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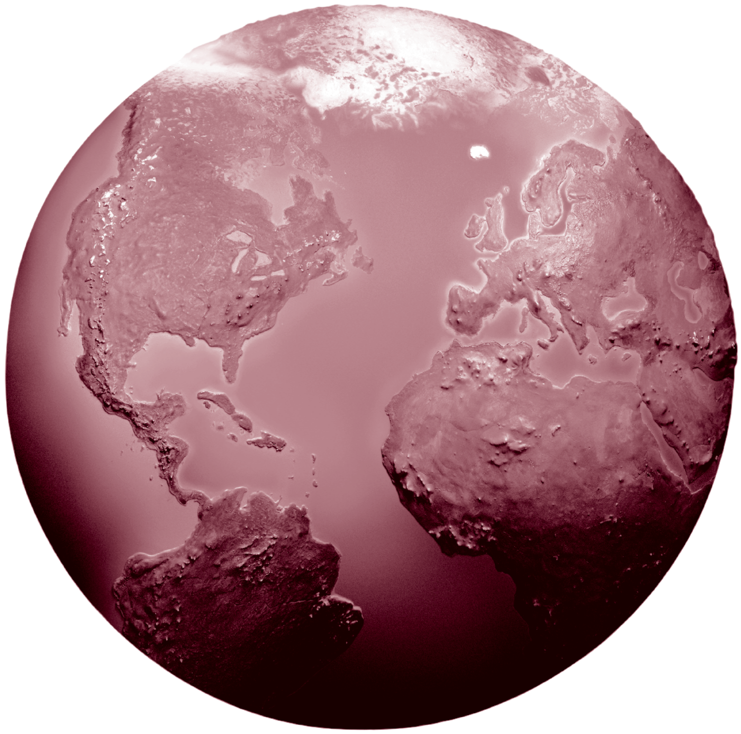

COMMENTARY BY AN HEI SPECIAL REVIEW PANEL SUMMARIZING AND EVALUATING THE INVESTIGATORS' REPORT:

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

McDuffie et al.

Health Effects Institute

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

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Research Report 210

Health Effects Institute

Boston, Massachusetts

Trusted Science · Cleaner Air · Better Health

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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.

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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

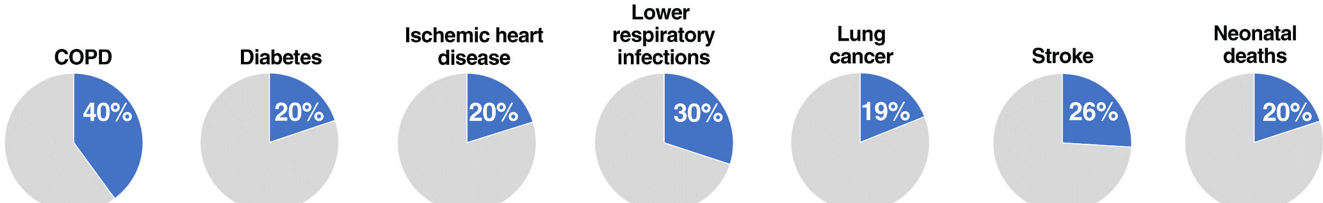
Since 2010, the GBD Study has incorporated the latest scientific evidence and methods annually to quantify and compare the burden of disease from hundreds of diseases, injuries, and risk factors. It reports the burden of disease results for air pollution and other risk factors as the population-attributable 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.

