STATE OF GLOBAL AIR /2017

A SPECIAL REPORT ON GLOBAL EXPOSURE TO AIR POLLUTION AND ITS DISEASE BURDEN

HEI

IHME

The State of Global Air is a collaboration between the Institute for Health Metrics and Evaluation's Global Burden of Disease Project and the Health Effects Institute.

What is the State of Global Air?

This first issue of the State of Global Air report brings into one place important information on outdoor air quality and health for all countries around the globe. It is based on the most recent data available to provide a comprehensive picture of the latest global levels and trends (since 1990).

Who is it for?

The report is designed to introduce citizens, journalists, policy makers, and scientists to the Global Burden of Disease project, a comprehensive effort to estimate and track human exposure to air pollution and its impact on human health around the world.

How can I explore the data?

This report has a companion interactive website, which provides the tools to explore, compare, and download data tables and graphics with the latest air pollution levels and the associated burden of disease in individual countries, as well as regions, and their trends over the last 25 years (1990–2015).

Where will I find information on:

INTRODUCTION

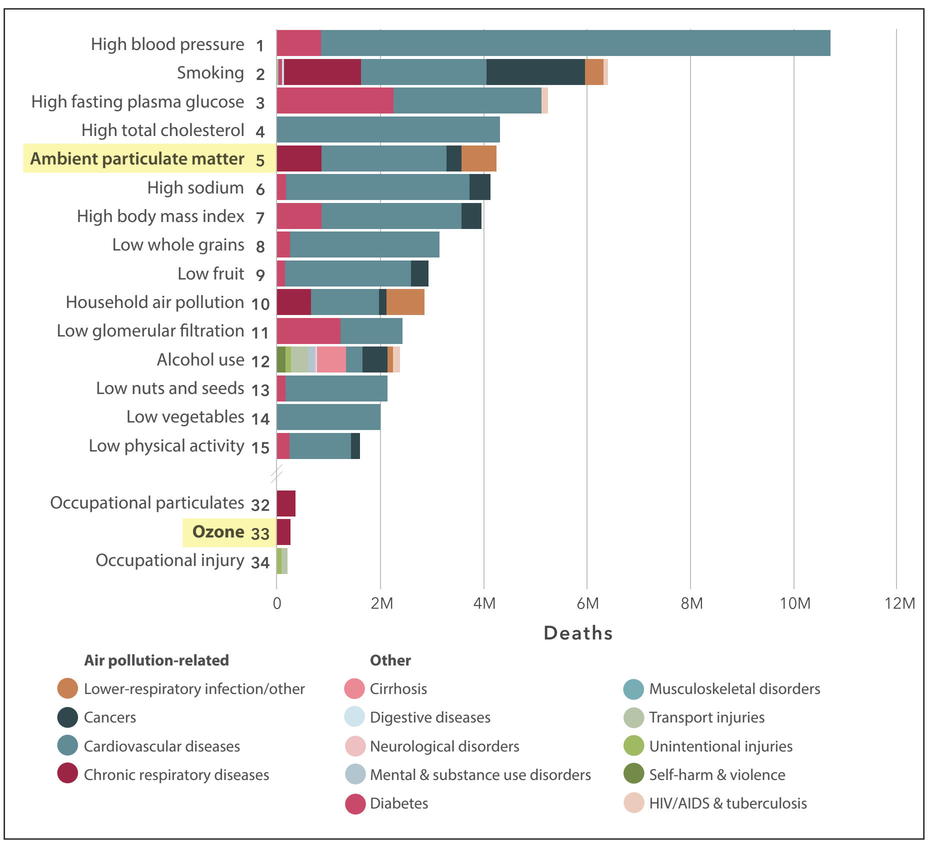
Air pollution is now clearly recognized as an important global risk factor for disease. Decades of research conducted in numerous cities throughout the world show that when air pollution levels increase, so do the numbers of people dying. More important, studies of long-term exposure to air pollution demonstrate that people living in more polluted locations die prematurely, compared with those living in areas with lower levels of pollution. Research also provides details on how air pollution affects human health, with evidence clearly showing impacts on the rates of cardiovascular disease and stroke, in addition to the more easily appreciated effects on respiratory disease. While these impacts on health are large, there is also cause for optimism: documented examples from locations where air quality management approaches have reduced pollution show that when air quality improves, so does population health.

Increasing public awareness of air quality and the burden of disease caused by air pollution is an essential step in reducing air pollution and improving public health. Here we present the first annual *State of Global Air Report* — and the accompanying rich data resources of the State of Global Air interactive website. Together these resources provide the most current and comprehensive information on air pollution levels and their health impacts throughout the world and allow for detailed comparisons between countries and over time. The State of Global Air site is the only source where the most up-to-date estimates of global air pollution levels are available for downloading.

To understand the importance of air pollution and its contribution to health, it is critical to place air pollution risks in the context of other widely recognized risk factors for disease (e.g., smoking and diet). To do this, we build on the Global Burden of Disease (GBD) project, an extensive effort led by the Institute for Health Metrics and Evaluation (IHME), involving more than 2,000 researchers, to enumerate and track death and disability and the role of an extensive set of behavioral, dietary, and environmental risk factors for more than 300 diseases and injuries, by age and sex, from 1990 to the present, in 195 different countries and territories. As the most comprehensive compilation and analysis of global health information available, this massive data set allows for comparisons over time, across age groups, and among populations, and is annually updated as new data and epidemiological studies become available. These data can then be used at the global, regional, national, and even local levels to track health and risk factor trends over time and may have important implications for policy action. Although estimates of health impact by multiple institutes exist, increasingly scientists are relying on methods developed by IHME for the GBD project (see "Numbers, Numbers Everywhere" textbox on the next page).

Exposure to $PM_{2.5}$, the leading environmental risk factor for death, accounting for about 4.2 million deaths, ranks 5th worldwide among all risks, including smoking, diet, and high blood pressure.

Figure 1. Global ranking of risk factors for total deaths from all causes for all ages and sexes in 2015.



Explore the rankings further at the IHME/GBD Compare site.

