of input data and processing steps (Figure 1). We first combined detailed global emission estimates for 2017 with the GEOS-Chem chemical transport model version 12.1.0 source code, updated to account for scientific updates to physical deposition, reactive nitrogen chemistry, and surface emissions (*https://github.com/emcduffie/GC_v12.1.0_EEM*), to develop a series of sensitivity simulations to quantify fractional source contributions to ambient $PM_{2.5}$ concentrations. We then combined these fractional source contributions with newly available high-resolution exposure estimates for both 2017 and 2019 to calculate absolute source contributions to ambient $PM_{2.5}$ and integrated these results with concentration–response relationships and baseline disease burden estimates from the 2019 GBD project to calculate the source sector–specific and fuel-specific disease burden contributions. In the following section we summarize the development of the novel input emissions dataset; the details of the chemical transport model simulations; the calculation of subnational, national, regional, and global fractional source contributions; the development of the high-resolution $PM_{2.5}$ exposure estimates; and the calculation of the attributable disease burden.

METHODOLOGICAL DETAILS

Global Inventory of Air Pollutants with Sector- and Fuel-Specific Emissions

Global emissions are the backbone of modeling source-contribution studies. We used the newly released Community Emissions Data System (CEDS) (Hoesly et al. 2018) and collaborated with the original developers at Pacific Northwest National Laboratory and the University of Maryland to develop a new, updated, and publicly available dataset of air pollutant emissions from 11 anthropogenic sources, that were split into contributions from three individual combustion fuel types and remaining noncombustion sources over the time period from 1970 to 2017 (McDuffie et al. 2020a). At the time of publication, this dataset, referred to as $CEDS_{GBD\ MAPS}$, provided the most contemporary global air pollutant emissions inventory to date and was the only publicly available inventory that included global emissions from multiple types of fuel use. For this work, CEDS also had the advantage of providing emission estimates with globally consistent definitions of sectors and fuel types, as well as incorporating regional and national-level inventories to potentially increase the accuracy of regional estimates, including in African countries (Marais and Wiedinmyer 2016) and India (Venkataraman et al. 2018). The development of emission trends (described in the Results section) also allowed for the estimate of relative future contributions, assuming the continuation of recent trends. CEDS covers the $PM_{2.5}$ precursors CH_4, NH_3, NO_x, SO_2, and nonmethane volatile organic compounds (NMVOCs), along with black carbon and organic carbon. For the purposes of this study, the updated CEDS inventory was augmented with estimates from other sources for the mineral dust component of primary $PM_{2.5}$, fires, and agricultural burning, aircraft, along with biogenic and other natural emissions (Table 1).

Base Global Model Simulation of $PM_{2.5}$ Mass

We have developed a base simulation of ambient $PM_{2.5}$ mass concentrations by coupling the $CEDS_{GBD\ MAPS}$ emission inventory with an updated version (v12.1.0) of the GEOS-Chem three-dimensional chemical transport model (Bey et al. 2001). The GEOS-Chem model solves for the evolution of atmospheric aerosols and gases using meteorological data, global and regional emission inventories, and algorithms that represent the physics and chemistry of atmospheric processes. Each simulation is driven by assimilated meteorological data from the Goddard Earth Observing System from the NASA

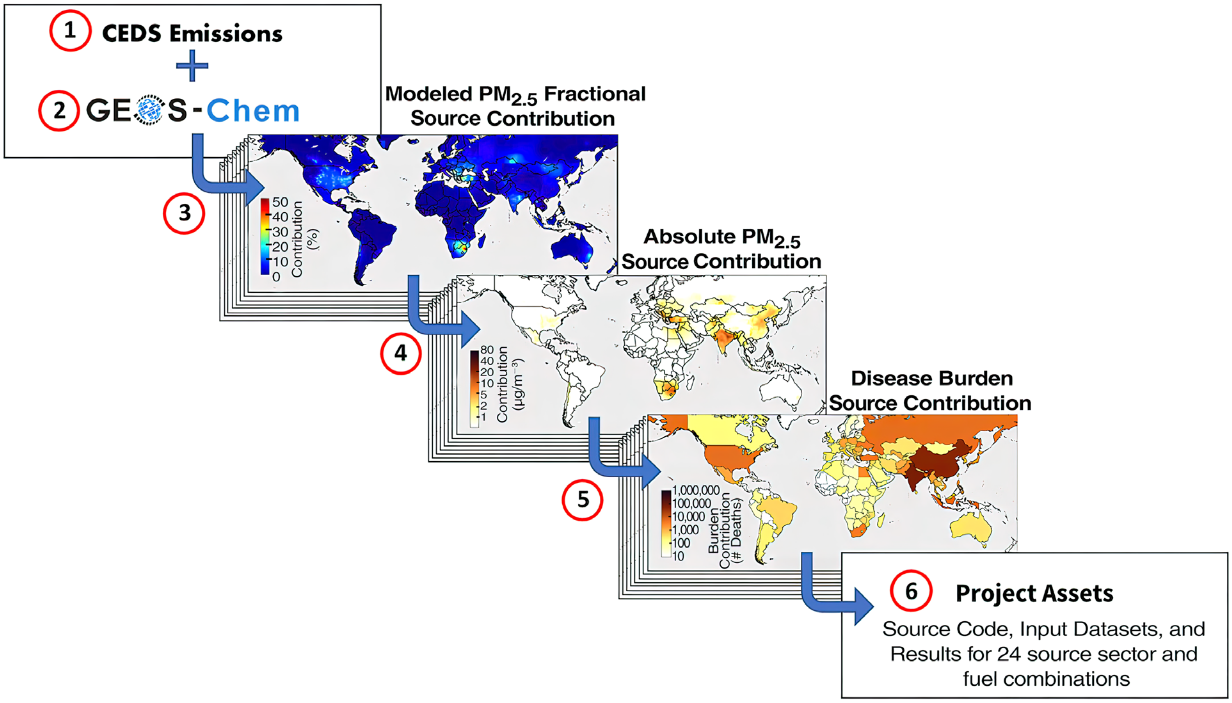

Figure 1. General schematic of the GBD MAPS global project methods. Each step is indicated by a number and is described in the main text. As an illustrative example, the modeled fractional, absolute, and $PM_{2.5}$ disease burden contributions from coal use in the energy sector are shown in Steps 3–5. These steps are repeated for each of the 24 individual source sector and fuel categories (Table 1). (Adapted from Hoesly et al. 2018; CC Attribution 4.0 License.)

Global Modeling and Assimilation Office. We used the NASA's MERRA-2 historical reanalysis product (*https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/*), archived at a 3-hour temporal resolution for three-dimensional fields and 1-hour for two-dimensional fields. The transport and chemistry timesteps were set to 10 and 20 minutes, respectively, to optimize simulation accuracy and computational efficiency. In this work, we used the GEOS-Chem "tropchem" chemical mechanism, which includes coupled aerosol-oxidant chemistry in the troposphere and stratosphere. Further, the default version (v12.1.0) of GEOS-Chem has been updated here to account for scientific advances in accordance with the peer-reviewed literature (Luo et al. 2019, 2020; McDuffie et al. 2018a, 2018b; Shah et al. 2018). GEOS-Chem simulations were run from December 2016 to January 2018 to allow for one month of spin-up. The base simulation was run globally at a resolution of 2° × 2.5° and was supplemented with three nested simulations with resolutions of 0.5° × 0.625° over North America, Europe, and Asia. The production of ambient $PM_{2.5}$ mass in the base simulation was evaluated against publicly available surface measurements of $PM_{2.5}$ mass and its individual chemical constituents, as described in the Methods section of Additional Materials 2 (available on the HEI website). These mechanistic updates reduced the normalized mean bias and improved the model–observational agreement of $PM_{2.5}$ components such as nitrate, ammonium, black carbon, and dust compared with the default model (Additional Materials 2, Supplementary Figure 5). Population-weighted average absolute simulated component concentrations of the updated models were within 0.6 μg/m³ of observations with the direction of bias varying by component. The relative contributions of different chemical components (e.g., organic and inorganic aerosol) agreed with available composition observations. In Additional Materials 2, Supplemental Figure 10 (available on HEI website) also shows that total $PM_{2.5}$ mass predicted by the model has a normalized mean bias of ~ 5% relative to available surface observations. Although both figures show that the observations of both total and speciated $PM_{2.5}$ mass are generally limited to North America, Europe, and select sites in Asia, where available, these evaluations provide confidence in the model's ability to accurately predict changes in the chemical production of $PM_{2.5}$ under various emission sensitivity simulations. Further evaluation of the high-resolution exposure estimates used for the disease burden analysis are discussed below.

Fractional Source and Fuel Contributions to $PM_{2.5}$ Mass

We utilized the detailed sector- and fuel-specific information in the input model datasets to develop 24 source sensitivity simulations (Table 1; 100 simulations in total). We use the common "zero-out" approach (Belis et al. 2020), where the mass of $PM_{2.5}$ produced when each source is individu-

Table 1. Model Emission Sensitivity Simulation Descriptions[a]

#	Sector Sensitivity Simulation	Dataset	Year	Reference
1	**Agriculture** Manure management, soil emissions, rice cultivation, enteric fermentation, and other noncombustion agriculture emissions	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
2	**Energy** Electricity production, central heat production, fuel production and transformation including refinery emissions, fugitives from solid fuel, oil, and gas extraction, flaring, and underground coal and oil and gas fires	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
3	**Industry** Industrial combustion (iron and steel, nonferrous metals, chemicals, pulp and paper, food and tobacco, nonmetallic minerals, construction, transportation equipment, machinery, mining and quarrying, wood products, textile and leather, and other industry combustion) and noncombustion industrial processes and product use (cement production, lime production, other minerals, chemical industry, metal production, food, beverage, wood, pulp and paper, and other noncombustion industrial emissions)	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
4	**Road Transport** Combustion emissions from cars, motorcycles, heavy- and light-duty trucks, and buses	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
5	**Nonroad Transport** Combustion emissions from rail, domestic navigation, and other transportation	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
6	Residential Combustion from residential heating and cooking	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
7	**Commercial** Commercial and institutional combustion	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
8	**Other Combustion (RCO-Other)** Combustion from agriculture, forestry, and fishing	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
9	**Solvents** Solvent use (degreasing and cleaning, paint application, chemical products manufacturing and processing, and other product use)	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
10	**Waste** Solid waste disposal, waste incineration, waste-water handling, and other waste handling	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
11	**International Shipping** Combustion emissions from international shipping and process emissions from tanker loading	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b; Vinken et al. 2011; Holmes et al. 2014
12	**Agricultural Waste Burning** Open fires from agricultural waste burning	GFED4.1s	2017	van der Werf et al. 2017; Mu et al. 2011
13	**Other Fires** Deforestation, boreal forest, peat, savannah, and temperate forest fires	GFED4.1s	2017	van der Werf et al. 2017; Mu et al. 2011
14	**AFCID Dust**[b] Anthropogenic fugitive, combustion, and industrial dust	AFCID	2012,2013, 2015	Philip et al. 2017

Continues next page

Table 1 (*Continued*). Model Emission Sensitivity Simulation Descriptions[a]

#	Sector Sensitivity Simulation	Dataset	Year	Reference
15	**Windblown Dust**	DEAD model	calculated	Fairlie et al., 2007, 2010
16	**Remaining Sources** All remaining emission sources:			
	volcanic SO_2	AeroCom	2017	
	aircraft	AEIC	2005	Stettler et al. 2011
	lightning NO_x	Light NO_x in GEOS-Chem	calculated	Murray et al. 2012
	biogenic soil NO	Soil NO_x in GEOS-Chem	calculated	Hudman et al. 2012
	ocean	SeaFlux, GEIA, SeaSalt, Inorg_Iodine in GEOS-Chem	calculated	Fischer et al. 2012; Millet et al. 2010; Breider et al. 2017; Riddick et al. 2012; Croft et al. 2016; Jaeglé et al. 2011; Carpenter et al. 2013
	biogenic emissions	MEGANv2.1 in GEOS-Chem	calculated	Guenther et al. 2012
	very short-lived iodine and bromine species	LIANG_BROMOCARB ORDONEZ_IODOCARB in GEOS-Chem	2000	Liang et al. 2010; Ordóñez et al. 2012
	decaying plants	DECAYING_PLANTS in GEOS-Chem		Millet et al. 2010
	Fuel Sensitivity Simulations	Dataset	Year	Reference
17	**Total Coal** Hard coal, brown coal, coal coke. Excludes coal ash emissions.[c]	$CEDS_{GBD-MAPS}$	2017	McDuffie et al. 2020a, 2020b
18	**Solid Biofuel** Solid biofuel	$CEDS_{GBD-MAPS}$	2017	McDuffie et al. 2020a, 2020b
19	**Liquid Oil and Natural Gas** Light and heavy oil, diesel oil, and natural gas	$CEDS_{GBD-MAPS}$	2017	McDuffie et al. 2020a, 2020b
20	**Process** Noncombustion CEDS "process" source emissions	$CEDS_{GBD-MAPS}$	2017	McDuffie et al. 2020a, 2020b
	Sector and Fuel Sensitivity Simulations	Dataset	Year	Reference
21	**Total Coal from Energy Production** Hard coal, brown coal, coal coke; includes electricity and heat production	$CEDS_{GBD-MAPS}$	2017	McDuffie et al. 2020a, 2020b
22	**Total Coal from Industrial Processes** Hard coal, brown coal, coal coke; industrial combustion (iron and steel, nonferrous metals, chemicals, pulp and paper, food and tobacco, nonmetallic minerals, construction, transportation equipment, machinery, mining and quarrying, wood products, textile and leather, and other industry combustion)	$CEDS_{GBD-MAPS}$	2017	McDuffie et al. 2020a, 2020b

Continues next page

Table 1 (*Continued*). Model Emission Sensitivity Simulation Descriptions[a]

#	Sector Sensitivity Simulation	Dataset	Year	Reference
23	**Total Coal from Residential Combustion** Hard coal, brown coal, coal coke; residential heating and cooking	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b
24	**Solid Biofuel from Residential Combustion** Solid biofuel; residential heating and cooking	$CEDS_{GBD\text{-}MAPS}$	2017	McDuffie et al. 2020a, 2020b

RCO-Other = residential, commercial, and other sectors.

[a] Note: "calculated" emissions depend on meteorological variables and are computed at the time of model simulation. For further details see Appendix B, Supplementary Table 2. CEDS emissions include NH_3, NO_x, SO_2, NMVOCs, BC, and OC but not the mineral component of primary $PM_{2.5}$ emissions; the latter are included separately in sectors 14 (AFCID dust) and 15 (windblown dust].

[b] Mineral component of primary $PM_{2.5}$ emissions from anthropogenic sources, including ash from solid fuel combustion, emissions from cement and metals production, construction and agricultural emissions, and resuspended road dust.

[c] Excludes coal ash emissions.

ally removed is compared with the base simulation and the sum of all sensitivity simulations to quantify the fractional contributions of each source to ambient $PM_{2.5}$ mass in the year 2017. The advantage of the zeroing-out method is that it predicts changes in total $PM_{2.5}$ mass and composition that would be expected after a complete elimination of emissions from each individual source category, given the current $PM_{2.5}$ chemical production regime in each grid-box (i.e., ammonia [NH_3]– vs. nitrogen oxides [NO_x]–limited production of ammonium nitrate aerosol). The example in Figure 1 shows the contributions from coal use in the energy production sector. As described below, population-weighted modeled fractional source contributions are multiplied by the total disease burden attributable to ambient $PM_{2.5}$ mass in each country to derive source-specific contributions.

Absolute Source and Fuel Contributions to $PM_{2.5}$ Mass

To improve the accuracy of population-exposure estimates and maintain consistency with the GBD project, we calculate the absolute $PM_{2.5}$ mass contributions from each source by applying the modeled fractional source contributions (from Step 3 shown in Figure 1) to the same $PM_{2.5}$ mass exposure estimates used in the 2019 GBD project (GBD 2019 Risk Factor Collaborators 2020). The $0.1° \times 0.1°$ GBD geophysical estimate of global surface-level $PM_{2.5}$ mass used here is an updated version that is derived from multiple satellite retrievals of aerosol optical depth that are combined with gridded predictions of the relationship of annual $PM_{2.5}$ to aerosol optical depth from GEOS-Chem chemical transport model (Hammer et al. 2020) and further calibrated to a recently updated database incorporating available annual average ground monitor observations of $PM_{2.5}$ mass using a spatially varying Bayesian hierarchical model (Shaddick et al. 2018a, 2018b). To further enhance the resolution of the $PM_{2.5}$ estimates, GBD exposure estimates were downscaled in this work to a $0.01° \times 0.01°$ spatial resolution using newly available high-resolution satellite-derived estimates from Hammer and colleagues (2020). The process of spatial downscaling is described in detail in Supplementary Text 10 and in Supplementary Figure 9 of Additional Materials 2. This downscaling process is independent of the model source contributions, maintains the average $PM_{2.5}$ mass concentration from the original GBD product (area average only), and incorporates additional high-resolution spatial information from the Hammer and colleagues (2020) product. An evaluation of the downscaled $PM_{2.5}$ concentrations relative to available annual average surface observations of total $PM_{2.5}$ mass (Additional Materials 2, Figure 1) showed a normalized mean bias of 11% with downscaled estimates exceeding surface observations.