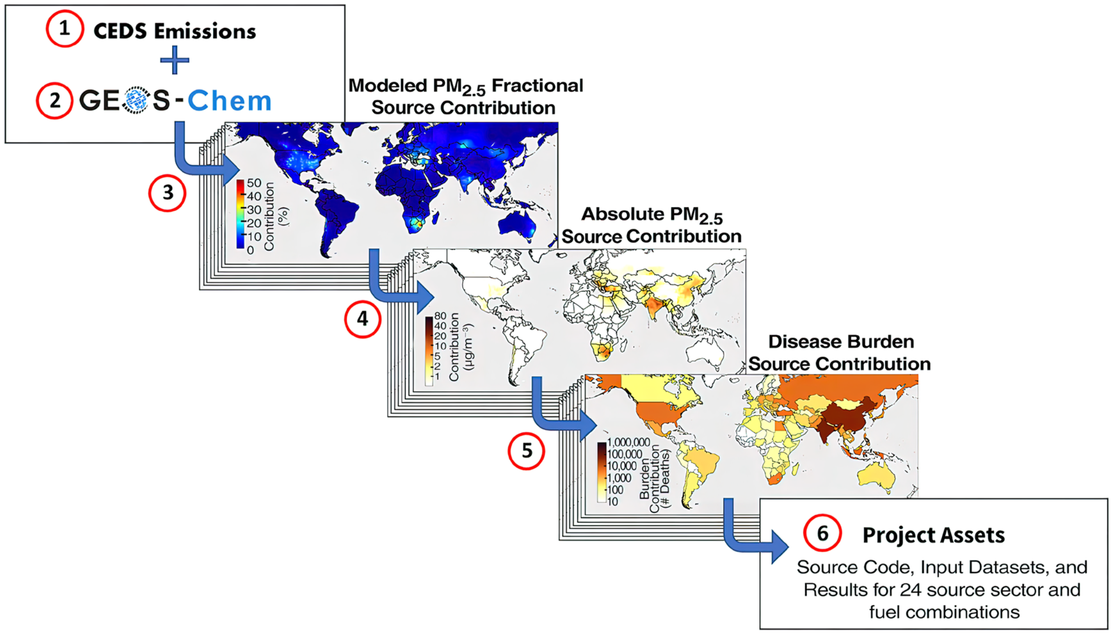
In their new research report, *Global Burden of Disease from Major Air Pollution Sources (GBD MAPS): A Global Approach*, McDuffie and colleagues describe a study that expanded the GBD MAPS approaches developed and tested in China and India to a global analysis. The investigators considered 11 anthropogenic 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.

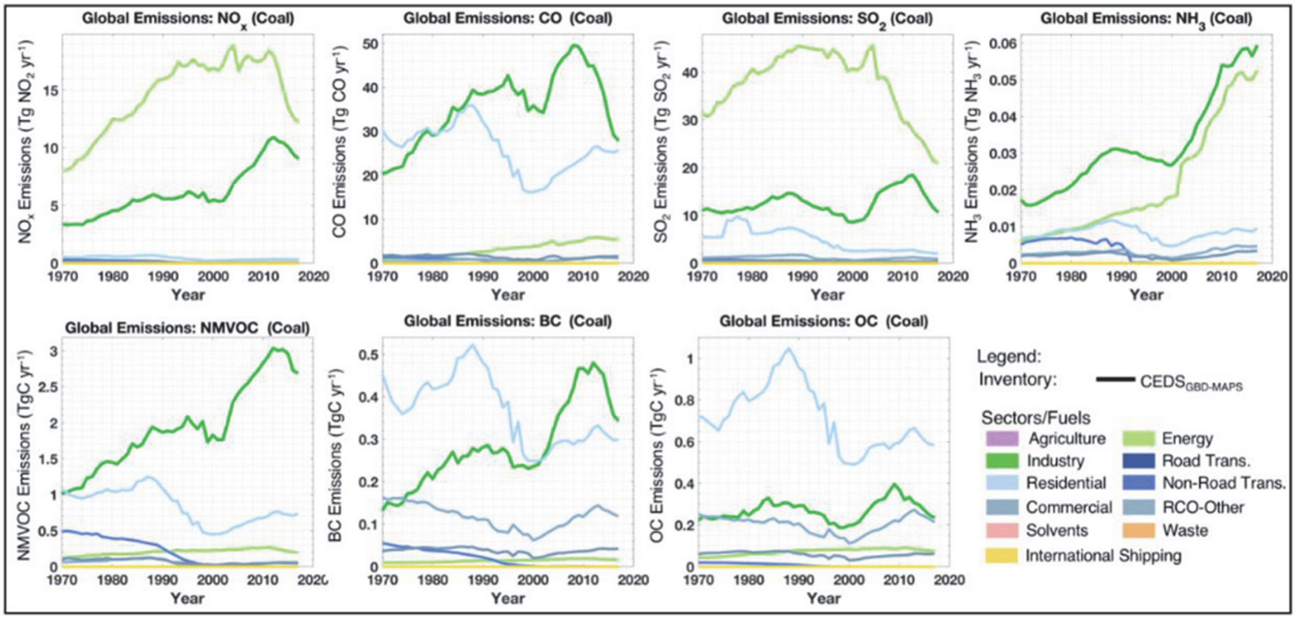
Finally, they calculated disease burdens attributable to the population-weighted $PM_{2.5}$ concentrations on global, world regional, and national scales. For each source sector and fuel category, they estimated the impact of the changes from removal of those emissions using new concentration–response 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