In this context, we focus on two measures of outdoor air pollution included in the GBD project — ambient fine particulate matter (airborne particles less than or equal to 2.5 micrometers in aerodynamic diameter, or $PM_{2.5}$) and ozone, a reactive gas — the most widely studied and monitored air pollutants worldwide.

From the most recent (2015) analysis of the GBD, exposure to $PM_{2.5}$ was the 5th highest ranking risk factor for death, responsible for 4.2 million deaths from heart disease and stroke, lung cancer, chronic lung disease, and respiratory infections. An additional 254,000 deaths were attributable to exposure to ozone and its impact on chronic lung disease (Figure 1). $PM_{2.5}$ was responsible for a substantially larger number of attributable deaths than other, more well-known risk factors, such as alcohol use or physical inactivity. It contributed to a similar number of deaths as did high sodium intake and high cholesterol. Although not the focus of this year's report, indoor air pollution from the household use of solid fuels (coal, wood, dung, etc.; see textbox on page 13) for cooking and heating also has a substantial impact on health, ranking 10th overall. It also contributes to outdoor air pollution.

This report describes key findings related to the levels of exposure to $PM_{2.5}$ and ozone and their impacts on health. On the State of Global Air website you can use the interactive feature to explore and visually compare air pollution levels and health impacts around the world in individual countries and among regions.

Numbers, Numbers Everywhere

As recognition of the world's air pollution problems has grown, estimates of the numbers of deaths and years of healthy life lost attributable to outdoor air pollution have proliferated. Most of these health burden estimates are from the World Health Organization (WHO) or from the Institute for Health Metrics and Evaluation (IHME) Global Burden of Disease (GBD) project. (This report is based on IHME estimates.)

In its most recent update, released in 2016, the WHO estimated there were 3 million deaths from $PM_{2.5}$ exposure for the year 2012, while the most recent GBD estimate was 4.2 million for the year 2015. Other estimates exist for outdoor air pollution–related deaths in individual countries or regions, alone and at times in combination with estimates for indoor air pollution. Over time, these numbers have been echoed in reports by several leading economic and energy institutions that have sought to put a monetary value on the health burden attributable to outdoor air pollution and its sources — the World Bank, the Organization for Economic Cooperation and Development, and the International Energy Agency, to name a few (see "Additional Resources" section for details).

What can we make of all these numbers? Do their differences matter?

The most important takeaway message is that they are all large numbers — the burden of disease from air pollution is substantial. And given the complexity of the process for developing them, these estimates are surprisingly consistent. Some variation from this kind of scientific analysis is to be expected. These are estimates made by different analysts at different points in time. They vary primarily because of different data or because of different methods used to assess exposure to pollutants, to characterize exposure–disease relationships, and to quantify the baseline rates of disease and mortality in populations — all of which go into estimates of the numbers of people affected by air pollution.

Increasingly, the methods for estimating the burden of disease are converging. Most of the data and methods have their origins with IHME's GBD project and, particularly, its major update in 2010, which substantially expanded the analyses. WHO and IHME now use essentially the same methodologies for estimating air pollution levels around the world. Their estimates are therefore most sensitive to changes in exposure–response relationships that occur as new evidence is incorporated and, to a lesser degree, to changes in the baseline disease and mortality rates. Differences in the choice of exposure–response relationships largely account for the differences between the most recent mortality estimates from WHO and GBD: WHO relied on exposure–response relationships from GBD 2013 and WHO population mortality rate estimates for 2012, whereas the GBD 2015 report used an updated exposure–response function that predicted higher rates of mortality from $PM_{2.5}$ exposure and 2015 estimates of population mortality rates.

Annual GBD Updates

The GBD project now updates its estimates annually and, with each update, provides an analysis of the trends over time (e.g., for the 25 years from 1990 to 2015). Although these updates include improvements in data and methods that themselves contribute to differences from previous GBD estimates (e.g., GBD 2010, GBD 2013), each GBD update recalculates the entire temporal sequence so that its trends (based, e.g., on the years 1990–2015) are internally consistent. These are the data that will be featured in future State of Global Air reports.

GLOBAL AMBIENT AIR POLLUTION LEVELS AND TRENDS

Air pollution is a complex mixture of gases and particles whose sources and composition vary over space and time. While hundreds of different chemical compounds can be measured in air, governments typically measure only a small subset of gases and particles as indicators of the different types of air pollution and major sources contributing to that pollution. $PM_{2.5}$ and ozone are the two indicators used to quantify exposure to air pollution in the GBD project. $PM_{2.5}$ is the most consistent and robust predictor of mortality in studies of long-term exposure to air pollution. Ozone, a gas produced via atmospheric reactions of precursor emissions, is associated with respiratory disease independent of exposure to $PM_{2.5}$. Exposure to each pollutant is represented by population-weighted average concentrations, which take into account the proportions of the population living with different levels of pollution (see also the textbox "How Are Air Pollution Levels Estimated Around the World?" on page 5).