Source- and Fuel-Specific Contributions to the $PM_{2.5}$ Disease Burden

We use methods consistent with the 2019 GBD project and previous studies (e.g., Gu et al. 2018 and Lelieveld et al. 2015), to quantify the total disease burden from six mortality endpoints and two neonatal disorders associated with exposure to annual average outdoor $PM_{2.5}$ mass across the global average, 21 world regions, 204 countries, and 200 subnational areas. First, cause-specific population-attributable fractions for each endpoint are calculated using national-level population-weighted mean $PM_{2.5}$ concentrations from the downscaled GBD exposure estimates and new relative risk curves, derived using a meta regression-Bayesian, regularized, trimmed (MR-BRT) spline from the 2019 GBD project (GBD 2019 Risk Factors Collaborators 2020). The population-attributable fraction reflects the proportional reduction in burden of disease that would occur if exposure to a risk factor, in this case $PM_{2.5}$, is reduced to a theoretical minimum risk exposure level. Following the GBD methodology, the theoretical minimum risk exposure level is a uniform distribution with lower and upper bounds defined by the mean (5.9 µg/m^3) and the fifth percentiles (2.4 µg/m^3) of ambient $PM_{2.5}$ concentrations in cohort studies conducted in North America, reflecting uncertainty in the shape of the concentration–response function at levels below the fifth percentile of these low exposure settings. Details of the input data and methodology used to develop the relative risk curves are provided in the Methods Appendices (pages 79–104) to the 2019 GBD risk factor publication (GBD 2019 Risk Factors

Collaborators 2020) with input data and lookup tables accessible from the Global Health Data Exchange (Global Health Data Exchange 2021). Next, these population-attributable fractions were multiplied by the age- and country-specific baseline mortality data for each disease and summed over all relevant age groups and diseases to obtain the total national-level $PM_{2.5}$ burden associated with exposure to both outdoor and household (indoor) $PM_{2.5}$ mass. The application of age, sex, and location-specific baseline mortality rates — a hallmark of the GBD — accounts for the underlying health status of the population, its size and age structure, which, together with the level of exposure, impacts the absolute amount of mortality attributable to $PM_{2.5}$ exposure. Lastly, contributions from outdoor exposure were separated from indoor household co-exposure by scaling the national-level total $PM_{2.5}$ excess mortality values by country-specific adjustment factors derived from a comparison of national-level burdens with those derived for outdoor exposure only in the 2019 GBD study.

We also applied the fractional source contribution results to GBD $PM_{2.5}$ exposures and attributable burden results for the year 2019 to provide a more contemporary set of results. These results are presented in Supplementary Text 1 of Additional Materials 2. The 2019 $PM_{2.5}$ exposure data are from the 2019 GBD project and are also downscaled following the same approach described above. Additionally, we conducted a sensitivity analysis in which we replaced the GBD relative risk curves with an updated version of the global exposure mortality model (GEMM). As described in more detail in Supplementary Text 2 of Additional Materials 2, the original GEMM was updated to include concentration–response curves for Type 2 diabetes, preterm births, and low birth weights as well as newly available observational studies. In contrast to the GBD, which includes disease-specific epidemiological risk estimates from studies of household air pollution and second-hand smoke exposure, the GEMM is based on studies of nonaccidental mortality and only includes studies of ambient $PM_{2.5}$. Results of this sensitivity analysis are discussed in detail in Supplementary Text 2 of Additional Materials 2.

Analysis Assets

In addition to two peer-reviewed journal articles (McDuffie et al. 2020a, 2021; included with this report as Additional Materials 1 and 2), all input datasets, model source code, analysis scripts, and results associated with the GBD MAPS Global project are made publicly available. Data visualizations have also been developed and are available at *https://costofairpollution.shinyapps.io/gbd_map_global_source_shinyapp/*. Further details about these project assets are provided at the end of this report.

RESULTS SUMMARY

The following sections provide a summary of the main results associated with the GBD MAPS Global project. Additional details about the results and further discussion, including more detailed comparisons with past studies are provided in the Additional Materials to this report.

GLOBAL EMISSION DATASET: DOMINANT SOURCES AND RECENT TRENDS

Global anthropogenic emission inventories remain vital for understanding the fate and transport of atmospheric pollution, as well as the resulting impacts on the environment, human health, and society. Rapid changes in today's society require that these inventories provide contemporary estimates of multiple atmospheric pollutants with both source sector and fuel-type information to understand and effectively mitigate future impacts. To fill this need, we updated the open-source CEDS (Hoesly et al. 2019) to develop a new global emission inventory, $CEDS_{GBD\ MAPS}$. This inventory includes emissions of seven key atmospheric pollutants (NO_x, carbon monoxide [CO], sulfur dioxide [SO_2], NH_3, nonmethane volatile organic compounds [NMVOCs], black carbon [BC], and organic carbon [OC]) over the time period from 1970–2017 and reports annual country-total emissions as a function of 15 sectors (agriculture, energy generation, industrial processes, road transport, non-road transport, residential, commercial, and other sectors (RCO-Other), solvents, waste, international shipping, agricultural waste burning, other fires, AFCID, and windblown dust) and four fuel categories (total coal, solid biofuel, the sum of liquid fuels and natural gas combustion, and remaining process-level emissions). The $CEDS_{GBD\ MAPS}$ inventory additionally includes global gridded (0.5° × 0.5°) emission fluxes with monthly time resolution for each compound, sector, and fuel type to facilitate their use in earth system models.

$CEDS_{GBD\ MAPS}$ utilizes updated activity data, updates to the core CEDS default calibration procedure, and modifications to the final procedures for emissions gridding and aggregation to retain sector- and fuel-specific information. These updates extend previous CEDS releases (Hoesly et al. 2018) from 2014 to 2017 and improve the overall agreement between CEDS and two widely used global bottom-up emission inventories (EDGAR v4.3.2 and GAINS) (Crippa et al. 2018; Klimont et al. 2017). The $CEDS_{GBD\ MAPS}$ inventory provides the most contemporary global emission estimates to date for seven key atmospheric pollutants and is the first to provide global estimates as a function of multiple fuel types across multiple source sectors.

Temporal emission trends were summarized by sector (Figure 2), fuel (Figure 3), and country (Figure 4). Dominant sources of global NO_x and SO_2 emissions in 2017 include the combustion of oil, gas, and coal in the energy and industry sectors, as well as on-road transportation and international shipping for NO_x. Dominant sources of global CO emissions in 2017 include on-road transportation and residential biofuel combustion. Dominant global sources of carbonaceous aerosol

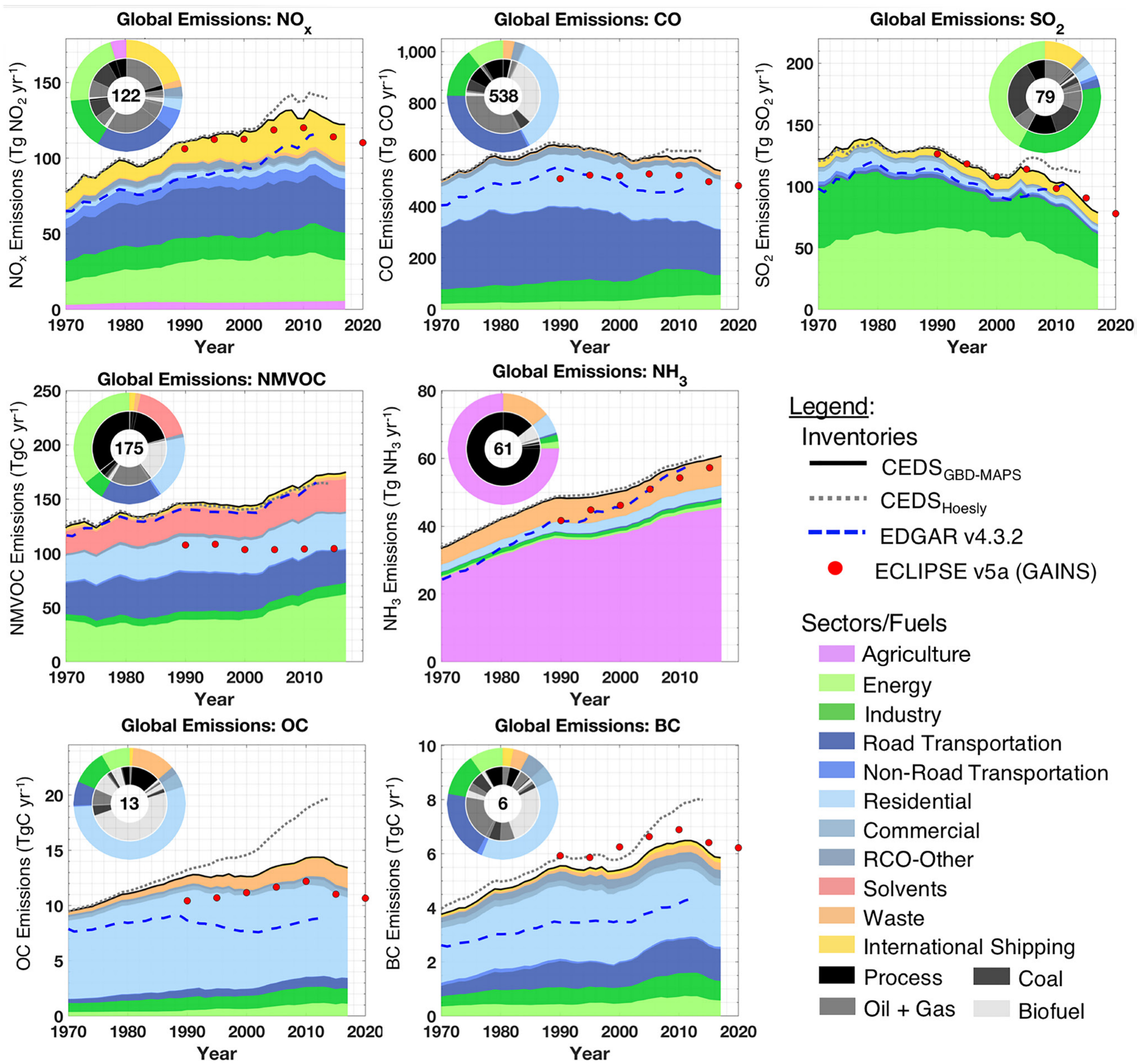

Figure 2. Time series of global annual emissions of NO_x (as NO_2), CO, SO_2, NMVOCs, NH_3, BC, and OC for all sectors and fuel types. Solid black lines are the $CEDS_{GBD\text{-}MAPS}$ inventory, with fractional sector contributions indicated by colors. Dashed gray lines are the original $CEDS_{Hoesly}$ inventory. Dashed blue lines are the EDGAR v4.3.2 global inventory. Red dots are ECLIPSE v5a baseline "current legislation" emissions with data in 2015 and 2020 from GAINS CLE projections. All inventories include international shipping but exclude aircraft emissions. Pie chart inserts show fractional contributions of emission sectors to total 2017 emissions (outer) and fuel type contributions to each sector (inner). Emission totals for 2017 (units: TgC yr^{-1} for NMVOCs, OC, and BC) are given inside each pie chart.

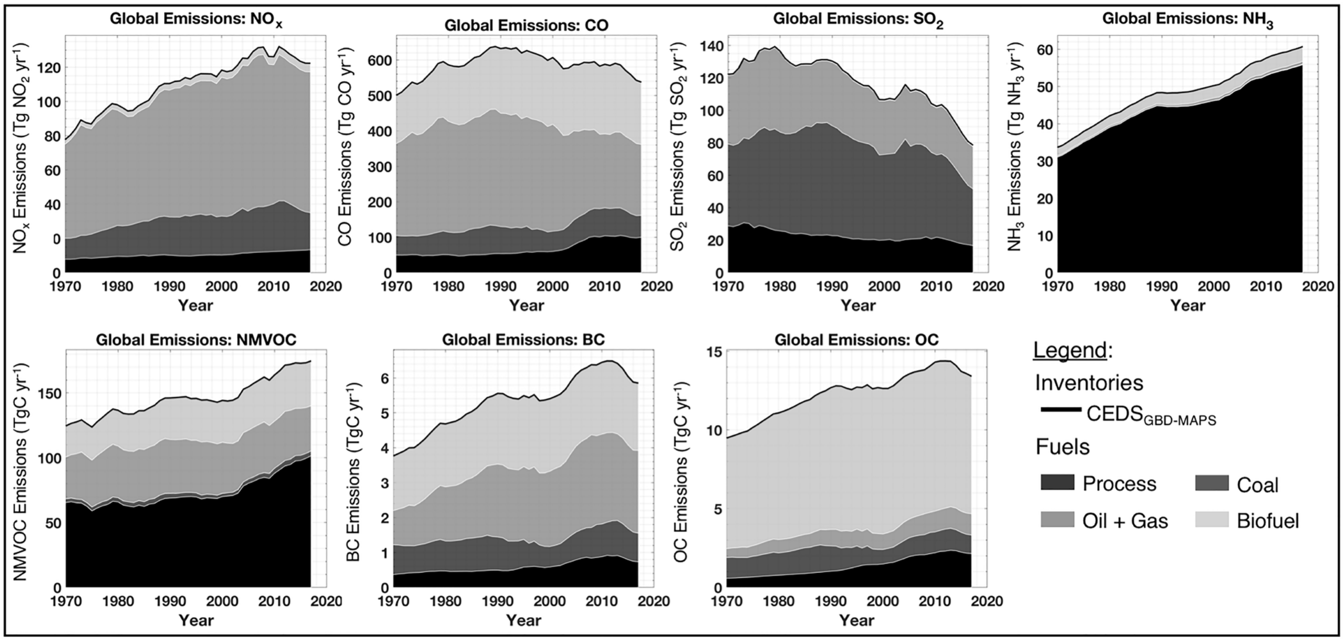

Figure 3. Time series of global annual emissions of NO_x, CO, SO_2, NH_3, NMVOCs, BC, and OC for all sectors, colored by fuel group.

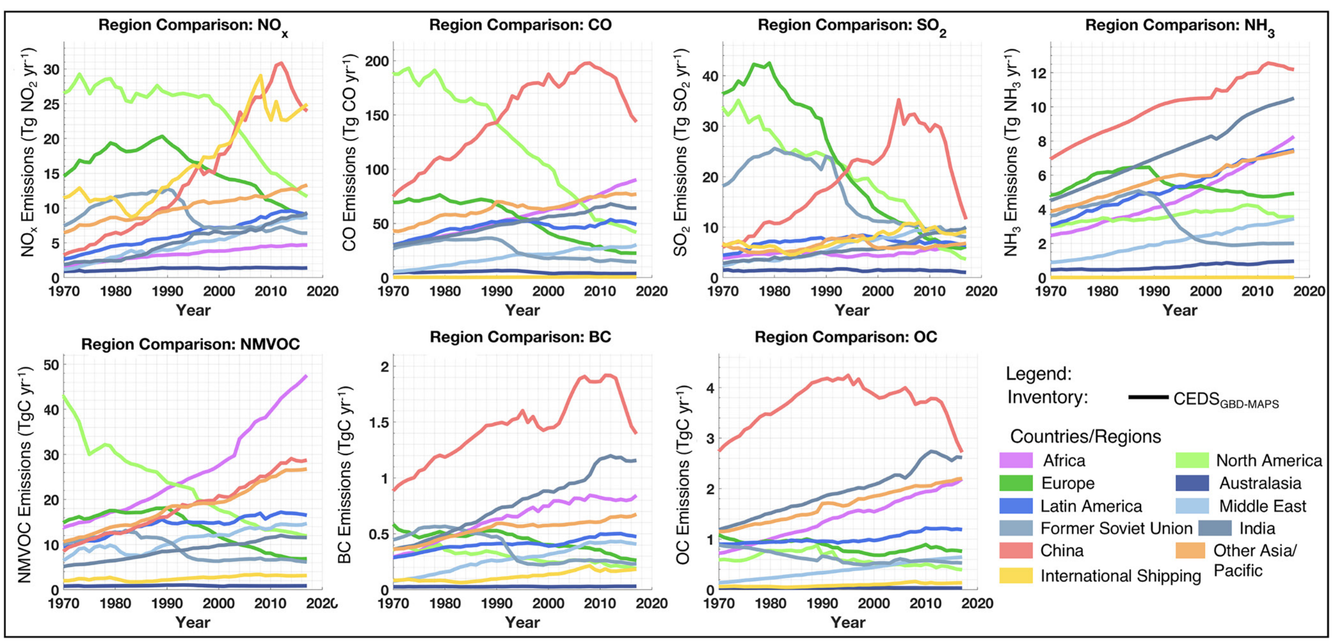

Figure 4. Time series of global annual $CEDS_{GBD\text{-}MAPS}$ emissions of NO_x, CO, SO_2, NH_3, NMVOCs, BC, and OC for all sectors and fuel types (excluding aircraft emissions), split into ten countries/regions.

in 2017 include residential biofuel combustion, on-road transportation (BC only), as well as emissions from waste. Global emissions of NO_x, SO_2, CO, BC, and OC all peaked in 2012 or earlier (Figure 4), with more recent emission reductions driven by large changes in emissions from China, North America, and Europe. As emissions in North America, Europe, and China continue to decrease, global emissions of NO_x, CO, SO_2, BC, and OC will increasingly reflect emissions in rapidly growing regions such as India, Africa, and countries in Asia and the Middle East. In contrast, global emissions of NH_3 and NMVOCs continuously increased between 1970 and 2017, with agriculture serving as a major source of global NH_3 emissions and solvent use, energy, residential, and the on-road transport sectors serving as major sources of global NMVOCs.

The $CEDS_{GBD\ MAPS}$ source code is publicly available online through GitHub at *https://github.com/emcduffie/CEDS/tree/CEDS_GBD MAPS*. The $CEDS_{GBD\ MAPS}$ emission inventory dataset (both annual country-total and global gridded files) is publicly available and registered under *https://doi.org/10.5281/zenodo.3754964* (McDuffie et al. 2020b).