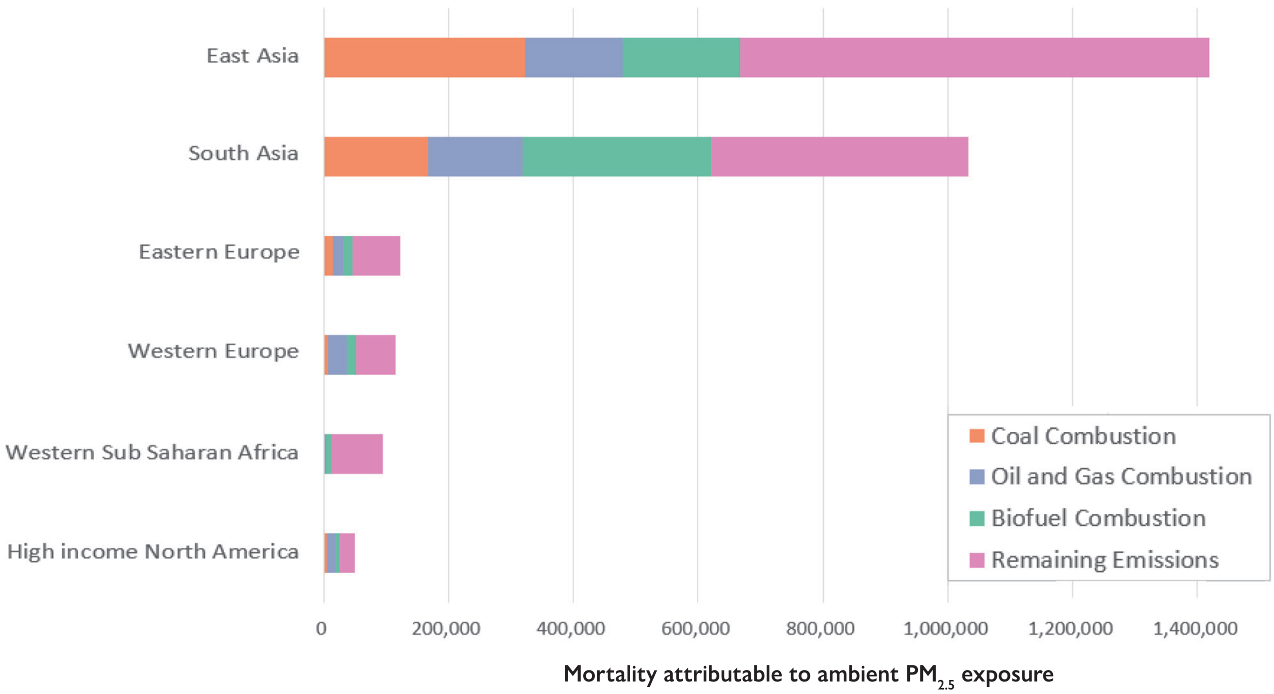
The global population–weighted estimate of mean $PM_{2.5}$ mass concentration in 2017 was 41.7 µg/m^3, and 91% of the global population lived in areas with annual average concentrations higher than the 2005 World Health Organization guideline of 10 µg/m^3, which as of September 2021 is Interim Target 4 towards the new guideline of 5 µg/m^3 (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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