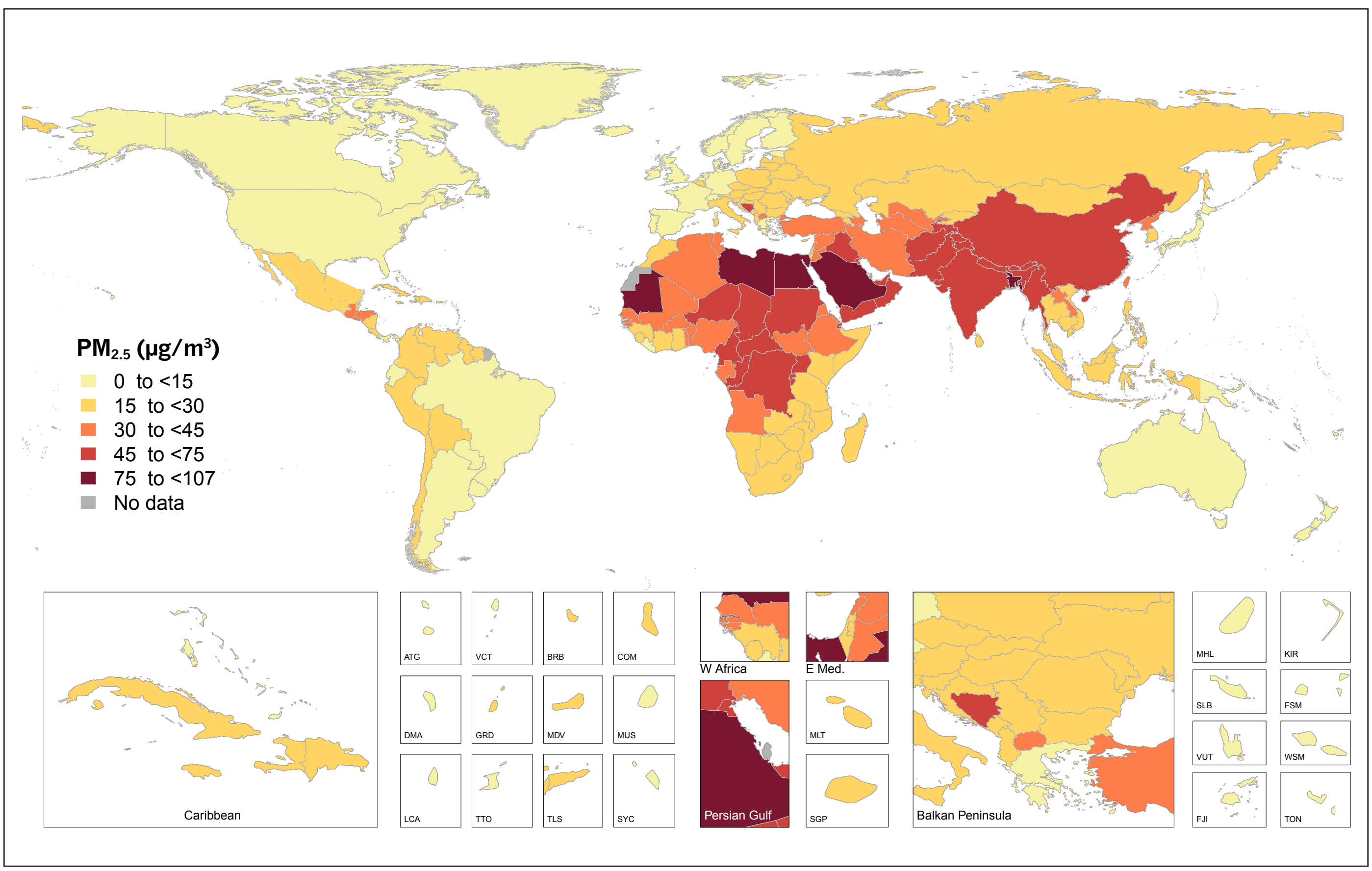
HOW AMBIENT $PM_{2.5}$ CONCENTRATIONS VARY

The global map of population-weighted annual average ambient concentrations of $PM_{2.5}$ in 2015 (see Figure 2) shows that there are marked differences in the levels of exposure experienced by human populations around the world. Identifying these patterns is an important first step toward understanding what sources and activities contribute to high levels of air pollution and, then, what can be done about them.

The highest concentrations of $PM_{2.5}$ in 2015 related to combustion sources were in South and Southeast Asia, China, and Central and Western sub-Saharan Africa.

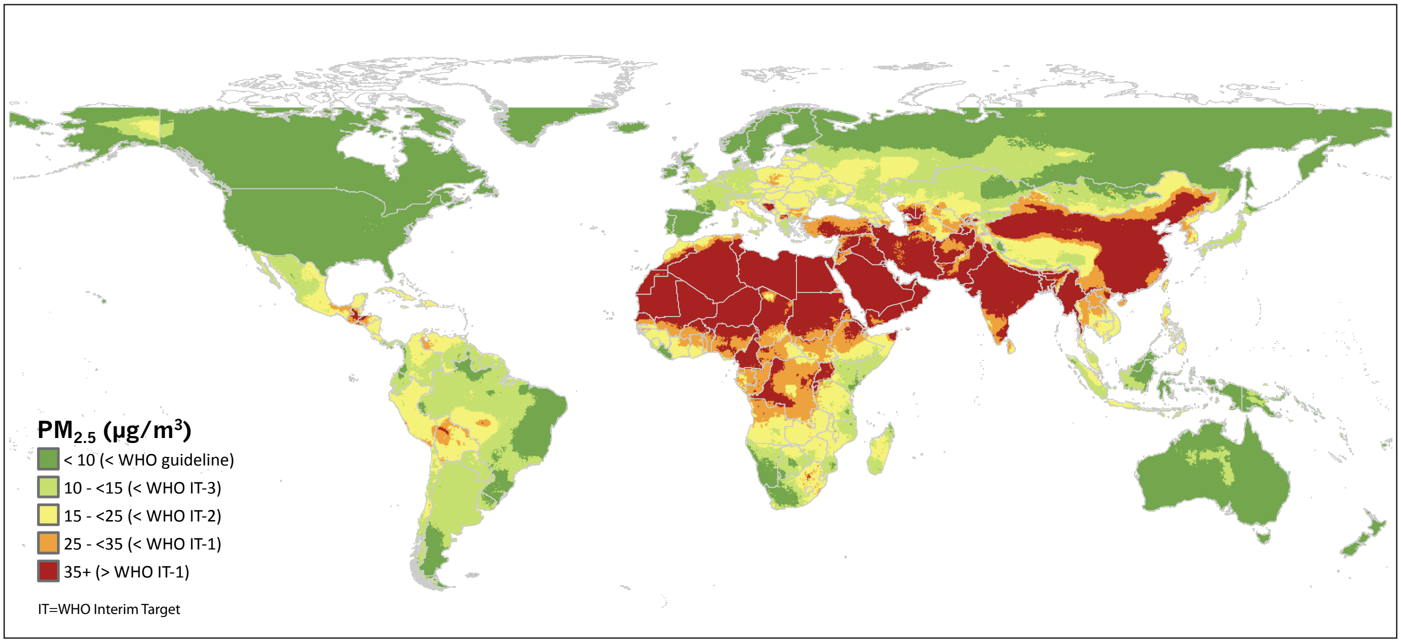
The highest concentrations of population-weighted average $PM_{2.5}$ in 2015 were in North Africa and the Middle East, due mainly to high levels of windblown mineral dust. At the country level, estimates of

Figure 2. Average annual population-weighted $PM_{2.5}$ concentrations in 2015.