AMBIENT $PM_{2.5}$ MASS AND ATTRIBUTABLE MORTALITY: SECTOR- AND FUEL-SPECIFIC CONTRIBUTIONS

Globally, the estimated population-weighted mean $PM_{2.5}$ mass concentration in 2017 was 41.7 μg/m^3. In this analysis, 91% of the world's population lived in areas with annual average concentrations higher than the World Health Organization (WHO) guideline of 10 μg/m^3. Ambient $PM_{2.5}$ exposure estimates were largest in countries throughout Asia, the Middle East, and Africa. The top left panel of Figure 5 shows that the integration of these $PM_{2.5}$ exposure estimates with the concentration–response relationships from the 2019 GBD resulted in an estimated 3.83 million attributable deaths worldwide in 2017 (95% UI: 2.72–4.97 million). To compare with the most recent GBD (2019) results, both exposure and burden estimates were additionally calculated for the year 2019 with updated 2019 exposure and baseline burden estimates (Supplementary Text 1, Additional Materials 2). In 2019, there was no change in the global population-weighted mean concentration relative to 2017, but due to changes in population characteristics (age, number, and location) in 2019 there were an estimated 4.14 million attributable deaths (95% UI: 3.45–4.80 million) (GBD 2019 Risk Factor Collaborators 2020). Attributable deaths in 2017 were primarily from ischemic heart disease and stroke (63%; top left, "disease" pie chart in Figure 5), followed by chronic obstructive pulmonary disease, lung cancer, lower respiratory infections, and Type 2 diabetes. In addition, there were a total of 2.07 million (95% UI: 0.02–5.02 million) attributable incidences of neonatal disorders (low birth weight and preterm births) worldwide (not shown). National-level results are also provided in the center panel of Figure 5. The largest numbers of attributable deaths occurred in China (~1.4 million [95% UI: 1.05–1.70 million]) and India (0.87 million [95% UI: 0.6–1.04 million]), together accounting for 58% of the global total ambient $PM_{2.5}$ mortality burden. The larger burden in China, despite a lower national $PM_{2.5}$ exposure level reflects differences in the population age distribution and the relative baseline mortality rates associated with each disease in each country (Supplementary Figure 1, Additional Materials 2). Figure 5 also shows a large $PM_{2.5}$ disease burden in countries such as the United States where country-level population-weighted mean $PM_{2.5}$ exposure levels are below the WHO interim target 4 — which is equal to the 2005 WHO Guideline — highlighting the risks associated with $PM_{2.5}$ exposures below 10 μg/m^3 but above the GBD counterfactual (theoretical minimum risk exposure level) distribution. Disease burden estimates calculated using the updated GEMM (Burnett et al. 2018) resulted in similar fractional disease contributions (Supplementary Text 2, Additional Materials 2), but a higher absolute number of attributable deaths (6.2 million deaths).

Globally, a large fraction of the $PM_{2.5}$ disease burden was attributable to residential (19.2%), industry (11.7%), and energy (10.2%) sector emissions, corresponding to 0.74 million (95% UI: 0.52–0.95 million), 0.45 million (95% UI: 0.32–0.58 million), and 0.39 million (95% UI: 0.28–0.51 million) deaths, respectively (Figure 5). Nearly 1.05 million (95% UI: 0.74–1.36 million) or 27.3% of total deaths attributable to $PM_{2.5}$ were associated with $PM_{2.5}$ mass formed from the combustion of fossil fuels (coal = 14.1%, oil and natural gas = 13.2%), with an additional 20% or nearly 0.77 million (95% UI: 0.54–0.99 million) deaths attributable to solid biofuel combustion, primarily for residential household heating and cooking. Following residential combustion, windblown dust was the second largest sectoral source of $PM_{2.5}$ mass at the global scale (16.1%), driven by large contributions throughout Africa and the Middle East. Windblown dust was estimated to lead to 0.62 million (95% UI: 0.44–0.80 million) attributable deaths worldwide under the assumption of equal toxicity of all $PM_{2.5}$ sources and components (see Discussion). Other $PM_{2.5}$ sources, such as on-road transportation, noncombustion agriculture, and anthropogenic dust, had relatively smaller global fractional contributions of between 6.0% and 9.3% (0.23 million [95% UI: 0.16–0.30 million] to 0.36 million [95% UI: 0.25–0.46 million] deaths). Additional source sectors each contributed to less than 5.2% at the global scale.

Although global contributions provide a snapshot of globally important sectors and fuel types, regional and country-level contributions provide additional insight for national-level strategies to more effectively reduce the impact of $PM_{2.5}$ on local mortality. As an example, we present in Figure 5 the relative contributions for nine countries with the largest numbers of premature deaths associated with long-term $PM_{2.5}$ exposure determined using the GBD 2019 concentration–response functions. Note that these countries differ from the countries with the highest population-weighted mean $PM_{2.5}$ exposures, highlighting the importance of demographic factors and

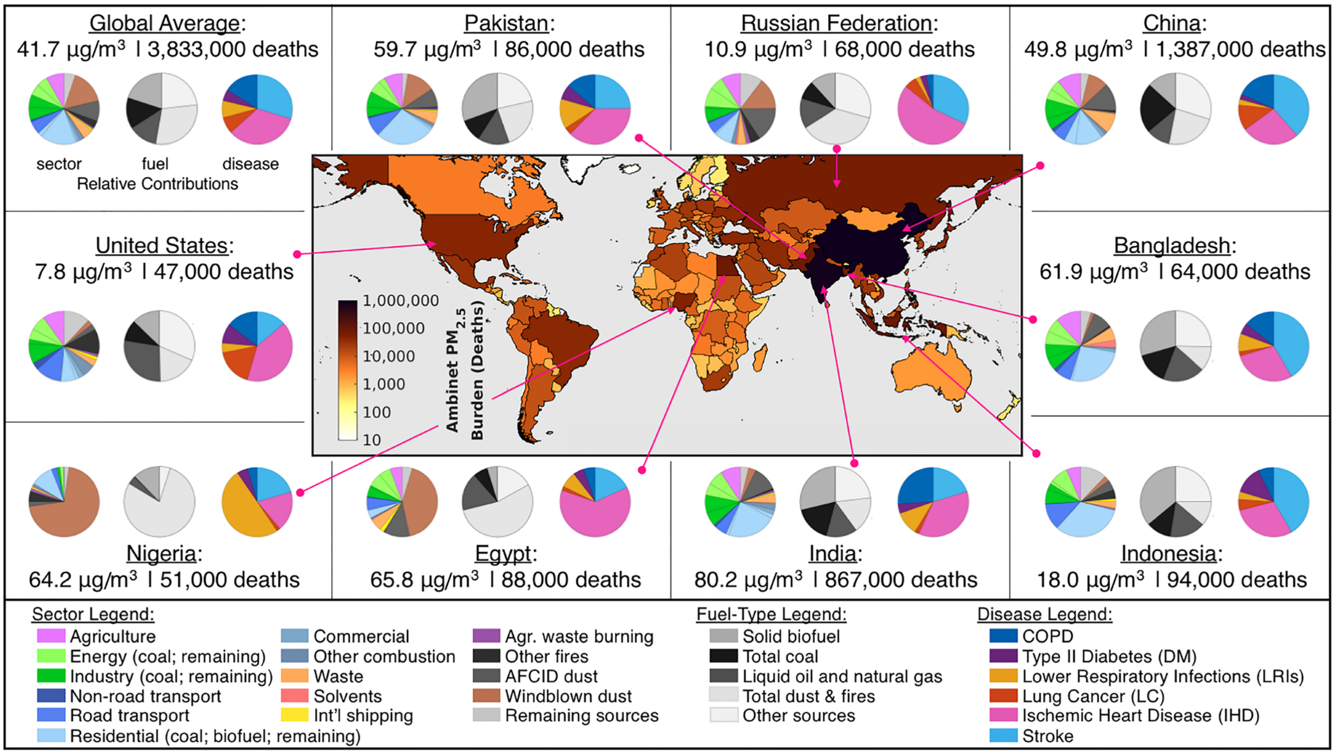

Figure 5. Ambient $PM_{2.5}$ burden, population-weighted mean $PM_{2.5}$ mass and fractional source sector, fuel, and disease contributions globally and for the nine countries with the largest burden. Map: National-level outdoor $PM_{2.5}$ disease burden in 2017 (from 2019 GBD concentration–response function). **Panels:** Annual population-weighted mean $PM_{2.5}$ exposure levels and attributable deaths (rounded to the nearest 1,000) for each country/region. **Pie charts in each panel:** (**Left**) fractional sectoral source contributions. "Other fires" include deforestation, boreal forest, peat, savannah, and temperate forest fires. Remaining sectoral sources include volcanic SO_2, lightning NO_x, biogenic soil NO, and oceanic and biogenic emissions (Table 1). Energy and industry sectors show separate contributions from coal use (lighter green); the residential sector separates contributions from coal and solid biofuel (two light blue wedges). (**Middle**) fuel-type contributions. "Total dust & fires" is the sum of windblown dust and AFCID dust (anthropogenic fugitive, combustion, and industrial dust), agricultural waste burning, and other fires. Other sources are noncombustion or uncategorized combustion sources (waste incineration, agriculture, solvents, biogenic secondary organic aerosols, etc.). (**Right**) relative disease contributions.

disease-specific baseline mortality estimates in calculating the total burden of disease. In most of these countries, the majority of attributable deaths were from stroke and ischemic heart disease. However, in Nigeria childhood lower respiratory infections were the largest cause of mortality attributable to ambient $PM_{2.5}$ exposure. "Sector" pie charts in Figure 5 indicate variation in source contributions between countries. For example, residential contributions ranged from 4.0% in Egypt to 33.1% in Indonesia and the sum of energy and industry emissions ranged from 3.2% in Nigeria to 27.3% in India. Windblown dust was the most variable sector in these countries, ranging from a 1.5% contribution in Bangladesh to 70.6% in Nigeria. Of the three anthropogenic fuel categories (coal, oil and natural gas, and solid biofuel), coal was the largest source of $PM_{2.5}$ mass and attributable mortality in China (22.7%; 315,000 [95% UI: 239,000–385,000] deaths), liquid oil and natural gas was the largest (13.7%–27.9%; 9,000 [95% UI: 4,000–16,000] to 13,000 [95% UI: 4,500–24,000] deaths) contributing fuel category in Egypt, Russia, and the United States, and solid biofuel combustion was the largest category (12.3%–36.0%; 6,000 [95% UI: 4,500–8,000] to 250,000 [95% UI: 196,500–300,000] deaths) in the remaining five countries.

Relative source contributions for 21 world regions and the 20 countries with the largest numbers of $PM_{2.5}$ attributable deaths are also provided for more holistic global comparisons (Figure 6). Similar to the sectoral contributions, regions with the larger numbers of attributable $PM_{2.5}$ deaths generally had higher relative contributions from fuel-combustion sources compared to countries where other sources dominated. Exceptions include Western and Central Sub-Saharan Africa, where windblown dust and fires had the largest combined contributions (81.0% and 68.4%). To remove the effects of population size, we further analyzed the premature deaths per 100,000 people attributable to population-weighted mean $PM_{2.5}$ mass from different sources. Figure 7 shows a spatial pattern of attributable death rates from major sources that was

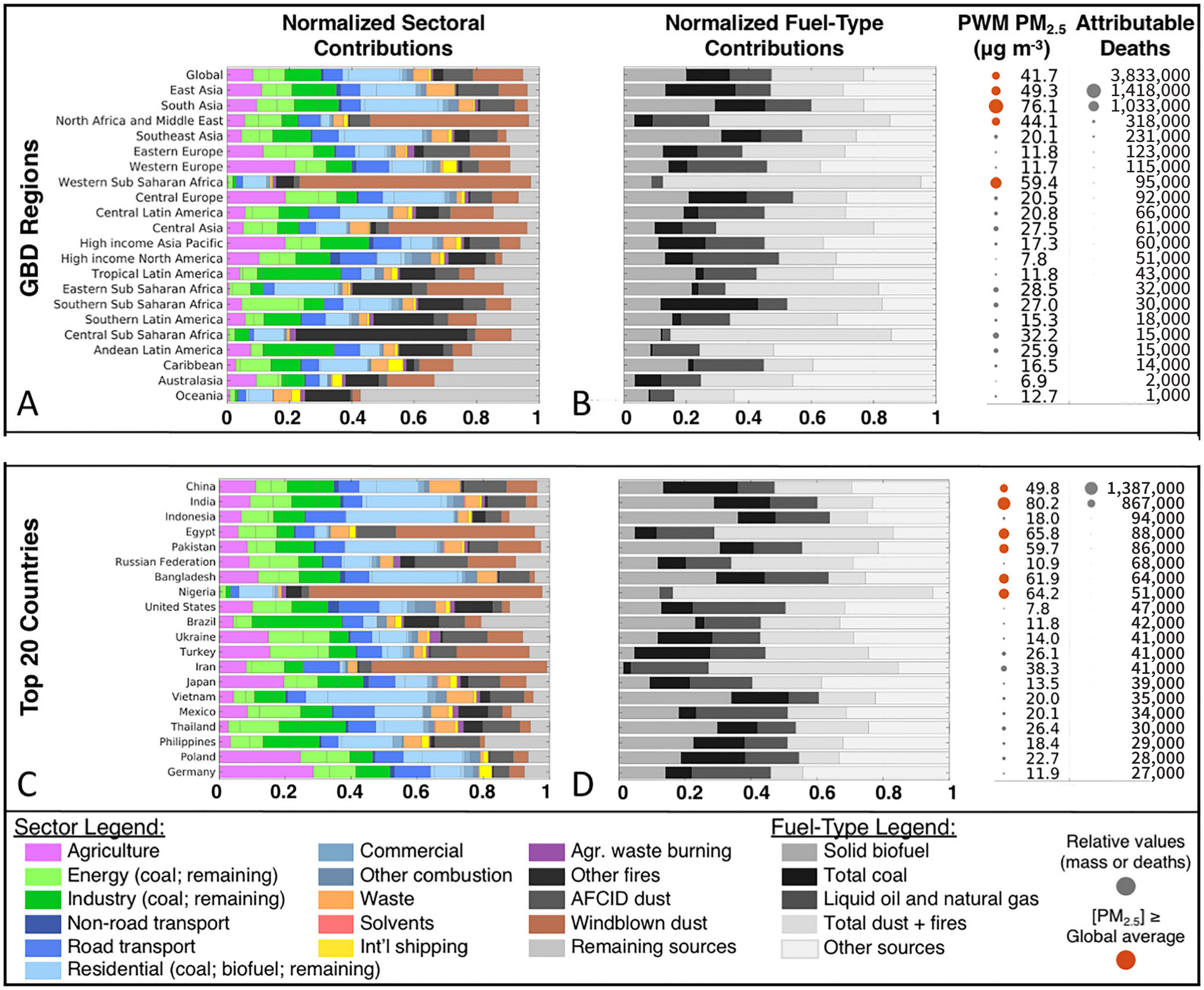

Figure 6. Relative source and fuel-type contributions to population-weighted mean ambient $PM_{2.5}$ mass and attributable deaths. (**A** and **C**): Normalized sectoral source contributions for the global average and 21 world regions (**A**) and the 20 countries with the most attributable $PM_{2.5}$ deaths (**C**), sorted by decreasing number of outdoor $PM_{2.5}$-associated deaths in 2017 (2019 GBD concentration–response functions, rounded to the nearest 1,000). (**B** and **D**): Normalized contributions from the combustion of three fuel types and remaining $PM_{2.5}$ sources. Sector categories are the same as Figure 5. To the right of **B** and **D** are annual average population-weighted mean $PM_{2.5}$ concentrations and associated attributable deaths for each region/country, with relative amounts illustrated by relative dot sizes. Concentrations above or equal to the global average are colored red.

distinct from the patterns of absolute numbers of attributable deaths. Nepal experienced the highest death per 100,000 people attributable to population-weighted mean $PM_{2.5}$ mass from the residential sector. The industry sector contributed to the largest attributable deaths per 100,000 people in the Democratic People's Republic of Korea, China, and India. In contrast, the energy sector was a leading contributor to deaths per 100,000 people in countries in southeastern Europe, such as North Macedonia, Serbia, and Bosnia and Herzegovina.

Figure 8a additionally highlights national variability in the dominant type of combustion fuel. For example, coal combustion was the dominant source of $PM_{2.5}$ mass and attributable deaths in 20 countries, including China, South Africa, Eswatini, and countries throughout Central and Eastern Europe, despite a recent decline in global coal emissions (McDuffie et al. 2020a). At the national level, South Africa and neighboring Eswatini both had the largest relative coal contributions of all countries at more than 36.5% each

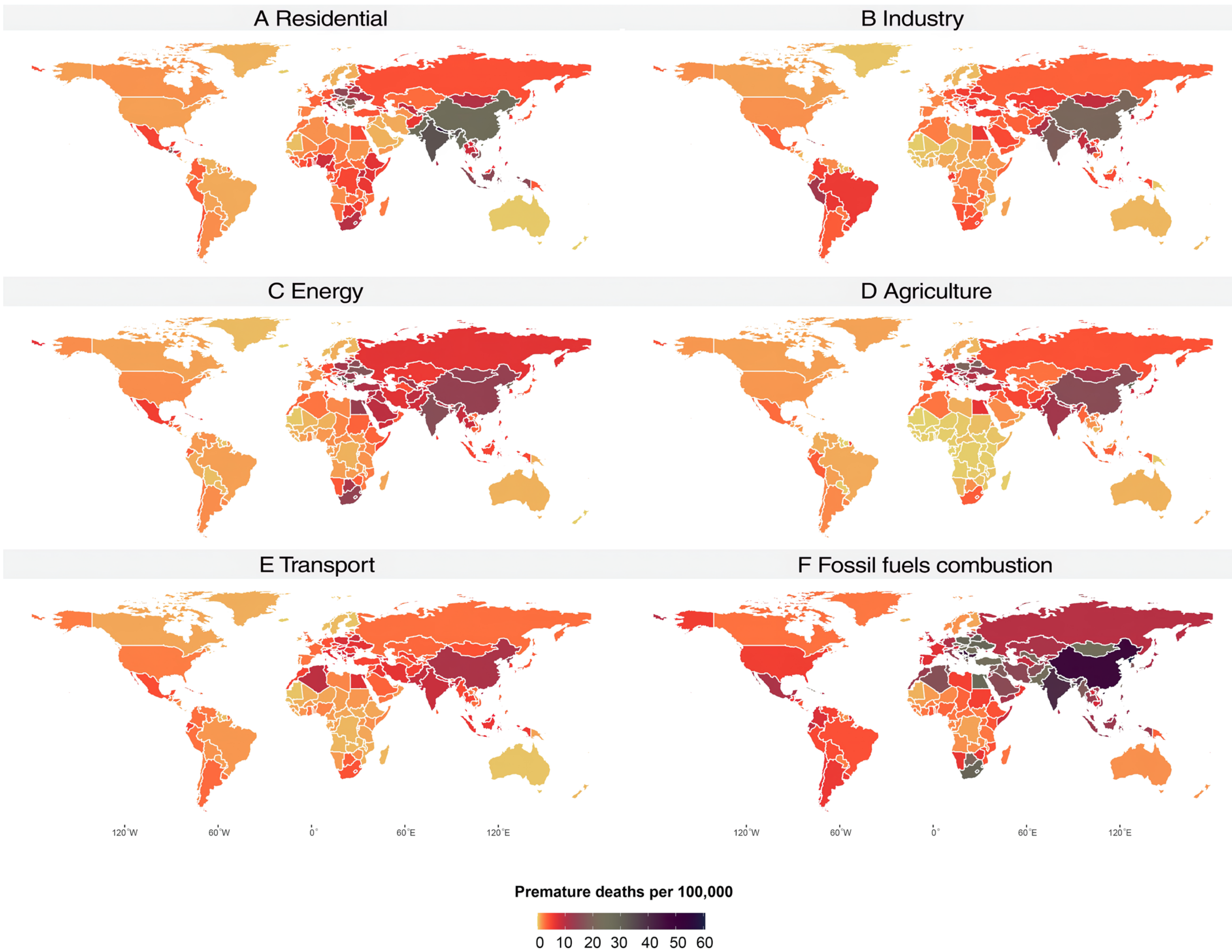

Figure 7. Premature deaths per 100,000 attributable to population-weighted mean ambient $PM_{2.5}$ mass from selected sectors in 2017. (A–E) The rate of deaths per 100,000 from residential, industry, energy, agriculture and transport (on road and nonroad) sectors in each country, respectively. (**F**) Deaths per 100,000 from all fossil fuel combustion (total coal plus liquid oil and natural gas) in each country.

(~9,000 [95% UI: 6,000–12,500] attributable deaths in total). Countries with the lowest relative coal contributions (<0.1%) included those in other regions of Africa, as well as small island nations. Oil and natural gas combustion typically dominated in more developed regions throughout North America, Australasia, and Western Europe, as well as parts of North Africa, the Middle East, Central Asia, and Eastern Europe. Of all world regions, North America and Western Europe had the largest relative oil and natural gas contributions of ~25% each (43,000 [95% UI: 19,500–72,500] deaths total), while the lowest was in Central Sub-Saharan Africa at 2.5% (less than 1,000 deaths total). In contrast, solid biofuel combustion contributions (largely from the residential sector) were largest in South and Southeast Asia at between 29.2% and 31.2% each (373,500 [95% UI: 279,500–465,000] deaths total for both regions combined), even though biofuel was the largest contributor of the three fuel types in 76 countries including those in Central, Eastern, and Western Sub-Saharan Africa; Central Europe; and Tropical Latin America. At the country level, biofuel use contributed to at least 40% of $PM_{2.5}$ mass and attributable deaths in Guatemala, Nepal, and Rwanda (9,500 [95% UI: 6,500–11,000] total deaths). The lowest biofuel use contributions (0.2%) to $PM_{2.5}$ mass were in small island nations such as the Cook Islands and Niue.

Figure 8b through 8d also provides an assessment of three detailed emission reduction strategies that test policy-relevant scenarios of select fuel and sector combinations. These panels show the fractional contributions of $PM_{2.5}$ mass and attributable mortality avoidable by eliminating the use of (Figure 8b) residential biofuel, (Figure 8c) industrial sector coal combustion, and (Figure 8d) energy sector coal combustion. Figure 8a reveals that while coal is the dominant fuel type in

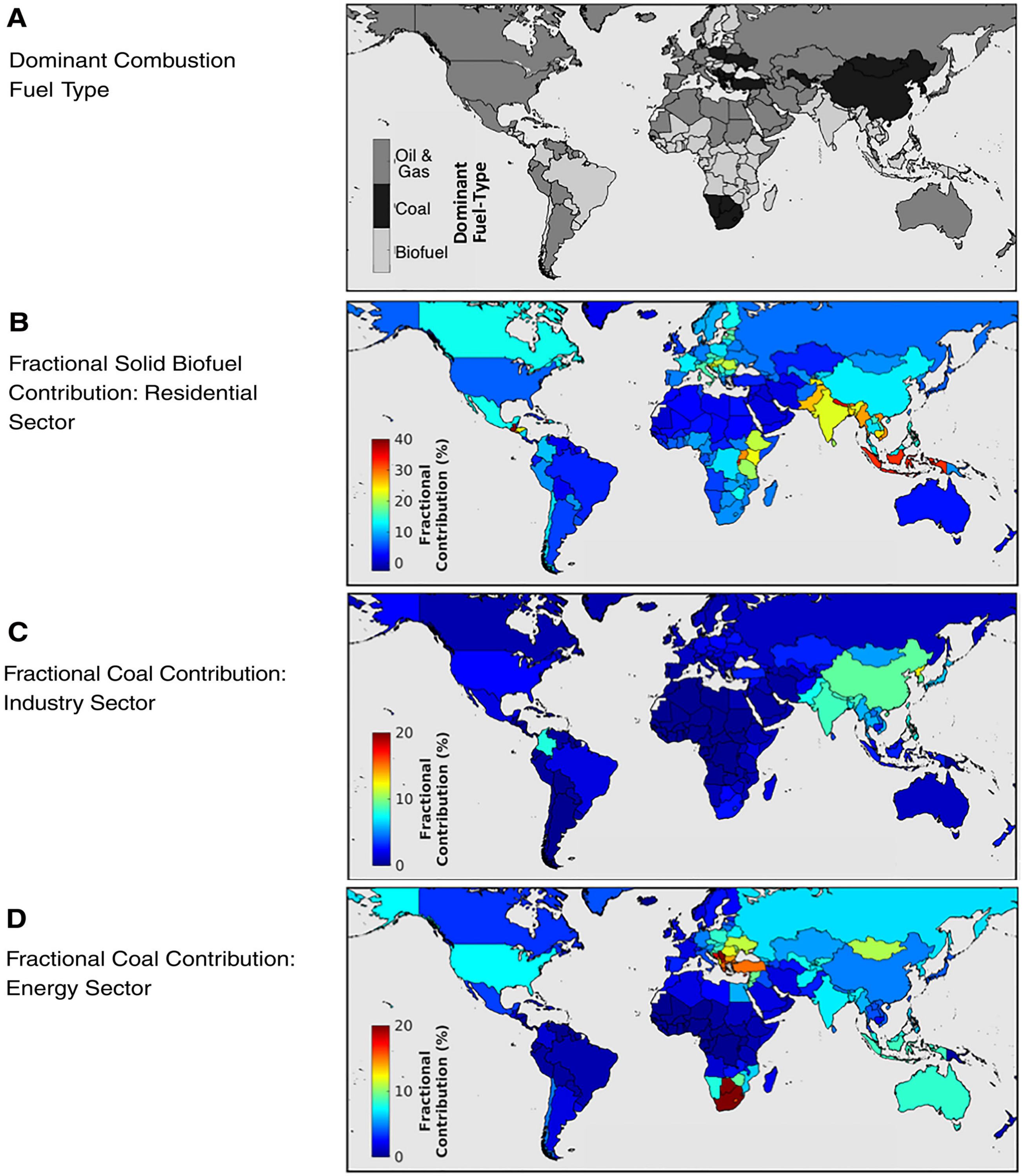

Figure 8. Fractional contributions from select combustion fuel types and sectors in 2017. (**A**) The combustion fuel type with the largest relative contribution to $PM_{2.5}$ mass and mortality in each country. (**B–D**) The fractional contributions to $PM_{2.5}$ mass and attributable mortality from solid biofuel combustion in the residential sector (**B**), coal combustion in the industry sector (**C**), and coal combustion in the energy sector (**D**). Note the color scale change between panels **B** and **C–D**.

both China and South Africa, coal from the energy sector contributes (Figure 8c and 8d) to a greater fraction of attributable deaths (20.5%) in South Africa than does coal from the industry sector (2.7%), while the opposite is true for China (4.7% energy sector coal, 9.1% industry sector coal). Similarly, in countries throughout Central and Eastern Europe where coal is the dominant contributing fuel, the targeted reduction of coal use in the energy sector may lead to immediately larger air quality benefits than targeting reductions in coal use in the industrial sector (Figure 8c and 8d). For residential biofuel use, the relative contributions are generally largest in regions where residential emissions are the dominant source sector (Figure 6a). At the national scale, the combustion of solid biofuel for home heating and cooking contributed up to 46.1% of the total $PM_{2.5}$ mass and attributable deaths in Guatemala. These examples highlight the potential air quality benefits from specific and achievable reduction strategies. Detailed comparisons across countries in Figure 8 can further identify opportunities with the greatest potential health gains and identify countries that have successfully managed reductions from these select sources.

DISCUSSION

We provided the most contemporary and comprehensive evaluation to date of attributable deaths from individual $PM_{2.5}$ source sectors and fuel types across global, regional, national, and subnational areas (source contributions only). This is also the first study to assess the global burden associated with the combustion of individual fossil fuels (coal, oil, and natural gas) and solid biofuels, as well as with the contributions of fossil fuels in dominant sectors such as energy generation, industry, and residential energy. This work is also the first to quantify the global $PM_{2.5}$ disease burden associated with the separate contributions from residential and commercial energy and on-road and nonroad transportation, as well as those contributions of relatively smaller sectors such as solvent use. Overall, we found that the residential, energy, and industrial sectors were globally dominant sources of $PM_{2.5}$ mass and attributable mortality. In general, the largest contributions from anthropogenic fuel combustion emissions occurred in regions with the highest absolute numbers of deaths attributable to ambient $PM_{2.5}$, although variations within national and subnational results demonstrate the potential health benefits from air quality strategies targeting specific sector and fuel combinations.

FUEL CONTRIBUTIONS

This is the first study to our knowledge that quantifies the fractional contributions of multiple combustible fuel types to the production of $PM_{2.5}$ at the national level for all countries. Previous three-dimensional modeling studies using similar methodologies have either combined all anthropogenic sources for global or regional scale analyses (Lacey et al. 2017; Lelieveld et al. 2019; Marais et al. 2019) or reported contributions from single or aggregate fuel types (Chafe et al. 2014), typically for select countries such as China and India (GBD MAPS Working Group 2016, 2018; Wu et al. 2019). Previous studies also provided estimates of years prior to 2017, which may not adequately capture recent trends in $PM_{2.5}$ chemical precursor emissions, such as recent reductions in China (Zheng et al. 2018).

In the year 2017, more than 1 million (27.3%) premature deaths could have been avoided by eliminating $PM_{2.5}$ mass formed from the emissions of fossil fuel combustion (total coal and oil and natural gas), adding to the growing evidence of the public health benefits from decarbonization strategies (Shindell and Smith 2019). Total coal contributions (14.1%) were slightly larger than those from oil and natural gas (13.2%) on the global scale, while the relative balance between these two fuel types varied at the regional, country (Figures 5 and 6), and subnational levels (Additional Materials 2). Global emissions of $PM_{2.5}$ precursors from fossil fuels have generally decreased in recent years, largely driven by reductions after 2010 in China (up to ~60% reductions), as well more moderate emission reductions in North America and Europe (Figures 7 and 8 in McDuffie et al. 2020a, included with this report as Additional Materials 1).

Differences between our estimates and previous analyses may arise from methodological differences such as emission inventories, emission sectoral definitions, chemical transport models, annual exposure estimates and their spatial resolution, as well as baseline burden data and concentration–response functions. Due to temporal trends, differences may also reflect these differing methodologies or real temporal changes in emissions and chemistry. The global fractional contribution from fossil fuels (27.3%) in this work was lower than a previous global estimate of 41% for the year 2015 from Lelieveld and colleagues (2019). Observed differences are largely driven by countries that have experienced recent reductions in fossil fuel emissions (McDuffie et al. 2020a) such as China, the United States, and Western European countries, including Germany and Italy. Absolute contributions in this work were also lower than recent estimates of fossil-fuel attributable mortality derived using different concentration–response functions (Butt et al. 2016). Compared with two previous national-level studies, fractional coal contributions in 2017 were also 17% smaller than a 2013 estimate for China (Shaddick et al. 2018a), but generally consistent to within 1% for a 2015 estimate for India (Shaddick et al. 2018b) (Supplementary Text 6, Additional Materials 2). Emission inputs suggest that $PM_{2.5}$ precursor emissions (e.g., SO_2) from coal combustion have decreased by up to 60% between 2013 and 2017 in China, while these same emission sources in India have increased by up to 7% between 2015 and 2017 (McDuffie et al. 2020a). Fossil fuel contributions in our analysis may also be lower limits as some subsectoral emission categories, such as flaring and fossil fuel fires, were not assigned to a fuel category in the emissions dataset (McDuffie et al. 2020a), but rather were included in the "other sources" category in this analysis (Supplementary Text 5, Additional Materials 2). Further, fossil fuel combustion emissions of noncarbonaceous primary PM were not included in these estimates.

The use of solid biofuel across all sectors in 2017 contributed to an additional 767,000 (95% UI: 543,000–994,500) attributable deaths worldwide (20%), with this source in India and China again responsible for roughly 11% of the global $PM_{2.5}$ disease burden. Solid biofuel emissions in countries throughout South and Southeast Asia, as well as Central and Western Sub-Saharan Africa were largely associated with residential solid biofuel use for household heating and cooking (Figure 8b). Large fractional contributions of this source were consistent to within 4% of the only previous global estimate (Holmes et al. 2014). Results in 2017 were also consistent to within 3% of two previous national-level estimates of fractional $PM_{2.5}$ disease burden contributions from residential heating and cooking in China in 2013 (Shaddick et al. 2018a) and in India in 2015 (Shaddick et al. 2018b) (Supplementary Text 6, Additional Materials 2). Although emissions from biofuel combustion have recently decreased in China, other world regions are experiencing a simultaneous increase (McDuffie et al. 2020a), highlighting the continued importance of residential solid biofuel emissions to future air quality improvement strategies and the importance of estimates at different spatial scales. Additional considerations of net air quality benefits will also be important in regions where a transition from residential solid biofuel use to fossil fuel energy sources may lead to immediate indoor and outdoor air quality improvements and health benefits (Silva et al. 2016), while at the same time increasing the relative fossil fuel contributions.

SECTORAL CONTRIBUTIONS

We find that relative contributions from major contributing sectors (Figure 5) are generally consistent with previous global and national-level studies, though differences again may arise due to real temporal changes or differences in input datasets, chemical transport models, or sectoral definitions used.

Comparisons with previous national-level studies are more variable, with more detailed comparisons provided in Supplementary Text 6 in Additional Materials 2. At the global scale, the residential energy sector was the single largest global source in 2017, with a relative contribution (~20%) similar to previous global estimates that ranged between 8% to 31% in 2000–2014 (Butt et al. 2016; Lelieveld et al. 2015; Silva et al. 2016; Weagle et al. 2018). At the national level, previous studies for India estimated residential contributions between 27% and 50% in 2010 and 2015 (GBD MAPS Working Group 2018; Lelieveld et al. 2015), while contributions here in 2017 were comparable but slightly lower (between 23% and 35%) when comparable subsectors (e.g., residential and waste) were considered. In China, previous residential estimates ranged from 25% to 32% in 2010 (Gu et al. 2018; Lelieveld et al. 2015) and ~19% to 22% in 2013 (GBD MAPS Working Group 2016; Hu et al. 2017), both consistent with 26% here in 2017. Emission estimates from the residential sector, however, are particularly uncertain in emission inventories compared with those from other large anthropogenic emission sources (Bond et al. 2004; Butt et al. 2016; Crippa et al. 2019; McDuffie et al. 2020a).

Contributions from the energy and industry sectors were also dominant anthropogenic sources in 2017, contributing to 10.2% and 11.7%, respectively, of the global population-weighted mean $PM_{2.5}$ mass. These sectors have been studied relatively extensively in past work compared with other $PM_{2.5}$ sources. The total magnitude of 22% of these combined sources was in the range of previous global estimates of 21% and 33% in 2010 and 2014, respectively (Lelieveld et al. 2015; Weagle et al. 2018).

Global estimates for dust, agriculture, transportation, and fires were generally consistent or slightly lower than previous global estimates, with variable levels of agreement with previous national-level results. For example, estimates for total dust contributions in two previous global studies were between 18% and 24% (Lelieveld et al. 2015; Weagle et al. 2018), which were consistent with the 25% global contribution from total dust (windblown and anthropogenic) reported by us. Previous national-level fractional dust estimates, however, were much smaller for North Africa, the Middle East (Giannadaki et al. 2014), and China (Hu et al. 2017), and were larger in India (GBD MAPS Working Group 2018) than the respective estimates of dust contributions in the year 2017 from the current study. In addition, previous studies have also shown that reductions in agricultural NH_3 emissions will serve as an effective control of ambient $PM_{2.5}$ mass concentrations at both regional (Guo et al. 2018; Pozzer et al. 2017) and global scales (Lee et al. 2015; Lelieveld et al. 2015; Pozzer et al. 2017; Weagle et al. 2018). In other studies, global contributions from the transportation sector ranged from 5% to 12% between years 2005 and 2015 (Anenberg et al. 2019; Lelieveld et al. 2015; Silva et al. 2016; Weagle et al. 2018), consistent with our results of 7.6%. In 2017, the global total fire contribution (4.1%) was also consistent with two previous estimates in 2010 and 2014 (Lelieveld et al. 2015; Weagle et al. 2018) though this source showed a large amount of regional variability.