Explore the data on the State of Global Air interactive website. For country abbreviations, see ISO3 website.

Figure 3. Comparison of annual average $PM_{2.5}$ concentrations in 2015 with WHO Air Quality Guidelines.



population-weighted average concentrations in 2015 were highest in Qatar (107 µg/m^3), Saudi Arabia (106 µg/m^3), and Egypt (105 µg/m^3).

The next highest concentrations appear in South Asia (especially northern India and Bangladesh) and Southeast Asia, eastern China, and Central and Western sub-Saharan Africa, due to combustion emissions from multiple sources, including household solid fuel use, coal-fired power plants, agricultural and other open burning, and industrial and transportation-related sources. The population-weighted annual average concentrations were 89 µg/m^3 in Bangladesh, 75 µg/m^3 in Nepal, and 74 µg/m^3 in India. The population-weighted average $PM_{2.5}$ concentration in China was 58 µg/m^3, with substantial variation in concentrations among provinces (19–79 µg/m^3).

In 2016, HEI published a report on the major sources of $PM_{2.5}$ related to human activity in China, a result of HEI's Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project. It found that coal-burning by industry, power plants, and households accounted for nearly 40% of population-weighted $PM_{2.5}$ concentrations in China overall (see the textbox "Understanding the Major Sources of $PM_{2.5}$: The GBD MAPS Project" on page 7).

Estimates for annual average population-weighted $PM_{2.5}$ concentrations were lowest (≤ 8 µg/m^3) in Brunei, Sweden, Greenland, New Zealand, Australia, Finland, Canada, and several Pacific and Caribbean island nations.

ASSESSING DIFFERENCES IN $PM_{2.5}$ CONCENTRATIONS

One approach to putting global air quality into perspective is to compare the ambient concentrations to the Air Quality Guidelines established by the WHO. In 2005, WHO set the Air Quality Guideline for annual average $PM_{2.5}$ concentration at 10 µg/m^3, with three interim targets (ITs) for reaching that goal set at progressively lower concentrations (35 µg/m^3, 25 µg/m^3, and 15 µg/m^3). Figure 3 shows where these limits are exceeded.

Over 90% of the world's population lived in areas with unhealthy air in 2015.

Based on these data and information about the populations in each country for 2015, 92% of the world's population lived in areas that exceeded the WHO 10 µg/m^3 guideline. Fifty percent of the global population resided in areas with $PM_{2.5}$ concentrations above the WHO Interim Target 1 (IT-1 of 35 µg/m^3); 64% lived in areas exceeding IT-2 (25 µg/m^3); and 81% lived in areas exceeding IT-3 (15 µg/m^3). Nearly all (86%) of the most extreme concentrations (above 75 µg/m^3) were experienced by populations in China, India, Pakistan, and Bangladesh.

MAIN TRENDS IN $PM_{2.5}$ CONCENTRATIONS

Global population-weighted $PM_{2.5}$ concentrations increased by 11.2% from 1990 (39.7 µg/m^3) to 2015 (44.2 µg/m^3). Since 2010, the increase was somewhat more rapid. This increase reflects major changes in air pollution levels in the most populous countries of the world.

Figure 4 illustrates the trends in population-weighted $PM_{2.5}$ concentrations for the 10 most highly populated countries in the world along with the European Union from 1990 to 2015. India, Bangladesh, and China have experienced both high levels and increasing trends in $PM_{2.5}$ exposure, but there are noteworthy distinctions between countries. Although in China substantial increases in population-weighted concentrations occurred between 1990 and 2010, reflecting in part the dramatic scale of economic development over the last 25 years, the increases in exposure appear to have stabilized since

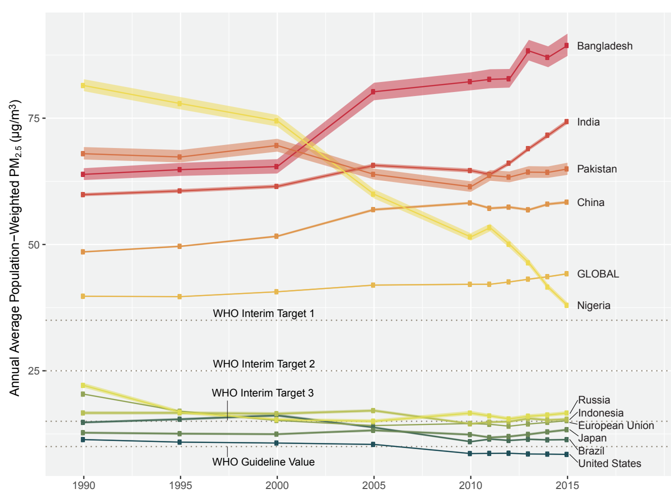
2010. Bangladesh and India, on the other hand, have experienced the steepest increases in air pollution levels since 2010 and now have the highest $PM_{2.5}$ concentrations among the countries shown here. In a reverse phenomenon, the trend data suggest dramatic declines in $PM_{2.5}$ exposures in Nigeria over the last 25 years; limited evidence points to declines in mineral dust emissions and open burning.

Among the 10 most populous countries and the EU, Bangladesh and India now have the highest exposures to $PM_{2.5}$, having experienced the steepest increases since 2010.

Populous countries with the lowest population-weighted concentrations of $PM_{2.5}$ are clustered at the bottom of the figure and include, in decreasing order, Russia, Indonesia, the European Union, Japan, Brazil, and the United States. Concentrations in all these locations have declined slightly since 1990 and, with the possible exception of Japan, appear relatively stable over the last 10 years.

The disparities among these large countries have grown substantially over time. Less-polluted locations have become cleaner, while $PM_{2.5}$ concentrations have increased in the more polluted locations. As a result, what was a 7-fold range in average population-weighted concentrations among these countries in 1990 increased to a 10-fold range in 2015.

Figure 4. Trends in annual average population-weighted $PM_{2.5}$ concentrations in the 10 most populous countries plus European Union.



Explore the data on the State of Global Air interactive site.

How Are Air Pollution Levels Estimated Around the World?

Although many high-income countries around the world operate extensive networks of air quality monitoring stations in urban areas, providing continuous hourly measurements of pollution levels each day, this is not the case for most countries. These ground measurements of air quality have been the basis for most studies of the potential health effects of air pollution and air quality management. However, other approaches are needed to provide a consistent view of air pollution levels throughout the world, including in the many rapidly developing urban areas of low- and middle-income countries and in the large rural and suburban areas that lack any air quality monitoring stations. For these areas, scientists rely on air quality observations from satellites, combined with information from global chemical transport models and available ground measurements, to estimate global annual average exposure to $PM_{2.5}$ systematically, beginning in blocks, or grid cells, covering 0.1° × 0.1° of longitude and latitude (approximately 11 km × 11 km at the equator). Taking into account the population in each block within a country, scientists then aggregate the estimated exposure concentrations to national-level population-weighted averages for a given year. The GBD analysis was conducted in 2016 using data in five-year intervals from 1990 to 2015, the most recent year for which the necessary data were available. For ozone, a global chemical transport model was used to calculate a seasonal (summer) average for each grid cell, while accounting for variation in the timing of the ozone season in different parts of the world. The process for estimating national-level population-weighted average ozone exposures was the same.

HOW AMBIENT OZONE CONCENTRATIONS VARY

The global map of seasonal average population-weighted ozone concentrations around the world (Figure 5) indicates that ozone concentrations are generally less variable spatially compared with $PM_{2.5}$. (Scientists focus on seasonal, rather than annual, averages of ozone because ozone concentrations are higher in the warm season in the mid-latitudes, where most epidemiological studies have been conducted.)

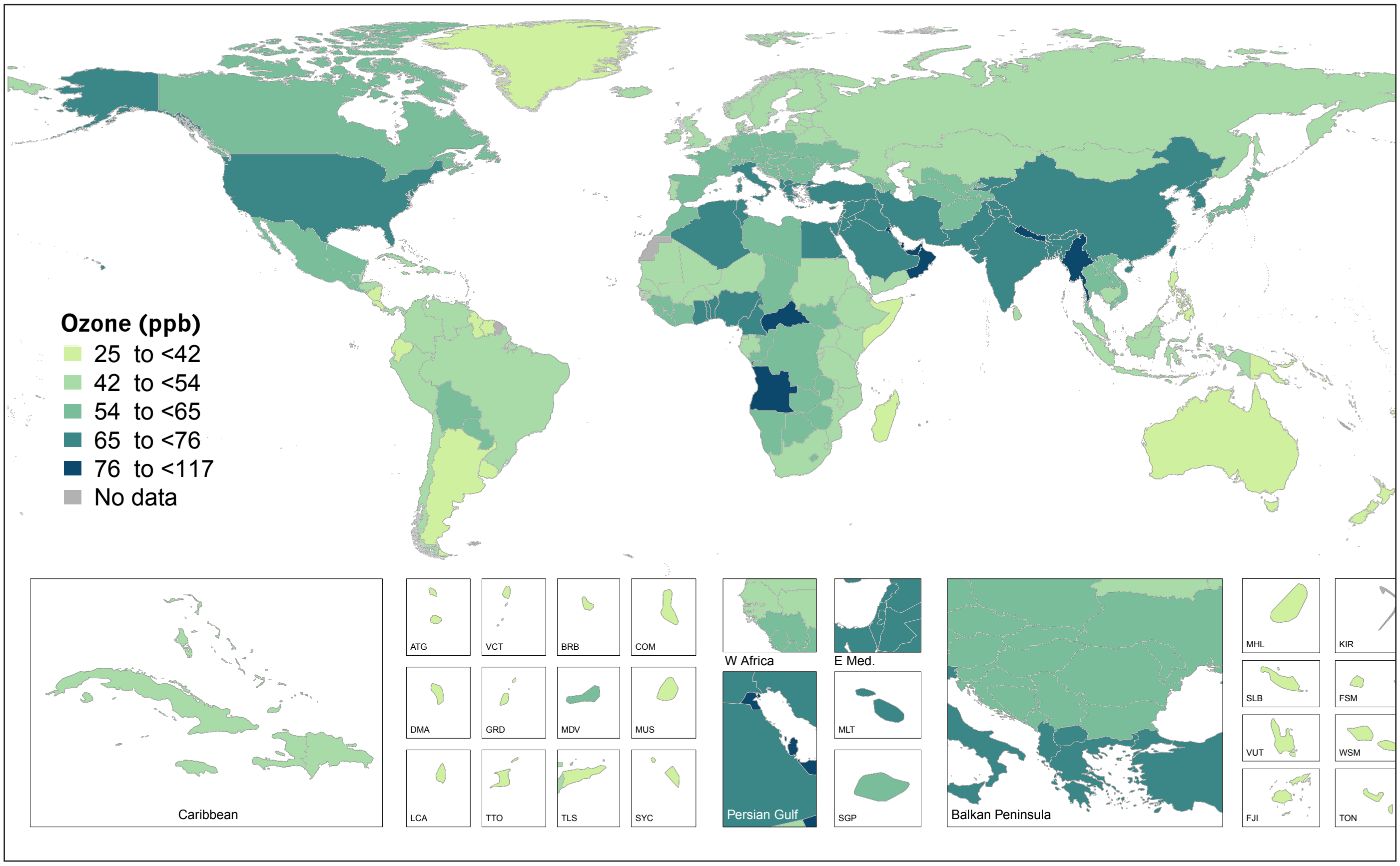
Population-weighted ozone concentrations were relatively higher in the United States, Western and Central sub-Saharan Africa, and throughout the Mediterranean, the Middle East, South Asia, and China.