Lastly, our study is unique in that we also present results across multiple spatial scales for relatively smaller $PM_{2.5}$ sources such as waste, solvent use, and international shipping. These sources have not been extensively studied but are important to consider as they can contribute significantly to national and subnational $PM_{2.5}$ variation (e.g., 18% contribution from waste in Sri Lanka and 16% contribution from international shipping in Ireland).

SOURCES OF UNCERTAINTY AND LIMITATIONS

Similar to similar previous studies, fractional and absolute source contributions to population-weighted mean $PM_{2.5}$ mass and the attributable disease burden are subject to uncertainties in the emissions datasets, $PM_{2.5}$ exposure estimates, three-dimensional chemical-transport model, national-level baseline mortality estimates, and the disease-specific 2019 GBD concentration–response functions. Following methods from previous similar studies (Breider et al. 2017; Pozzer et al. 2017; Riddick et al. 2012), the 95% UI of the 2017 $PM_{2.5}$ disease burden is derived from uncertainties in the 2019 GBD concentration–response functions, resulting in a range of 2.72 million to 4.97 million global attributable deaths. An additional sensitivity study is presented in Supplementary Text 7 of Additional Materials 2 to test the impact of uncertainties associated with the baseline mortality data, which for the majority of world regions resulted in smaller uncertainty bounds than those associated with concentration–response function uncertainties (Supplementary Figure 7, Additional Materials 2). As described in the Methods, our GEOS-Chem simulation is evaluated against available surface observations. Due to similar development methods and underlying datasets, the $CEDS_{GBD\ MAPS}$ emissions are expected to have consistent sources of uncertainty as other bottom-up inventories and are discussed in detail in Section 4.2.2. in Additional Materials 1 (available on the HEI website) (McDuffie et al. 2020a). In addition, subnational fractional source contributions are limited to the resolution of the model and emissions, while the urban exposure estimates are further subject to greater uncertainties in the satellite-derived products for small spatial scales (Burnett et al. 2018; Ordóñez et al. 2017). Additional discussion on the uncertainty of the satellite-derived high-resolution exposure estimates can be found in Hammer and colleagues (2020). Future developments of global high-resolution simulations, as well as increasing the accuracy and precision of satellite-derived $PM_{2.5}$ estimates, will serve to reduce these uncertainties in $PM_{2.5}$ mass and source contributions at both the national and subnational scales.

Our methodology follows that employed in the GBD MAPS China and India reports (GBD MAPS Working Group 2016, 2018) and assumes that the proportional contribution of an individual source sector to the attributable disease burden is a simple proportion of that sector's contribution, represented by the sector's proportion multiplied by the overall population-attributable fraction. In the GBD MAPS China report (GBD MAPS Working Group 2016), this assumption is shown to be mathematically equivalent to averaging the population-attributable fraction over all possible changes in concentration within the overall concentration distribution. This approach therefore reflects that populations are exposed to all sources simultaneously and does not require assumptions regarding the order at which individual sources may be removed or reduced. This proportional approach also has the inherent property that the sum of source-sector burden estimates is equal to the total burden attributable to $PM_{2.5}$, whereas removing exposure from a single source at a time does not have this property.

In addition to uncertainties in the general methodology, this work also assumes equitoxicity of aerosol mass and its sources, including from windblown mineral dust which is associated with mortality in a number of analyses (Querol et al. 2019). Some studies suggest that combustion-derived particles are more toxic than secondary sulfates, nitrates, and crustal material (Tuomisto et al. 2008). However, mixed evidence of differential $PM_{2.5}$ toxicity by components and sources, complicated mechanisms, and insufficient evidence to develop component or source-specific concentration–response functions make it challenging to capture and quantify variation in exposure–concentration functions by source (Kim et al. 2020). Therefore, this assumption is necessary for use with the 2019 GBD and GEMM concentration–response functions and is consistent with assessments by the U.S. Environmental Protection Agency (2019a) and WHO (2013). This assumption may under- or overestimate the relative $PM_{2.5}$ contributions from select sectors provided they contribute to more or less toxic components of total $PM_{2.5}$ mass. For example, disease burden estimates attributable to windblown dust in Western Sub-Saharan African countries might be overestimated due to its potential lower toxicity compared with other sources (Lin et al. 2019; Meng et al. 2019; U.S. Environmental Protection Agency 2019b; WHO 2013).

The separate contributions from local and transboundary emissions may be investigated in future studies by testing sensitivities to country-specific emissions or using different modeling approaches such as tagged-tracer or adjoint modeling. As the implementation of mitigation policies is typically constrained to political borders, specific policies may need to consider regional influence on local pollution levels. We also note that results from the sensitivity simulations largely reflect changes in $PM_{2.5}$ mass associated with the complete elimination of each individual emission source. Therefore, the same relative contributions may not be expected from studies that test more moderate reduction strategies or simultaneous reductions of multiple sources if emissions to ambient concentration relationships are nonlinear (Additional Materials 2, Supplementary Text 7). Due to this nonlinearity, fractional and absolute contributions predicted from this method may not be consistent with simulations that implement more moderate reduction strategies (i.e., <20% to 50% emission reductions), or strategies that simultaneously target multiple emission sectors (e.g., simultaneous reductions in both energy and industry sources). Though $PM_{2.5}$ emission reduction generates substantial health benefits, efforts to reduce $PM_{2.5}$ emissions may also be costly. In addition, these costs likely vary with sources and policy strategies. It is, therefore, essential to implement in-depth studies on the benefit–cost analysis of various pollution reduction strategies by sector and fuel types. Optimal resource allocation of different polluting sectors can be critical, especially for low-income countries, to maximize health benefits with lowest cost pollution reduction programs.

The contemporary relevance of our estimates benefitted from our updating of emissions inventories, the application to recent satellite-derived concentration estimates and ground monitoring data, and the most recently available concentration–response functions, which incorporate relative risk information from recently published epidemiological studies. However, as emissions may change dramatically over time, especially in rapidly developing economies, future updating of the estimates of contributions to ambient $PM_{2.5}$ and associated health burden that reflect updates to the emissions inputs will be warranted. The CEDS inventory is expected to be updated annually and our framework, code, and publicly available input datasets will allow others to extend this work to future years.

Despite these limitations and sources of uncertainty, the novel and comprehensive nature of our analysis has provided the type of detailed source information necessary to develop national and subnational $PM_{2.5}$ mitigation strategies, as well as estimates of the avoidable deaths associated with each scenario as a means to quantify potential health benefits and motivate policy action. These estimates can be used at the regional, national, and local levels as initial information on source contributions to inform and prioritize air quality management, especially in settings without available air quality monitoring or locally developed quantitative source contribution data. Verification and evaluation with targeted measurements will be necessary to evaluate effectiveness of actions directed toward specific source sectors. Further, by providing the datasets and estimation framework as a global public good, we encourage others to evaluate specific policy scenarios to reduce $PM_{2.5}$ and its attributable disease burden at multiple spatial scales. Future efforts to improve the spatial resolution of the emissions inputs and simulation developments to provide more finely resolved sector contributions will help to improve the utility of such estimates for air quality management. In addition, uncertainty in the concentration–response relationships, can be reduced with additional epidemiological research especially in high concentration settings. Our sensitivity analysis comparing the sum of the disease-specific GBD concentration–response functions to all-cause mortality studies used in the GEMM indicates that other causes of mortality not yet included in the GBD are likely to be associated with $PM_{2.5}$. As with the inclusion of Type 2 diabetes and neonatal mortality in recent cycles of the GBD, future iterations will likely evaluate additional health outcomes (e.g., dementia and chronic kidney disease) and with sufficient evidence will expand to include these health outcomes. New cohort analyses evaluating outcomes not yet included in the GBD will aid in this effort.

CONCLUSIONS

The novel features and comprehensive nature of our analysis provide detailed source information to inform $PM_{2.5}$ mitigation strategies at the national and subnational level and provide potential health benefit estimates to further motivate action. Roughly 1 million (95% UI: 0.74–1.36 million) deaths could be avoided by the global elimination of fossil fuel combustion, with 20% of this burden associated with fossil fuel use in China and India alone. Despite recent global reductions in air pollutant emissions from coal, this fuel is still the dominant combustible fuel type contributing to the $PM_{2.5}$ disease burden in 20 countries, including China and countries throughout Southern Sub-Saharan Africa and Central Europe. Solid biofuel was a primary source of emissions from the residential sector and was the dominant contributing combustible fuel in 78 countries, especially throughout the tropics. While natural sources of $PM_{2.5}$ mass are dominant contributors in more arid regions, countries with the greatest $PM_{2.5}$ disease burden generally have the largest relative contributions from anthropogenic sources. These estimates are made publicly available via provided data files, code, and interactive visualizations to inform additional analyses and applications and can be used to support effective policy actions toward improvement of air quality across the globe.

PROJECT ASSETS

In addition to two published reports, the GBD MAPS Project has produced a number of assets that are publicly available. By publishing these assets, we hope to increase the transparency and reproducibility of our analysis and to aid in future studies using similar methods.

1. CEDS GBD-MAPS Dataset. Available and registered with a DOI at Zenodo: *https:// zenodo.org/record/3754964*. Between April 26, 2020, and May 8, 2021, the dataset has 1,101 views and has been downloaded 1,165 times. This dataset has been incorporated into the default version of the GEOS-Chem 3D Chemical Transport Model and is slated for the U.S. National Weather Service global aerosol forecast model.
2. CEDS GBD-MAPS Source Code. Available at: *https://doi.org/10.5281/zenodo.3865670*.
3. GEOS-Chem Simulation and Disease Burden Analysis Scripts. Available at: *https://zenodo.org/record/4642700*.
4. GEOS-Chem Source Code. Available at: *https://zenodo.org/record/4718622*.

5. Gridded Modeled Fractional Source Contribution Results. Available at: *https://zenodo.org/record/4739100*.
6. Interactive (Results) Data Visualizations. Available at: *gbdmaps.med.ubc.ca*.
7. Supplemental Data in Additional Materials 2: McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, et al. 2021. Source sector and fuel contributions to ambient $PM_{2.5}$ and attributable mortality across multiple spatial scales. Nat Commun 12:3594; doi:10.1038/s41467-021-23853-y.

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MATERIALS AVAILABLE ON THE HEI WEBSITE

Additional Materials 1 and 2 contain supplemental material not included in the main report. They are available on the HEI website at *www.healtheffects.org/publications.*

Additional Materials 1: McDuffie EE, Smith SJ, O'Rourke P, Tibrewal K, Venkataraman C, Marais EA, et al. 2020. A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): An application of the Community Emissions Data System (CEDS). Earth Syst Sci Data 12:3413–3442; doi:10.5194/essd-12-3413-2020.

Additional Materials 2: McDuffie EE, Martin RV, Spadaro J, Burnett R, Smith SJ, O'Rourke P, et al. 2021. Source sector and fuel contributions to ambient $PM_{2.5}$ and attributable mortality across multiple spatial scales. Nat Commun 12:3594; doi:10.1038/s41467-021-23853-y.

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OTHER PUBLICATIONS RESULTING FROM THIS RESEARCH

Additional Materials 1: McDuffie EE, Smith SJ, O'Rourke P, Tibrewal K, Venkataraman C, Marais EA, et al. 2020. A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970–2017): An application of the Community Emissions Data System (CEDS). Earth Syst Sci Data 12:3413–3442; doi:10.5194/essd-12-3413-2020.

Additional Materials 2: McDuffie EE, Martin RV, Spadaro J, Burnett R, Smith SJ, O'Rourke P, et al. 2021. Source sector and fuel contributions to ambient $PM_{2.5}$ and attributable mortality across multiple spatial scales. Nat Commun 12:3594; doi:10.1038/s41467-021-23853-y.

COMMENTARY
HEI Special Review Panel

HEI

Research Report 210, *Global Burden of Disease from Major Air Pollution Sources (GBD MAPS): A Global Approach*, E. McDuffie et al.

INTRODUCTION

Exposure to air pollution has long been associated with mortality and shortening of life expectancy, and over the last several years it has been acknowledged as a major contributor to global disease burdens. Exposures lasting a few hours to a few days can contribute to ear, nose, and throat irritation; can aggravate existing lower respiratory tract conditions and chronic conditions, such as asthma, allergies, and bronchitis; and can increase mortality (Atkinson et al. 2014; Cai et al. 2016; U.S. EPA 2019; WHO 2016). A substantial body of scientific evidence shows that long-term exposure to air pollution increases the risk of dying early from heart disease, chronic respiratory diseases, lung cancer, diabetes, stroke, and lower respiratory tract infections (U.S. EPA 2019; WHO 2016). Air pollution has also been associated with other conditions and diseases, including disorders of the central nervous system (e.g., dementia in adults and delayed neurodevelopment in children) and adverse birth outcomes, and evidence is emerging for other health effects, such as chronic kidney disease (e.g., Liu et al. 2020; Peters et al. 2019; Power et al. 2016; Simoncic et al. 2020; U.S. EPA 2019; Volk et al. 2020; Weuve et al. 2021). Among all air pollutants, fine particulate matter ($PM_{2.5}$*) has been identified as a substantial public health concern because it is small enough to penetrate the pulmonary alveolar region of the lungs and can cause systemic inflammation and oxidative stress, which contribute to important adverse effects on health. $PM_{2.5}$ in the air and resultant exposures and health effects are the result of many sources including those in the broad areas of energy production, industry, and transportation.

Authoritative global assessments of the health burden attributable to ambient $PM_{2.5}$ exposure have been published in recent years by the World Health Organization (WHO 2016) and the Global Burden of Disease (GBD) Study (Murray et al. 2020). These assessments inform policy by providing information on the impacts of ambient $PM_{2.5}$ and other air pollutants on population health, which is known as the burden of disease, but they have not provided detailed information on which sources of air pollution are the greatest contributors to the health burden.

In 2014, HEI initiated the Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project to expand on the GBD Study by determining which air pollutant sources or fuels contribute most to the ambient $PM_{2.5}$ concentrations and their associated health burden. The first two GBD MAPS reports examined the relative contribution of major sources to $PM_{2.5}$ — including coal combustion, residential fuel burning, windblown dust, and waste combustion — to current and future health burdens in China and India (GBD MAPS Working Group 2016, 2018). The first phase of the project was completed in 2016 and estimated the burden of disease that could be attributed to major air pollution sources in China in 2013 and in 2030 under four policy-relevant scenarios (GBD MAPS Working Group 2016). Estimates for current and future scenarios in India were published in early 2018 (GBD MAPS Working Group 2018).

The current report is the latest in the GBD MAPS series. In 2019, following the publication of the reports on major air pollution sources in China and India, HEI solicited a proposal from a member of the GBD MAPS working group, Dr. Michael Brauer at The University of British Columbia (working collaboratively with Dr. Randall Martin of Washington University in St. Louis), to conduct a global analysis of source contributions to ambient air pollution and related health effects using updated emissions inventories, satellite and air quality modeling, and relationships between air quality and health. After a review process that included an external review and deliberation among the members of the HEI Research Committee, HEI funded Drs. Brauer and Martin — who recruited Dr. Erin McDuffie as the analytical project lead — to undertake the study because they would generate credible and comparable data on sources of air pollution and their relative impacts on public health in countries around the world. The data would also be incorporated into annual updates to the State of Global Air assessment of global air quality and associated health effects (a joint project of HEI and the Institute for Health Metrics and Evaluation; available at *https://www.stateofglobalair.org*) and could help to prioritize source-specific policies and interventions.

The 3-year study, "Global Burden of Disease from Major Air Pollution Sources (GBD MAPS): A Global Approach," began in January 2019. The study team was conducted by Dr. Erin McDuffie (project lead) and Dr. Randall Martin (co-PI) of Washington University in St. Louis, Missouri, Dr. Michael Brauer (co-PI) at The University of British Columbia in Canada, and colleagues. Total expenditures were $342,925. The draft Investigators' Report was received for review in February 2021. A revised report, received in May 2021, was accepted for publication in June 2021. During the review process, an HEI Special Review Panel and the investigators had the opportunity to exchange comments and to clarify issues in both the Investigators' Report and the Panel's Commentary.

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

This Commentary was prepared by an HEI Special Review Panel convened to review this study and members of the HEI scientific staff. The Commentary includes the scientific background for the research, a summary of the study's approach and key results, and the Panel's evaluation of the Investigators' Report (IR) highlighting strengths and weaknesses of the study.

SCIENTIFIC BACKGROUND ON HEALTH BURDEN ATTRIBUTABLE TO $PM_{2.5}$ EXPOSURE

GLOBAL BURDEN OF DISEASE STUDY

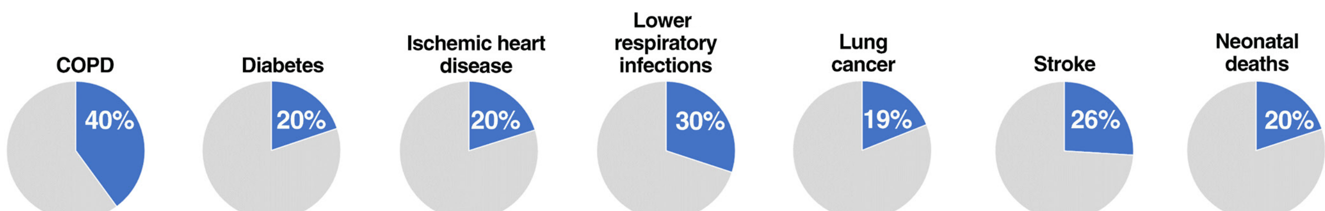
Since 2010, the GBD Study has incorporated the latest scientific evidence and methods annually to quantify and compare the burden of disease from hundreds of diseases, injuries, and risk factors. It reports the burden of disease results for air pollution and other risk factors as the population-attributable disease burden, which is the burden of disease (number of deaths or disability adjusted life years) that can be estimated to occur due to exposure to a particular risk factor. The GBD Study includes analysis of health burden for exposure to ambient $PM_{2.5}$, ozone, and household air pollution. The latest *Lancet* special issue on the GBD study can be found at *https://www.thelancet.com/gbd,* and additional detailed information on the GBD Study — including methods, data, and publications — can be found at *https://www.healthdata.org*. A summary of the methods used in the GBD Study to assess the burden of disease from ambient $PM_{2.5}$ is provided in Sidebar 1.

The GBD Study estimated that air pollution contributed to 6.67 million deaths (95% uncertainty interval [UI]: 5.90 to 7.49 million) worldwide in 2019, nearly 12% of the global deaths (*https://www.stateofglobalair.org*). This large burden of disease reflects the substantial contribution that long-term exposures to air pollution make to chronic noncommunicable diseases and, more specifically, to some of the world's leading causes of death (Commentary Figure 1). About 80% of air pollution's burden is attributed to noncommunicable diseases. For example, in 2019, exposure to air pollution (including ambient $PM_{2.5}$, ambient ozone, and additional household air pollution from use of solid polluting fuels for household cooking) contributed to 40% of deaths from chronic obstructive pulmonary disease (COPD, a highly debilitating lung disease), 30% of lower respiratory tract infection deaths, and 20% of infant mortality in the first month of life.

MAJOR SOURCES OF AIR POLLUTION

The GBD Study and several other previous global studies of the health burden from air pollution have focused on ambient $PM_{2.5}$ from all sources combined (Murray et al. 2020; WHO 2016). Other global studies have explored ambient $PM_{2.5}$ from one or a few sources (Bauer et al. 2019; Chafe et al. 2014; Lelieveld et al. 2015; Vohra et al. 2021). Additionally, studies conducted at the national level — including the two preceding studies in the GBD MAPS series — have studied the air quality and health burden associated with ambient $PM_{2.5}$ from individual sources of air pollution (Conibear et al. 2018; GBD MAPS Working Group 2016, 2018).

The GBD MAPS studies conducted in China and India used the same general approaches as GBD and additionally analyzed burden due to specific sectors by preparing a series of exposure estimates for current and future scenarios with each sector excluded in turn. The contributions of each sector to $PM_{2.5}$ and health burden were calculated as the difference between the GBD estimates from all sources and the estimates with that sector's emissions removed from the air quality models. This is known as a zero-out approach, which assumes that all effects of any individual source sector are small enough to be linear in the changes and that all sectors have similar levels of uncertainty. The earlier GBD MAPS studies provided useful insights. For example, coal combustion contributed to more air pollution–related deaths in China in 2013 with increasing health burdens expected in the absence of further action to reduce emissions from coal combustion (GBD MAPS Working Group 2016). Emissions from residential biomass burning and coal combustion from electricity generation and industry were the major sources of



Commentary Figure 1. Percentage of global deaths in 2019 from specific causes attributable to air pollution as estimated by the Global Burden of Disease Study. (Source: Figure 13 in State of Global Air 2020, available at *www.stateofglobalair.org.*)

SIDEBAR 1: OVERVIEW OF METHODS APPLIED IN THE GLOBAL BURDEN OF DISEASE (GBD) STUDY

General Approach

The GBD Study's estimation of the burden of disease from air pollution begins with an evaluation of the strength of evidence for a particular exposure–outcome pair (e.g., $PM_{2.5}$ and lung cancer). For risk–outcome pairs for which sufficient data are available, the GBD Study then calculates air pollution's burden of disease in each country using

- Estimates of population exposure to ambient $PM_{2.5}$, ambient ozone, and additional household air pollution.
- Mathematical functions that are derived from epidemiological studies and relate different exposures to the increased risk of death or disability from each cause, by age and sex, where applicable.
- Country-specific data on underlying rates of disease and death for each pollution-linked disease.
- Population size and demographic data (age and sex).

The estimates are expressed for the population in every country in several ways, including total number of deaths (mortality) in a given year that can be attributed to air pollution and likely occurred earlier than would be expected in the absence of air pollution, disability-adjusted life years (DALYs, a broader measure of health-related loss that includes the years lost due to ill health or disability in addition to mortality), and age-standardized rates.

Air Pollutant Emissions

Detailed multipollutant emissions inventories (i.e., databases of total emissions of air pollutants) for nitrogen oxides (NO_x), sulfur dioxide (SO_2), black carbon (BC), organic carbon (OC), nonmethane volatile organic compounds (NMVOCs), and other pollutants for major sources or sectors are generated using data from published literature and government reports. Completeness and accuracy of the emissions data for any given location rely on the availability and quality of the existing data.

Exposure to Ambient $PM_{2.5}$

Exposures of human populations to ambient $PM_{2.5}$ are estimated as annual averages based on maps of $PM_{2.5}$ concentrations and population density that are developed using the best available globally consistent data and methods. The $PM_{2.5}$ concentration maps are generated by combining information from ground-based measurements of $PM_{2.5}$, satellite measurements of aerosol optical depth, pollutant emissions inventories, and chemical transport models. These ambient concentrations are converted to population-weighted $PM_{2.5}$ (known as population-weighted exposure) by taking the average concentrations for the residential locations of all individuals within a geographic area (e.g., country or region).

Confidence in the exposure estimates tends to be highest in the areas with the densest ground-based measurements and highest-quality emissions inputs (e.g., urban areas in high-income countries in North America and Europe) and lower in other areas where the data are scarcer. In each annual iteration of the GBD Study, estimates of exposure are revised to include new data as close to the present as possible to track changes in emissions and air quality over time and to account for improvements in the data sources.

Concentration–Response Functions

The health burden attributable to ambient air pollution exposures is calculated by using a concentration–response function that is based on large epidemiological cohort studies of the relationship between adverse health outcomes — including mortality and morbidity — and ambient $PM_{2.5}$ concentrations. In each iteration of the GBD analyses, estimates of the health burden attributable to $PM_{2.5}$ going back to 1990 are updated to incorporate the most recent concentration–response functions.

In GBD 2018 and earlier, the concentration–response functions used were integrated exposure–response functions (IERs) for PM and lung cancer, COPD, lower respiratory tract infections, type 2 diabetes, heart disease, and stroke. In the development of the integrated exposure–response functions, the GBD researchers relied on evidence from active smoking data to characterize risks at high exposures. With the availability of new studies of high air pollution conditions in China, evidence from active smoking data is no longer used in the exposure–response functions as of GBD 2019. The GBD 2019 iteration incorporated a new statistical methodology known as meta regression-Bayesian, regularized, trimmed spline (MR-BRT) to improve the selection and modeling of all exposure–response relationships. For GBD 2019, scientists revised the exposure–response functions for 10 exposure–outcome pairs within air pollution: PM pollution (ambient and household) and birthweight, preterm birth, lung cancer, COPD, lower respiratory tract infections, type 2 diabetes, ischemic heart disease, and stroke; ozone and COPD; and household air pollution and cataracts.

Another concentration–response function, known as the global exposure mortality model (GEMM), adds a parameter to the estimated relationship between outcomes and exposures to increase the flexibility of the shape of the curve and incorporates total mortality in addition to cause-specific mortality (Burnett et al. 2018). It is generally considered to be an upper estimate of the mortality that can be attributed to ambient $PM_{2.5}$ and has mostly been used to assess sensitivity of results to which the concentration–response function is applied.

Furthermore, in preparing the estimates, there is potential for some double counting of the disease burden in populations ex-

Continues next page

SIDEBAR 1: (*Continued*).

posed to $PM_{2.5}$ from both ambient and household air pollution. To avoid that issue, the GBD Study estimates the health burden of exposure to ambient $PM_{2.5}$ and then estimates the additional health burden due to cooking with solid fuels beyond the health burden experienced from ambient $PM_{2.5}$ (Lee et al. 2020; Shupler et al. 2018).

Importantly, each concentration–response function adopts an assumption of equitoxicity (i.e., every atmospheric particle has the same toxicity per unit mass regardless of its chemical composition and physical properties). This standard assumption is recommended by WHO because of the few robust cohort studies that report concentration–response functions for particles from different sources or of different composition.

Demographic Factors

Mortality that can be attributed to a given cause, such as air pollution, also depends on other factors related to population demographics, particularly the age distribution, the baseline disease rates, and other social and economic factors that influence the underlying health and vulnerability of populations. Such factors are also included in the GBD Study. In some cases, changes in population size and age structure can have the largest impacts on trends in the health burden of air pollution. For example, even if exposures to air pollution are decreasing, the overall burden of disease attributable to air pollution can, in absolute numbers, increase if a population is growing faster than exposures are falling. By the same token, a population that is aging will likely face a higher burden of disease because older people have a higher baseline rate of diseases linked with air pollution than younger people do. Together, population growth and aging of the global population are estimated to account for more than half of the increased deaths attributed to ambient $PM_{2.5}$ exposure over the past decade (*www.stateofglobalair.org* 2019).

Assessment of Uncertainty

UIs reported for results in the GBD study are based on uncertainty of the concentration–response function relating health outcomes to air pollution concentrations and on the concentration estimates. They do not account for uncertainty in the estimates of emissions. Sensitivity analyses may be conducted using alternative underlying rates of disease or concentration–response functions to assess uncertainty in the estimates.

concern in India (GBD MAPS Working Group 2018). However, these studies were restricted to those two countries because accessing and standardizing sector-specific emissions data on a global scale has been challenging.

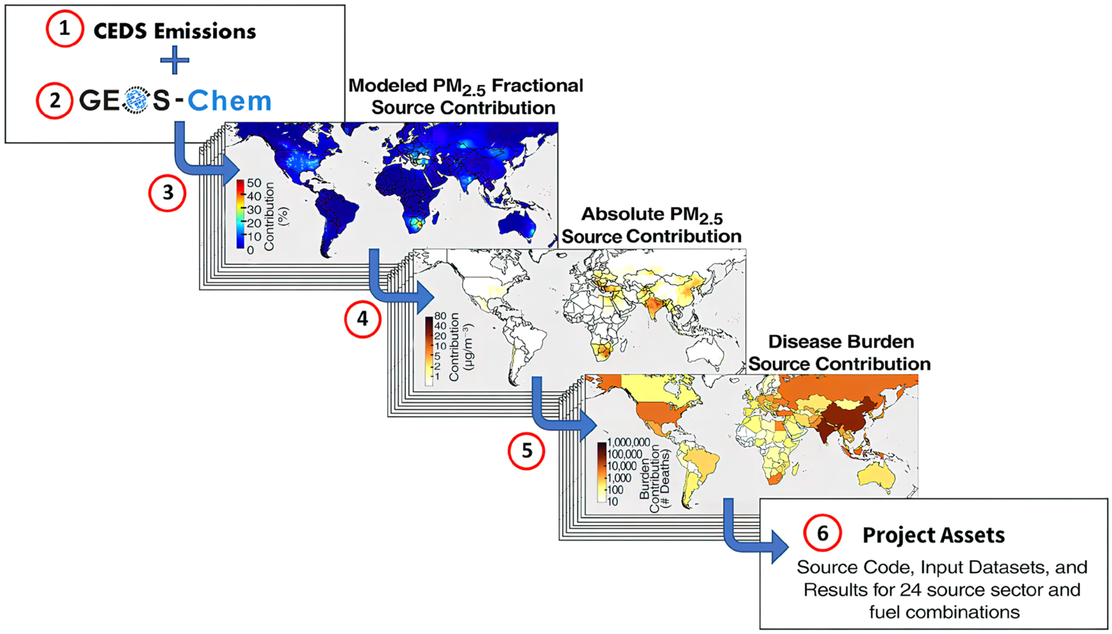
In their new research report, *Global Burden of Disease from Major Air Pollution Sources (GBD MAPS): A Global Approach*, McDuffie and colleagues describe a study that expanded the GBD MAPS approaches developed and tested in China and India to a global analysis. The investigators considered 11 anthropogenic and three other air pollutant sectors and separately looked at four fuel types. They assessed air pollutant emissions, their impacts on ambient $PM_{2.5}$ concentrations, and the resultant mortality that can be attributed to ambient $PM_{2.5}$ at global, world regional, and national scales. Additionally, they assessed the emissions, concentration, and mortality impacts at metropolitan (which they refer to as subnational) scales. Their findings will be useful to inform future policy and will be incorporated into future iterations of State of Global Air reports (*https://www.stateofglobalair.org*).

INVESTIGATING THE MAJOR SOURCES OF AIR POLLUTION: SUMMARY OF THE STUDY

AIM AND APPROACH

The aim of the GBD MAPS Global project was to identify and quantify the dominant sources of ambient $PM_{2.5}$ pollution and their contribution to the disease burden at global, world regional, country, and metropolitan area scales. It was designed to assess potential health benefits that could result from air quality strategies targeted towards specific sector and fuel combinations. The approach was built on the existing GBD Study (see Sidebar 1) and GBD MAPS framework and applied using globally consistent data and methods to inform policy and enable potential inclusion of results into future annual iterations of the GBD analyses (Commentary Figure 2).

McDuffie and colleagues started by expanding and updating detailed global emissions data that were allocated into 11 anthropogenic air pollution source sectors and four fuel categories for 1970–2017 (Commentary Table). They used the emissions data in an updated global atmospheric chemical transport model (GEOS-Chem) that was integrated with high-resolution satellite-derived $PM_{2.5}$ exposure estimates to attribute the country– or world region–specific population exposure and burden of disease to each source sector or fuel type. To find the fraction of total $PM_{2.5}$ contributed by each sector or fuel, they compared the difference in ambient $PM_{2.5}$ in the simulations excluding that sector or fuel to the total ambient $PM_{2.5}$. They then multiplied the fractional contributions by the total ambient $PM_{2.5}$ concentrations to find source contributions to ambient $PM_{2.5}$ concentrations. Finally, the investigators applied relationships between air pollution and health, baseline health data, and demographic data to quantify the deaths attributable to ambient $PM_{2.5}$ exposure. Emissions, ambient $PM_{2.5}$ concentrations, and average population exposures to ambient $PM_{2.5}$ were assessed at global, world regional, country, and metropolitan area scales. Health burden was assessed at the global, world regional, and country scales; the necessary cause-specific mortality data were not generally available in public datasets for metropolitan areas.



Commentary Figure 2. Schematic of project methods. Project stages are (1) developing emissions inventories, (2) running the GEOS-Chem model with all emissions sources of interest included (base simulation), (3 and 4) modeling fractional and absolute source contributions to $PM_{2.5}$, (5) calculating source contributions to disease burden, and (6) providing public access to code, input data, and results. (Source: Figure 1 in the Investigators' Report.)

METHODS

McDuffie and colleagues applied the same methods as those used in earlier GBD MAPS studies but with several important innovations (Commentary Figure 2). First, they updated and applied a publicly available global emissions inventory of $PM_{2.5}$ and its precursors — the Community Emissions Data System (CEDS) — to generate global gridded emissions for the period from 1970 to 2017 with monthly time resolution for seven key atmospheric pollutants (i.e., NO_x, carbon monoxide [CO], SO_2, ammonia [NH_3], NMVOC, BC, and OC), 11 anthropogenic sectors (including agriculture, energy, industry, and transportation), and four fuel categories (i.e., coal, biofuel, liquid fuel, and remaining other emissions) as a new dataset that they called $CEDS_{GBD\text{-}MAPS}$ (Commentary Table), which is different from the emissions inventories used in the GBD Study. In the $CEDS_{GBD\text{-}MAPS}$ emissions inventory, some sector definitions do not completely align with the definitions that are typical for national-scale inventories. For example, primary noncarbonaceous PM emissions, such as those from coal fly ash, are included in the anthropogenic, fugitive, combustion, and industrial dust (AFCID) sector, and the transportation sector contributions do not include nontailpipe emissions of PM from road, brake, and tire wear. Additionally, residential generators are not explicitly included in the inventory and the investigators have explored ways to account for them. Technical details on how the emissions inventory was produced are described in the IR Additional Materials 1 (available on the HEI website).

The investigators used the $CEDS_{GBD\text{-}MAPS}$ emissions data in global simulations of ambient $PM_{2.5}$ concentrations based on the widely used GEOS-Chem model at a resolution of 2° × 2.5° and supplemented with three nested simulations with resolutions of 0.5° × 0.625° over North America, Europe, and Asia (note the different resolutions from the underlying emissions dataset). They evaluated the performance of the GEOS-Chem model for the simulations that included all source sectors (IR section "Base Global Model Simulation of $PM_{2.5}$ Mass" and Additional Materials 2, Supplementary Information Text 3 and Text 4). Next, they combined the model simulations with multiple satellite retrievals of aerosol optical depth and calibrated the results by incorporating available annual average ground monitor observations to obtain 0.1° × 0.1° estimates of global surface-level concentrations of ambient $PM_{2.5}$ mass for the period 1970 to 2017. Finally, they used newly available high-resolution satellite-derived estimates (Hammer et al. 2020) to downscale the GBD exposure estimates to a 0.01° × 0.01° spatial resolution.

McDuffie and colleagues estimated ambient $PM_{2.5}$ concentrations, source sector and fuel category contributions, and population-weighted concentrations for the global average, 21 world regions, 204 countries, and 200 metropolitan areas that each had more than 100,000 inhabitants circa 2010. Using data for 2017, they modeled the fractional source contributions to ambient $PM_{2.5}$ from individual source sectors and fuel categories using the zero-out method applied in earlier GBD MAPS studies.

Commentary Table. Key Features of the Emissions Inventory Produced Using the Community Emissions Data System (CEDS) Updated for the GBD MAPS Project [a]

Feature	Details
Years	1970–2017
Atmospheric Pollutants	NO_x, SO_2, CO, NH_3, NMVOCs, BC, OC
Resolution	Country: annual emission totals, kg/yr Global: monthly average gridded (0.5° × 0.5°) fluxes, kg/m^2-sec
Anthropogenic Sectors[b]	1. Agriculture (noncombustion sources only, excludes open fires) 2. Energy (transformation and extraction) 3. Industry (combustion and noncombustion processes) 4. On-road transportation 5. Off-road/nonroad transportation (rail, domestic navigation, and other) 6. Residential combustion 7. Commercial combustion 8. Other combustion from agriculture, forestry, and fishing 9. Solvents 10. Waste (disposal and handling, including burning of agricultural waste) 11. International shipping
Fuel Categories[b]	1. Total coal combustion (hard coal + brown coal + coal coke) 2. Solid biofuel combustion 3. Liquid fuel (light oil + heavy oil + diesel oil) plus natural gas combustion 4. Remaining emissions that could not be cleanly allocated to combustion of one of the above fuels (e.g., fugitive emissions, windblown dust, or industry sources that use multiple fuels)

[a] See IR Table 1 for more details on the anthropogenic sectors and fuel categories. Source contributions from windblown dusts, AFCID dust, agricultural fires, and other fires were included outside of the emissions inventory.