MAIN TRENDS IN OZONE CONCENTRATIONS

From 1990 to 2015, population-weighted ozone concentrations increased by about 7% globally (see global trend in Figure 6). This trend reflects a combination of factors, including increased emissions of ozone precursors such as nitrogen oxides, coupled with warmer temperatures, especially at mid-latitudes in rapidly developing economies.

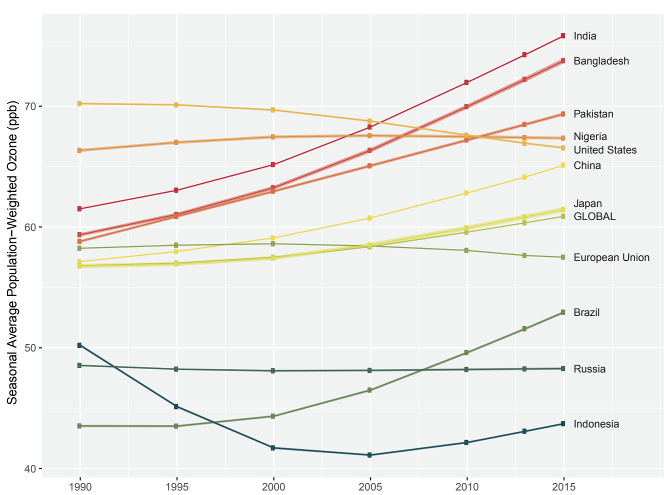
Among the world's 10 most populous countries and the European Union, the largest increases (14% to 25%) in seasonal average popu-

Figure 5. Seasonal average population-weighted ozone concentrations in 2015.



For country abbreviations, see ISO3 website.

Figure 6. Trends in seasonal average population-weighted ozone concentrations in the most populous countries.



Explore the data on the State of Global Air interactive site.

lation-weighted concentrations of ozone over the last 25 years were experienced in China, India, Pakistan, Bangladesh, and Brazil (Figure 6). In Indonesia, decreases observed until 2005 have begun to be offset by more recent increases, reflecting regional trends in precursor emissions.

Not all regions of the world have seen these increases. In the United States, estimated population-weighted ozone concentrations have decreased by about 5% since 1990 and, in the European Union, by about 2% since 2000. These decreases most likely reflect the impact of air quality management programs.

Understanding the Major Sources of $PM_{2.5}$: The GBD MAPS Project

We know that air pollution from fine particulate matter (less than or equal to 2.5 μm in aerodynamic diameter, or $PM_{2.5}$) exacts a toll on human health, both globally and in individual countries. The Global Burden of Disease (GBD) 2015 report estimates that $PM_{2.5}$ contributed to more than 4 million deaths worldwide, over 50% of which occurred in China and India.

Coal-burning by industry, power plants, and for home heating accounted for 40% of $PM_{2.5}$ exposures and an estimated 366,000 deaths in 2013.

To reduce that toll requires that policy makers have a deeper understanding of the major sources of ambient $PM_{2.5}$, both now and in the future. To meet that need, HEI launched the Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project beginning with its 2016 publication of a major report, Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China . The bar graph here shows the major source sectors named in that report that contribute to deaths attributable to $PM_{2.5}$.

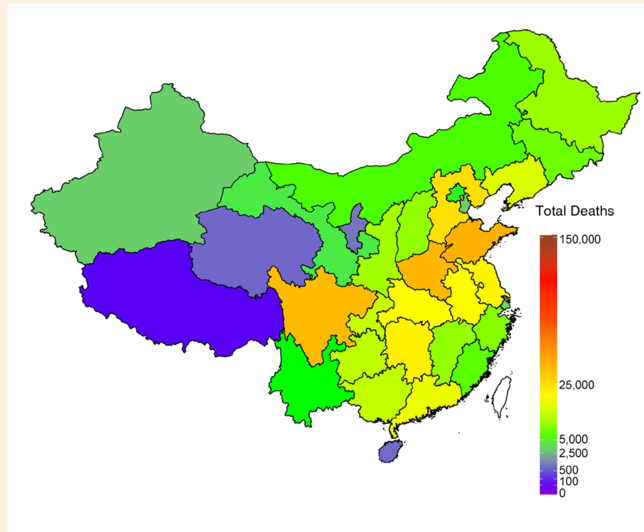
The study found that coal-burning — by industry, by power plants, and for domestic heating — was the most important contributor to ambient air pollution in China (see map in this textbox). Coal-burning from these three sectors combined accounted for 40% of population-weighted ambient $PM_{2.5}$ concentrations and an estimated 366,000 deaths in 2013. China's coal consumption rose from 1,055 billion metric tons in 1990 to 4,244 billion metric tons in 2013, making it the largest producer and consumer of coal in the world.

The industrial sector, comprising both coal (155,000 deaths) and noncoal (95,000 deaths) sources, was the largest contributor to mortality attributable to ambient $PM_{2.5}$, accounting for about 27%. However, household burning of both coal and biomass (e.g., wood and agricultural waste) is also an important contributor to the burden of disease attributable to ambient $PM_{2.5}$. Household combustion of these solid fuels had a combined impact (177,000 deaths) in 2015 that was larger than that from transportation (137,000 deaths) and power plant emissions. Although not represented here, additional mortality is associated with indoor exposures to air pollution from household use of solid fuels (see "How Household Burning of Solid Fuels Affects Public Health" textbox on page 13).

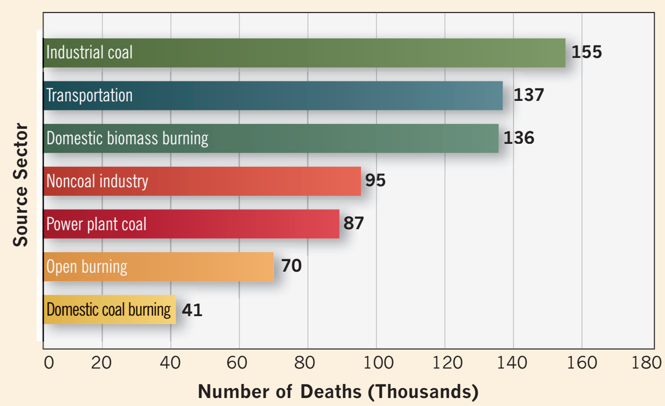
The GBD MAPS China report developed four policy scenarios to evaluate the impacts of different levels of future energy use and pollution control in China. Even under the most stringent policy scenarios, coal was projected to remain the single largest source contributor to ambient $PM_{2.5}$ and to continue to impose the largest health burden from exposure in China in 2030. The findings demonstrated the air quality and health benefits associated with continued aggressive strategies to reduce emissions from coal combustion, along with reductions in emissions from other major sources.