[b] The sum of emissions from all anthropogenic sectors and the sum of emissions from all fuel categories are equal.

Then for 2017 and 2019, they assigned gridded absolute $PM_{2.5}$ source contributions by multiplying the fractional source contributions in 2017 times the total ambient $PM_{2.5}$ from that year. The investigators calculated population-weighted exposures for 2017 and 2019 from the gridded concentrations and impacts of individual emissions sectors by comparing the models run with and without each source sector and fuel category of interest.

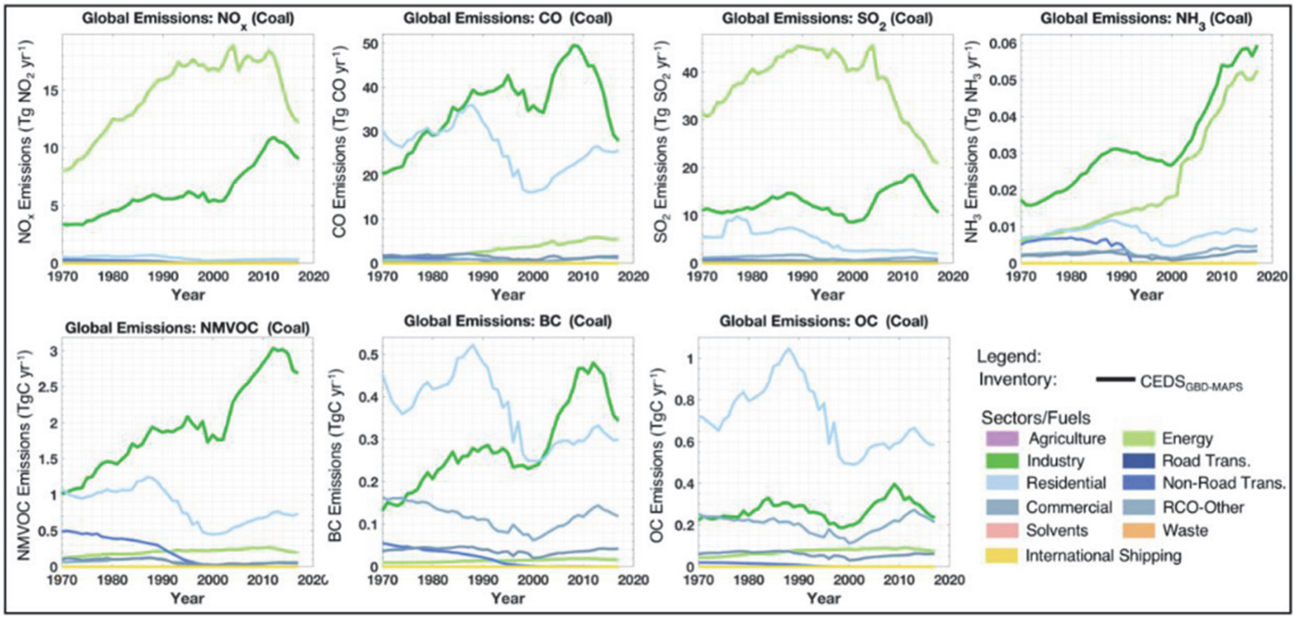
Finally, they calculated disease burdens attributable to the population-weighted $PM_{2.5}$ concentrations on global, world regional, and national scales. For each source sector and fuel category, they estimated the impact of the changes from removal of those emissions using new concentration–response curves introduced in the 2019 GBD Study and cause-specific mortality rates specific to the geographic area.

SUMMARY OF RESULTS

The investigators' report presents the first comprehensive global estimates of diverse source contributions to population-weighted $PM_{2.5}$ exposures at national and metropolitan scales and the first estimates of cause-specific disease burden that provide detailed information at global and national scales by using detailed publicly available emissions inventories. Key results at the global and national scales are briefly summarized here, acknowledging that much of the richness of the results will come from detailed comparisons of individual source sectors, fuel categories, and geographic areas as users apply the data to specific questions of interest for their own geographic areas or compare the data for different geographic areas. Results for the metropolitan areas can be found in IR Additional Materials 2.

Emissions

The investigators updated the open source CEDS to include global emissions of seven key atmospheric pollutants (NO_x, SO_2, NH_3, NMVOCs, BC, and OC) from 1970 to 2017 by sector and fuel type at country and gridded 0.5° × 0.5° resolutions (see Commentary Table). Dominant sources of air pollutant emissions in 2017 included the combustion of oil, gas, and coal in the energy and industry sectors; on-road transportation and international shipping; residential biofuel combustion; and emissions from waste and agriculture. Recent emissions trends reflected decreases in China, North America, and Europe and increases in India, Africa, and other countries in Asia and the Middle East. Global air pollutant



Commentary Figure 3. Time series of global sectoral emissions associated with coal combustion. (Source: McDuffie et al., 2020, reproduced in the Investigators' Report, Additional Materials 1, Figure S13.)

emissions related to coal have trended downward for most pollutants (e.g., NO_x and SO_2) in recent years (Commentary Figure 3; IR Additional Materials 1, Figure S13). Although global NH_3 emissions have increased for coal combustion associated with industry and energy, these emissions (about 0.6 Tg/year in 2017) remain small compared to NH_3 emissions from agriculture (about 45 Tg/yr in 2017).

Global Population–Weighted $PM_{2.5}$ Exposures

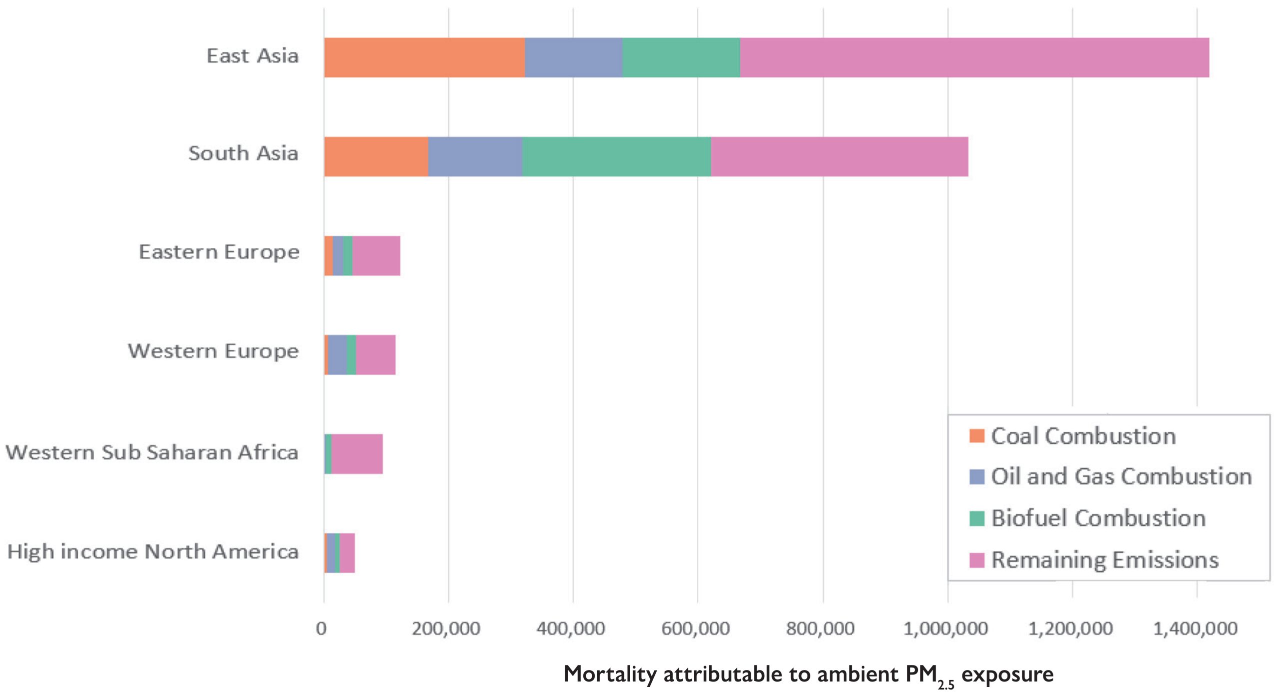
The global population–weighted estimate of mean $PM_{2.5}$ mass concentration in 2017 was 41.7 μg/m³, and 91% of the global population lived in areas with annual average concentrations higher than the 2005 World Health Organization guideline of 10 μg/m³, which as of September 2021 is Interim Target 4 towards the new guideline of 5 μg/m³ (World Health Organization 2021). Ambient $PM_{2.5}$ exposure estimates (averaged from 0.01° × 0.01° resolution gridded concentrations) were highest in countries in Asia, the Middle East, and Africa. The investigators reported that they were highly confident in these estimates of $PM_{2.5}$ exposures because annual average estimates of ambient $PM_{2.5}$ concentrations agreed very well (r = 0.98) with surface observations (IR Additional Materials 2, Figure 1) across global regions.

Global Mortality Attributable to $PM_{2.5}$

Using the most recent concentration–response relationships from the GBD 2019 Study (i.e., MR-BRT), McDuffie and colleagues estimated that globally there were 3.83 million deaths attributable to ambient $PM_{2.5}$ exposure in 2017. More than half (58%) of all those deaths occurred in China and India. The largest source of $PM_{2.5}$ mass that contributed to disease burden at the global scale was residential combustion (0.74 million deaths or 19.2% of disease burden), followed by windblown dust (0.62 million deaths or 16.1% of $PM_{2.5}$ mass). A large fraction of the global $PM_{2.5}$ disease fraction could be attributed to industrial (11.7%) and energy sector (10.2%) emissions. On-road transportation, noncombustion agricultural sources, and anthropogenic dust each contributed 6.0% to 9.3% of global deaths attributable to $PM_{2.5}$, and all other sectors contributed less than 5.2%. Across all sectors, approximately 27.3% of the global mortality attributable to ambient $PM_{2.5}$ exposure — or about one million deaths, 800,000 of which were in South Asia or East Asia — were associated with the combustion of fossil fuels, and 20.0% were related to solid biofuel consumption. Biofuel and remaining emissions from fossil fuels and other sources also had substantial contributions that exceeded those of fossil fuels in some places.

Country-Specific Exposures and Attributable Deaths

The nine countries with the highest numbers of deaths that could be attributed to $PM_{2.5}$ exposure were China (1,387,000), India (867,000), Indonesia (94,000), Egypt (88,000), Pakistan (86,000), Russian Federation (68,000), Bangladesh (64,000), Nigeria (51,000), and the United States (47,000) (IR Figure 5). In these countries, most deaths that were attributed to $PM_{2.5}$ exposure were from stroke and ischemic heart disease, except in Nigeria where childhood lower respiratory tract infections were the largest cause of $PM_{2.5}$-related mortality.



Commentary Figure 4. Deaths for selected regions that could be attributed to population-weighted $PM_{2.5}$ mass exposure from coal, liquid oil and natural gas, biofuel, and remaining emissions, which could not be cleanly allocated to one of the above fuels (e.g., fugitive emissions, windblown dust, or industry sources that use multiple fuels). Fossil fuel combustion contributions are the sum of coal, liquid oil, and natural gas. (Source: Data from McDuffie et al., 2021, reproduced in the Investigators' Report, Additional Materials 2, Supplementary Data File 2.)

The major sources of $PM_{2.5}$ varied substantially by country. Residential cooking and heating was the largest source sector. Energy generation (including both electricity and fuel production) and industry were important source sectors in many countries. Windblown dust was the source sector with the most variation, accounting for 1.5% of attributable deaths in Bangladesh and 70.6% in Nigeria. Agriculture was an important contributor to health burdens from exposure to ambient $PM_{2.5}$ in some regions because of emissions of NH_3, which is a precursor to $PM_{2.5}$.

The largest contributing anthropogenic fuel categories also varied. Overall, fossil fuel combustion contributed to more than one million (27.3%) deaths that could have been avoided by eliminating $PM_{2.5}$ mass formed from the emissions of fossil fuel combustion, with coal having higher impacts than any other fossil fuel (Commentary Figure 4). At country levels, coal was the largest fuel category in China, liquid oil and natural gas were the largest in Egypt, the Russian Federation, and the United States, and solid biofuel combustion was highest in Pakistan, the Russian Federation, India, Bangladesh, and Indonesia. Some countries (e.g., United States) had high burdens of disease even with relatively low population-weighted exposures because demographic differences (e.g., older populations) and lower prevalence of infectious diseases play an important role in the burden of disease.

Comparisons with Other Studies

McDuffie and colleagues report that their results — using source contributions from 2017 — were generally consistent with other previous global and national estimates of the burden of disease that could be attributed to total and sector-specific $PM_{2.5}$ mass. For example, fractional source contributions to emissions, air quality, and health burden were nearly identical to those from the earlier GBD MAPS study in India (e.g., coal accounted for 16% of the air pollution and mortality in 2015 and 17.1% of the air pollution and mortality in the current study) (GBD MAPS Working Group 2018). On the other hand, there were substantial differences in source allocations in China: the proportion of mortality that could be attributed to ambient $PM_{2.5}$ exposure from specific fuels was reduced from 40% in 2013 to 23% in 2017 for coal and similarly from 23% to 15% for residential biofuel combustion (GBD MAPS Working Group 2016). The investigators interpreted the findings to indicate that the mix of air pollutant sources had remained similar in India between 2015 and 2017 and that policies in China intended to reduce reliance on coal and biofuels might have been effective at reducing those sector emissions between 2014 and 2017.

The investigators reported that it was challenging to compare the results of the current study directly with other recent global studies of the health burden associated with air pollution because of a combination of year-to-year differences in actual emissions and health burdens, methodological differences (e.g., use of different emissions inventories, chemical transport models, and assumptions in the baseline mortality data and concentration–response functions), and large uncertainty in some sectors. Of note, the current study estimated lower global mortality estimates attributable to fossil fuel use than another recent study, at least partly because the estimates in that other study were derived using different concentration–response functions, substantially lower emissions of dusts and biomass burning, regional emissions inventories, and different chemical mechanisms and meteorology in the air quality models (Vohra et al. 2021).

Cross-region comparisons for the residential and transportation sectors were generally consistent across studies globally, although the exact estimates of contributions for individual sectors varied. For example, North America had lower contributions of residential emissions and higher contributions of transportation emissions than many parts of Asia. At scales of countries or world regions, the magnitude of residential contributions to ambient $PM_{2.5}$ varied greatly across studies (e.g., 27% to 50% of fractional source contribution in India) (GBD MAPS Working Group 2016, 2018; Gu et al. 2018; Hu et al. 2017a; Lacey et al. 2017; Lelieveld et al. 2015; Marais et al. 2019). Some of the differences between studies could be explained by recent trends in emissions for both residential and transportation sources and the scale (e.g., national or urban) of the analyses. The investigators have provided a more detailed comparison of the current study and earlier studies in Additional Materials 2, Supplementary Text 6.

Data Access

To aid in future studies using similar methods and to increase the transparency and reproducibility of their analysis, the investigators have made all assets of the study publicly available. See the Sidebar 2 for information on how to access the datasets, code, and visualizations.

SIDEBAR 2: ACCESSING THE DATA

To access complete data on emissions, air quality, and disease burden, we refer the reader to the following sources.

Emissions

CEDS GBD-MAPS Dataset. Available at: *https://zenodo.org/record/3754964.*

CEDS GBD-MAPS Source Code. Available at: *https://doi.org/10.5281/zenodo.3865670.*

Air Quality and Disease Burden

GEOS-Chem Simulation and Disease Burden Analysis Scripts. Available at: *https://zenodo.org/record/4642700*.

GEOS-Chem Source Code. Available at: *https://zenodo.org/record/4718622*.

Gridded Modeled Fractional Source Contribution Results. Available at: *https://zenodo.org/record/4739100*.

Supplemental Data in Additional Materials 2: McDuffie EE, Martin RV, Spadaro JV, Burnett R, Smith SJ, O'Rourke P, et al. 2021. Source sector and fuel contributions to ambient $PM_{2.5}$ and attributable mortality across multiple spatial scales. Nat Commun 12:3594; doi:10.1038/s41467-021-23853-y.

Interactive Visualizations of Results

Interactive (Results) Data Visualizations. Available at: *gbdmaps.med.ubc.ca.*

REVIEW PANEL EVALUATION

The GBD MAPS Global project provides a contemporary and comprehensive evaluation of sector- and fuel-specific contributions to ambient $PM_{2.5}$ concentrations and exposures globally for 21 world regions, 204 countries, and 200 metropolitan areas and for the disease burden that can be attributed to $PM_{2.5}$ in those world regions and countries. In its independent review of the report, HEI's ad hoc Special Review Panel commended the authors for this ambitious work to generate valuable analyses and comprehensive datasets that are useful resources for the global community. They observed that the rich data generated by this study will enable further detailed comparison of the effects of different source sectors and fuels across and within geographic areas. The report fills an important knowledge gap about sources and their relative impact on the burden of disease globally, including countries where such estimates were not available previously.

Strengths of the approach are that it used (1) the most recent updated emissions data available, (2) state of the science methods for modeling air pollution sources and combining the models with observations to assess and improve model performance, and (3) methods consistent with GBD methods to allow comparisons with previous GBD MAPS research. Additionally, this study provides open access to data resources along with open-source code on a standard platform for use by other groups.

GOING BEYOND TOTAL GLOBAL $PM_{2.5}$ MASS

Sector- and Fuel-Specific Results

A key strength of this report identified by the Panel is that it goes beyond analyzing disease burden attributable to exposure to total $PM_{2.5}$ to identify the magnitude of risk from 11 anthropogenic air pollution source sectors and four fuel categories across spatial scales using globally consistent data inputs and methods. The Panel appreciated the inclusion of detailed and contemporary input data — especially the updated emissions inventory — and the up-to-date evaluation of deaths attributable to individual $PM_{2.5}$ source sectors and fuel types over multiple spatial scales. They found the study notably comprehensive in estimating the relationship between mortality and the emissions from different sectors and use of different fuels because earlier similar studies had been limited to assessment of global ambient $PM_{2.5}$ from all sources combined (Murray et al. 2020; WHO 2016), global ambient $PM_{2.5}$ from one or a few sources (Bauer et al. 2019; Chafe et al. 2014; Lelieveld et al. 2015; Vohra et al. 2021), or national ambient $PM_{2.5}$ from individual sources of air pollution (Conibear et al. 2018; GBD MAPS Working Group 2016, 2018).

The inclusion of $PM_{2.5}$-related burden of disease associated with the combustion of coal, oil and natural gas, and solid biofuels was useful, as were the estimates of contributions of each fuel in dominant sectors, such as energy generation, industry, and residential energy. The Panel noted some interesting results, for example, that the fossil fuel with the highest emissions and deaths was coal, which also has been associated with adverse effects on climate. Some previously understudied sectors (e.g., international shipping) were shown to have large effects.

Application of a Standardized Methodology

The Panel appreciated that the investigators used an extension of standard GBD methods that are already being widely applied so that their results can be interpreted in the context of those more established methods. Use of standardized methods from the GBD Study will also be important in the future as the results are integrated into annual State of Global Air updates at *https://www.stateofglobalair.org*.

The investigators acknowledged and discussed inherent assumptions and limitations of the methodology and their potential levels of importance throughout the report. The Panel saw the inclusion of quantitative UIs in the estimates of deaths that could be attributed to air pollution — based on the concentration–response functions — as a valuable indicator of the level of confidence in the results and appreciated the inclusion of sensitivity analyses to assess the importance of baseline level of disease and upper estimates of health burden. Qualitative discussion of assumptions related to the underlying methods, for example equitoxicity and the type of data needed to conduct the analyses, was also useful. These assumptions were necessary in the current study and could not be quantitatively assessed; the Panel concluded that such assumptions should be tested and refined in future targeted analyses.

A remaining question is the impact of concentration–response functions versus other factors that contribute to uncertainty, for both this work and the GBD Study as a whole. Although the investigators stated that the largest sources of uncertainty were the concentration–response functions, the Panel concluded that further quantitative exploration of the other underlying assumptions and uncertainties (e.g., in the emissions inventory, chemical transport model, source apportionment, and exposure assessment) will be needed as the methods continue to be developed and applied more broadly. Some of those sources of uncertainty are discussed below because the Panel thought they had the potential for differential regional effects.

SOURCES OF UNCERTAINTY WITH POTENTIAL DIFFERENTIAL REGIONAL EFFECTS

Some of the uncertainties in the analysis have the potential for differing degrees of error at the various geographic scales (global, world regional, national, and metropolitan area) and for different time periods. The Panel discussed emissions data, the air pollution model, the global zero-out approach, and windblown dust and the equitoxicity assumption as sources of uncertainty that could result in differential regional effects. They thought that the estimates should be considered most reliable in the regions with the highest-quality and most abundant air pollution and health data and that the estimates should also be considered informative — but interpreted with caution — in regions with sparser data and fewer studies. Overall, they found that the major conclusions of the analysis are valuable additions to our understanding of how the range of different sources of air pollution contribute to exposure and health burdens.

Emissions Data

A key contribution of the project has been a substantial update of an open-source global emissions inventory to provide the most recent global emissions estimates for key atmospheric pollutants as a function of multiple fuel types and source sectors (Commentary Table). The investigators included many sectors and helpfully provided descriptions of those sectors with how they correspond to the more refined sectors in the original reference (IR Table 1).

Although the data are of relatively high quality, readers should note that some sector definitions vary from those typically used in national emissions inventories, certain sources are omitted from the underlying data, and some emissions sources are better characterized than others (see Methods). In general, as for other studies, the emissions were likely estimated with less uncertainty in high-income countries than in low- and middle-income countries where many of the greatest health burdens are experienced. For example, in China and India the uncertainties in emissions inventories related to incomplete activity data, the apportionment of emissions between urban and rural areas, and the application of assumptions based on data from other countries that have not been tested outside of those countries are well-documented (e.g., Hu et al. 2017b; Li et al. 2017; Saikawa et al. 2017a, 2017b; Wang et al. 2018; Young et al. 2018). Although quantification of the associated uncertainties might be difficult at present, a qualitative discussion of the approach will be useful to indicate the consequences (including the direction of the possible error) of the existing data deficiencies. Nonetheless, the emissions dataset generated by the investigators and shared with the public represents a major advance on previous global emissions inventories and will only improve as more data with higher accuracy and precision become available in the future.

Air Pollution Model

McDuffie and colleagues used an updated global atmospheric chemistry transport model that is integrated with high-resolution satellite-derived $PM_{2.5}$ exposure estimates to attribute the country- or region-specific population exposure and burden of disease to each source sector or fuel type. The investigators included considerable detail on the databases available for air quality model evaluation and reported a high correlation between modeled annual average ambient $PM_{2.5}$ concentrations and surface observations. However, as the investigators noted and the Panel concurred, there were few ground-based measurements in certain locations (e.g., rural areas, Africa, the tropics, and the global South) and more ground-based measurements where few monitors exist — especially those areas with less precise emissions data and with complex terrains (e.g., mountainous areas) — would be needed to calibrate and validate the model more thoroughly. As more data become available, future studies comparing model performance in diverse geographies can explore in more detail the implications of air quality data that are scarcer in some areas on regional differences (e.g., Shaddick et al. 2020).

The Panel also considered several modeling decisions that could have affected the estimates of ambient $PM_{2.5}$ concentrations. For example, the choice of chemical mechanisms used for secondary organic aerosols might be important in such places as China where secondary organic aerosols contribute significantly to $PM_{2.5}$ concentrations (e.g., Qiao et al. 2018), and the difference in the GEOS-Chem spatial resolution north of the equator (0.5° × 0.625°) from the resolution south of the equator (2° × 2.5°) may contribute to spatially varying uncertainty. Future studies building on this work could include richer assessment of model performance that includes evaluation of the sensitivity of $PM_{2.5}$ concentrations to alternate approaches of representing the sources, chemical and physical processing, and fate of $PM_{2.5}$ either by applying different models or sensitivity analyses within a given model. Because the uncertainty may vary spatially, the Panel recommends that those studies report numerical estimates of model performance – for example, the normalized mean bias — in different locations in addition to the global value.

Global Zero-Out Approach

Use of the global zero-out approach to estimate sectoral contributions is an important limitation that warrants more discussion because air pollution controls and changes in fuels and technologies are often made at the national level and can vary across countries. Separation of air pollutant contributions of local sources from long-range transport of pollution may therefore be important for policy and could be informed by targeted studies to identify how best to address the source sectors or fuels that contribute the most to health burdens. Similarly, the sector-based zero-out approach does not accommodate technologies that only reduce some of the air pollutants emitted from the sector rather than all of them at once; flue gas desulfurization is one example. Exploring the effect of adopting different policy measures is a logical next step that would be informed by the results of this study.

Another source of uncertainty — as noted by the investigators — was that removing all emissions for a certain sector (i.e., the zero-out approach) could change the atmospheric chemical conditions enough to affect the linearity of the relationship between emissions and $PM_{2.5}$ concentrations. Comparing the sum of the $PM_{2.5}$ concentrations attributed to each sector to the baseline simulations that contain all sources would provide information on the influence of nonlinearity between emissions and $PM_{2.5}$ (Zhao et al. 2017, 2019). Looking forward, the Panel suggested that the results could be compared with other studies that considered reductions in a single pollutant at a time, or sensitivity analyses could be conducted that address sensitivity to small changes in emissions of individual pollutants to better understand the implications of the global sector-based approach (e.g., by adjoint modeling as previously done for the United States and Canada [Pappin and Hakami, 2013]).

Windblown Dust and the Equitoxicity Assumption

The investigators have reported that a high proportion of deaths in 2017 could be attributed to wind-blown dust in the western sub-Saharan region and Nigeria. Given the dominance of soil dust and other natural sources of PM in these and other regions, the Panel thought that it will be important in the future for researchers to pay attention to and find additional ways to address the uncertainty in natural PM sources. They noted that there is generally higher confidence in emissions inventories and resultant air quality impacts for well-defined and centralized sources (e.g., industry) than from more dispersed sources (e.g., agricultural burning or windblown dust). Additionally, although there have been some studies that show respiratory and cardiovascular effects of desert dust, additional research is needed to assess the health effects associated with desert dust exposure and conduct source-specific health impact assessment (Aghababaeian et al. 2021; Querol et al. 2019).

In the absence of more information, it has been generally assumed that the same concentration–response functions can be applied for all air pollutant sources and global regions (U.S. EPA 2019). However, as health burdens continue to be assessed at ever more local scales, it will be important to understand how robust the results are in regions where windblown dust is a major contributor to ambient $PM_{2.5}$ concentrations and exposures.

Assessing the Implications of these Uncertainties for the Study's Overall Conclusions

There are, as in any such global analysis, significant uncertainties needing additional investigation in the future as described above. Having said that, the Panel found that, overall the major conclusions of the analysis, especially at the global scale, are valuable additions to our understanding of how the range of different sources of air pollution contribute to exposure and health burdens.

POLICY RELEVANCE

Fuel and sectoral contributions to ambient $PM_{2.5}$ are fundamental areas of policy interventions to improve air quality. This report has provided information on how fuels and air pollutant source sectors affect air quality and human health based on information on how the dominant sources of $PM_{2.5}$ and its precursor emissions have experienced different trends over time in different global regions.

Prioritizing Sectors to Address

The results of the current study suggest that the sources of $PM_{2.5}$ associated with high mortality appear to be largely anthropogenic except in parts of Africa (see discussion of windblown dust above). The Panel noted that the results suggest more deaths attributable to $PM_{2.5}$ in China from the residential sector compared with heating or transport even though China has banned burning of coal for heating and introduced gas as an alternative in some megacities (although not yet in all rural areas). In addition, agriculture is a significant contributing sector in many countries, including Germany and Poland. That result is consistent with recent studies that show that ammonia emissions are a strong contributor to aerosol formation. Across Europe, reduction of ammonia emissions from agriculture would substantially reduce $PM_{2.5}$ mass concentrations (Giannakis et al. 2019; Pozzer et al. 2017). Exploring those and other results will inform future models and potentially identify sectors that should be prioritized for emissions reductions and could have been previously overlooked.

Assessing the extent to which other broad results about specific anthropogenic sources are robust to uncertainties at national and metropolitan scales may require finer grained analyses of sources and exposures, especially at the smaller scales where local conditions may differ and many air quality management decisions are made. The Panel considered whether inclusion of other forms of uncertainty (e.g., unequal data scarcity) would change which sectors would have the largest estimated health burden in some regions. They thought it was likely that the rankings are robust enough to identify key source sectors and fuel types to address with policies on the global and regional level but possibly not on the national level in every country. Although it might not be possible to answer these questions about robustness fully at a global scale, the robustness of sector rankings should be evaluated further in future source apportionment work in specific countries and metropolitan regions during the consideration of specific policies to target those sources which were identified as some of the larger contributors to ambient $PM_{2.5}$ concentrations in those areas.

Addressing Regional Transport of Pollution

The current study was designed to assess potential health benefits that could result from air quality strategies targeted towards specific sector and fuel combinations. The investigators did not consider whether emissions were from local or regional sources, and the study cannot answer questions about long-range or regional transport of air pollution. Although this issue might not be a problem for large countries or world regions, developing mitigation strategies at the national and local level might be especially challenging for those countries located downwind of countries or regions with high emissions if the air quality policies and the structure of the emissions sources vary between the adjacent areas. The investigators and the Panel agreed that research to address issues of transboundary pollution would be complementary to the current study, especially where long-range transport is likely to contribute to high mortality attributable to ambient $PM_{2.5}$.

Ensuring Access to Data

The investigators compiled policy-relevant datasets that are consistent at local, national, and global scales. The Panel noted that these datasets will likely be useful for countries that would like access to those data to be able to compare them to their own policy analyses and as a starting point for other countries that have not yet done their own analyses. The Panel appreciated the investigators' attempts to assess where the different assessments agree or diverge and looks forward to future studies with more detailed comparisons. They noted that the investigators have publicly released all input data sources, analysis codes, and results; this increases the transparency of the project and enables its verification and reproduction and future upgrades of the data and methods. The Panel also observed that many aspects of energy, emissions, and pollution have changed since 2017. Therefore, they found it worthwhile that the investigators intend to operationalize their methods for inclusion of updated analyses in future GBD assessments and the associated State of Global Air communications.

SUMMARY AND CONCLUSIONS

Each year, the GBD Study releases estimates of the total burden of disease from exposure to ambient $PM_{2.5}$. In this report, McDuffie and colleagues provide a valuable complement to the estimation of impacts of total ambient $PM_{2.5}$ exposure by determining which air pollutant sources or fuels contribute most to the ambient $PM_{2.5}$ concentrations and associated health burden at global, world regional, and national scales. The strengths of the study include the global perspective, the availability of data and code, and the application of standardized methods.

The results of this study are the first comprehensive global estimates of source contributions to exposure and cause-specific disease burden that provide detailed information at national levels and contributions to exposure at metropolitan levels by using detailed publicly available emissions inventories. Some interesting results include the finding that fossil fuels contribute substantially to exposure and health burdens, with an estimated one million deaths globally (27.3% of all mortality) and 800,000 of those deaths in South Asia or East Asia (32.5% of air pollution related deaths in those regions) attributable to fossil fuel emissions. Within fossil fuel, coal remains the fuel with the highest emissions and attributable deaths. International shipping and agriculture sectors had higher contributions to $PM_{2.5}$ concentrations and therefore higher contributions to $PM_{2.5}$-related mortality than are widely recognized. Additionally, the investigators compared their findings to earlier studies using the same methods in China and India and reported that the mix of air pollutant sources had remained similar in India between 2015 and 2017 and that emissions from combustion of coal and biofuels in China were reduced between 2014 and 2017.

The Panel observed that the rich data generated by this study will be a valuable resource to mine for additional details for years to come. The report contains a wealth of information generated using several advances to the methodological approach:

- New contemporary and comprehensive global emissions inventory disaggregated by sector and fuel.
- Incorporation of new regional inventories for India and Africa.
- New high-resolution $PM_{2.5}$ exposure estimates derived from satellite and surface monitoring data.
- Use of disease-specific premature death concentration–response functions that support transfer of estimates from one country or world region to another.
- Estimates that are comparatively up to date, with fractional source contributions developed for 2017.
- Open access to source code, emissions inventories, and analysis scripts.

Inherent assumptions that contribute to uncertainty in the analyses presented in the current report include linearity of effects for the zero-out method, the clustering of most ground-based air quality monitoring in urban areas of higher-income countries, and the inability to include uncertainty in the exposure assessment in the final reported UIs. Several sources of uncertainty were identified that likely vary in magnitude by location and source sector: (1) the assumption that all particle mixtures had equal effects on mortality; (2) the quality and quantity of emissions and air quality data in different regions, and (3) the global zeroing out of entire source sectors as opposed to considering national-level policy changes or control technologies that do not uniformly reduce emissions of all pollutants from a given source.

The equitoxicity assumption in particular could have important implications for policy given that natural sources with high uncertainty in emissions estimates appear to dominate anthropogenic sources in several regions (e.g., windblown dust in the western sub-Saharan Africa region). Because the magnitude of the uncertainties was not consistent for all locations, geographic scales, and source sectors, the Panel thought that the global results were probably the most robust. The more granular results may be more useful for comparison with local data or identification of potential sources to consider for more detailed policy evaluations.

There are, as in any such global analysis, significant uncertainties needing additional investigation in the future as described above. Having said that, the Panel found that overall, the major conclusions of the analysis, especially at the global scale, are valuable additions to our understanding of how the range of different sources of air pollution contribute to exposure and health burdens.

The Panel commends the investigators for conducting the most comprehensive study of this type to date and for identifying the limitations as future opportunities for improvement on their current methods. The information on air pollutant source sectors and fuel types that contribute to mortality associated with ambient concentrations of $PM_{2.5}$ in various countries and regions will have important implications for the prioritization of which air pollution source sectors to address with policies. Although the results inevitably will need additional validation and evaluation in areas where results were less expected or derived with less confidence, they do point the way forward for active development of finer scale source-specific air quality management strategies in the future. Additional analyses and in-depth exploration of all aspects of this study will be facilitated by the investigators' open access of data and open-source code. The results of this study will also be incorporated in future GBD assessments and the associated State of Global Air communications.

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ABBREVIATIONS AND OTHER ITEMS

AFCID	anthropogenic, fugitive, combustion, and industrial dust
BC	black carbon
CEDS	Community Emissions Data System
CO	carbon monoxide
COPD	chronic obstructive pulmonary disease
DALYs	disability-adjusted life years
GBD	Global Burden of Disease
GBD MAPS	Global Burden of Disease from Major Air Pollution Sources
GEOS-Chem	global 3-D model of atmospheric chemistry
GEMM	Global Exposures Mortality Model
IR	investigators' report
MR-BRT	meta-regression Bayesian, regularized, trimmed
NH_3	ammonia
NMVOCs	nonmethane volatile organic compounds
NO_x	nitrogen oxides
OC	organic carbon
PI	principal investigator
$PM_{2.5}$	ambient fine particulate matter
RCO-Other	residential, commercial, and other sectors
SO_2	sulfur dioxide
SoGA	State of Global Air
UI	uncertainty interval
U.S. EPA	U.S. Environmental Protection Agency
WHO	World Health Organization

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