GBD MAPS is a multiyear collaboration among HEI, IHME, Tsinghua University, the University of British Columbia, and other leading academic centers. The next GBD MAPS report, on major air pollution sources in India, will be published in 2017.

Deaths attributable to ambient $PM_{2.5}$ from coal combustion by province in China in 2013.



Source sector contributions to deaths attributable to $PM_{2.5}$ in China in 2013.

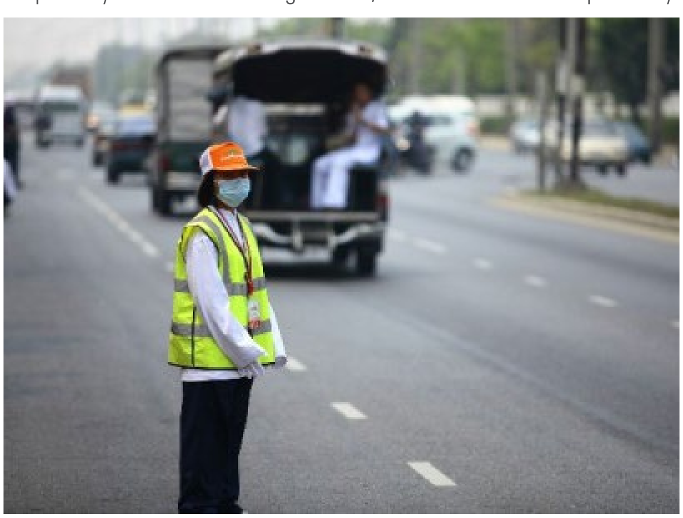


BURDEN OF DISEASE ATTRIBUTABLE TO AMBIENT AIR POLLUTION

What do we mean by "burden of disease" and how is it measured in the GBD project? The GBD project measures the burden of disease for all risk factors including air pollution in terms of (1) deaths in a given year and (2) healthy years of life lost from death or disability, represented by "disability-adjusted life-years," or DALYs (see textbox "Understanding the Burden of Disease: Deaths and DALYs" on page 9). For each risk factor, such as air pollution, considered by the GBD project, these measures of disease burden are estimated for each country or subnational area at 5-year intervals from 1990 to 2015.

Estimating deaths and disease burdens attributable to ambient air pollution in geographical regions over time requires three major components: (1) estimates of population-weighted exposure to $PM_{2.5}$ and ozone, as described earlier in this report (these are compared against a "minimum risk exposure level," an exposure level below which there is no evidence of additional risk of mortality or disease); (2) mathematical functions, derived from epidemiological studies, that relate the different levels of exposure to age, sex, and cause-specific health impacts (e.g., mortality from heart disease and stroke, and incidence of lung cancer); and (3) detailed spatial and temporal estimates of the underlying number of deaths and DALYs for each of the causes of death or disability linked to air pollution. References with more information on these methods are listed in "Additional Resources" at the end of this report.

What are air pollution's effects on health? An extensive scientific literature has documented that long-term exposure to ambient air pollution increases mortality and morbidity from cardiovascular and respiratory disease and lung cancer, and reduces life expectancy.



Systematic reviews of this literature have been undertaken by organizations such as the WHO, the International Agency for Research on Cancer, and the U.S. Environmental Protection Agency, among others (see "Additional Resources"). Based on this large body of evidence, the GBD project concluded that certain diseases could be causally linked with exposure to ambient $PM_{2.5}$ — ischemic heart disease, cerebrovascular disease (ischemic stroke and hemorrhagic stroke), lung cancer, chronic obstructive pulmonary disease (COPD), and lower respiratory infections (LRIs). The GBD project includes only COPD in its assessment of the health impacts attributable to ozone.

A number of studies have also suggested associations between long-term and acute exposure to air pollution and a number of other diseases (e.g., asthma, various adverse birth outcomes, diabetes, and neurological disorders). To date, that evidence has not built to a level sufficient to be included in the GBD project, but it continues to be evaluated for potential inclusion in future GBD and State of Global Air reports.

In 2015, long-term exposure to $PM_{2.5}$ contributed to 4.2 million deaths and to a loss of 103 million years of healthy life. China and India together accounted for 52% of the total global deaths attributable to $PM_{2.5}$.

THE BURDEN OF DISEASE IN 2015 FROM $PM_{2.5}$

In 2015, long-term exposures to ambient $PM_{2.5}$ contributed to 4.2 million deaths (Figure 7) and to a loss of 103 million years of healthy life (DALYs), making $PM_{2.5}$ exposure responsible for 7.6% of all global deaths and 4.2% of all global DALYs. China and India each had the highest absolute numbers of deaths attributable to $PM_{2.5}$. Together, these two countries accounted for 52% of the total global $PM_{2.5}$-attributable deaths and 50% of the DALYs. On a global basis, long-term exposure to ambient $PM_{2.5}$ was responsible for 17.1% of mortality from ischemic heart disease, 14.2% from stroke, 16.5% from lung cancer, 24.7% from LRIs, and 27.1% from COPD in 2015. Of all deaths attributable to ambient $PM_{2.5}$ in 2015, deaths from ischemic heart disease and stroke accounted for the majority (together 57%).

Mainly because of age-related differences in mortality from chronic diseases, $PM_{2.5}$ disproportionately affects very old and very young people. DALYs for those over 70 years old constituted 28% of the total attributable burden, with 21% for children younger than 5 years old. Sixty-one percent of the overall burden attributable to

Understanding the Burden of Disease: Deaths and DALYs

The burden of disease due to exposure to a pollutant is calculated using an estimation of the *number of deaths* and *disability-adjusted life-years* (DALYs). The number of deaths attributable to air pollution in a given year includes deaths that have likely occurred months or even years earlier than might be expected in the absence of air pollution (as in the case of a child dying from an LRI). DALYs provide an overall measure of the loss of healthy life expectancy and are calculated as the sum of the years of life lost from a premature death and the years lived with disability (for example, blindness, caused by the disease diabetes). An important insight gained by using DALYs rather than just the numbers of deaths is that DALYs account for the age at which disease or death occurs. For example, air pollution contributes to LRIs in children, but the number of deaths is small relative to the numbers of primary air pollution–related deaths from heart disease, which tend to occur in older adults. However, because children who die from LRIs have lost many more years of healthy life, this burden is appropriately reflected in a larger number of DALYs.

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

ambient $PM_{2.5}$ was restricted to people 50 and older.

Deaths attributable to long-term exposure to ambient $PM_{2.5}$ in 2015 varied considerably among countries, which reflects the joint influence of air pollution levels and underlying social, demographic, and economic differences among populations. The GBD project has sought to measure these latter characteristics using a sociodemographic index (SDI; see Glossary on the interactive website). In countries with the highest levels of socioeconomic development, exposure to ambient $PM_{2.5}$ contributed to 4.9% of total deaths in 2015, compared with 9.3% in middle-SDI countries and 4.6% in low-SDI countries. These differences in $PM_{2.5}$-attributable deaths largely reflect differences among countries in the fraction of total deaths accounted for by cardiovascular disease, one of the major impacts of air pollution.

After accounting for population size and age structure, age-standardized rates of deaths due to $PM_{2.5}$ exposure differed widely by region of the world. The highest mortality rates were observed in southern (133 deaths/100,000 people), central (85 deaths/100,000 people), and eastern (83 deaths/100,000 people) Asia. Rates were 4- to 8-fold lower in high-income North American (26 deaths/100,000 people), Asia-Pacific (44 deaths /100,000 people), and Western European (41 deaths /100,000 people) countries.

The interactive website allows for detailed comparisons of ambient air pollution–attributable deaths and DALYs (both in absolute numbers and in age-standardized rates) between countries and among various regional groupings (including SDI, for example) for the 1990–2015 time period.

TRENDS IN BURDEN OF DISEASE ATTRIBUTABLE TO $PM_{2.5}$ EXPOSURES

On a global scale, the absolute number of deaths attributable to $PM_{2.5}$ increased from 3.5 million in 1990 to 4.2 million in 2015, due both to increases in air pollution and to growth and aging in the global population.

While the absolute numbers of deaths attributable to $PM_{2.5}$ increased by 20% from 1990 to 2015 globally, there was an overall 12.2% decrease in the rate of deaths attributable to $PM_{2.5}$, indicating that the increase in total deaths is largely due to changes in population characteristics. The global trend in $PM_{2.5}$-attributable deaths broadly reflects a balance among different trends in high-, low-, and middle-income countries. The global numbers and trends in $PM_{2.5}$-attributable mortality, while intriguing, can obscure important patterns at the country level that are likely to be more useful to scientists and policy makers interested in understanding and addressing the health burden attributable to poor air quality. India and Bangladesh experienced some of the largest increases in $PM_{2.5}$-attributable mortality, on the order of 50% to 60%. India now approaches China in the number of deaths attributable to $PM_{2.5}$.

Figure 7. Trends in numbers of deaths attributable to $PM_{2.5}$ exposure in the most populous countries for all ages and sexes.

	1990	1995	2000	2005	2010	2015
China	945,300	981,600	1,039,300	1,140,100	1,098,800	1,108,100
India	737,400	795,200	857,300	895,900	957,000	1,090,400
European Union	329,700	302,600	269,700	244,700	240,500	257,500
Russia	133,200	162,000	157,300	157,700	138,100	136,900
Pakistan	82,300	98,200	110,800	115,700	123,600	135,100
Bangladesh	81,200	80,300	85,700	101,000	110,300	122,400
United States	106,000	107,200	106,200	100,000	83,400	88,400
Indonesia	53,200	57,300	64,400	71,100	71,400	78,600
Japan	38,100	40,700	41,800	48,200	50,800	60,600
Brazil	42,200	45,900	49,300	46,900	43,100	52,300
Nigeria	76,800	78,900	79,400	67,700	59,800	50,900

Deaths: 1,000,000; 400,000; 150,000; 50,000

	1990	1995	2000	2005	2010	2015
GLOBAL	3,476,700	3,654,800	3,794,000	3,934,300	3,944,700	4,241,100

Deaths: 4,200,000; 4,000,000; 3,800,000; 3,600,000

Figure 8. Trends in age-standardized DALY rates (DALYs/100,000 people) due to $PM_{2.5}$ exposure.

	1990	1995	2000	2005	2010	2015
Pakistan	3,600	3,800	3,800	3,500	3,300	3,100
Bangladesh	4,100	3,700	3,400	3,400	3,200	3,000
India	4,100	3,900	3,700	3,300	3,000	2,900
Nigeria	4,100	3,700	3,400	2,600	2,100	1,600
GLOBAL	2,500	2,300	2,100	1,900	1,600	1,500
China	3,200	2,900	2,600	2,200	1,800	1,500
Russia	1,700	2,100	2,000	1,900	1,500	1,300
Indonesia	1,500	1,400	1,300	1,300	1,100	1,100
Brazil	1,300	1,200	1,000	800	600	600
European Union	1,000	800	700	500	500	400
United States	700	600	500	500	400	300
Japan	400	400	300	300	300	300

DALY rate: 4000; 3000; 2000; 1000

Explore the data on the State of Global Air interactive site.

India and Bangladesh experienced some of the largest increases in $PM_{2.5}$-attributable mortality, on the order of 50% to 60%. India now approaches China in the number of deaths attributable to $PM_{2.5}$.

In the 10 most populous countries and the European Union, trends in the numbers of $PM_{2.5}$-attributable deaths (Figure 7) reflect a combination of sometimes competing factors — changes in $PM_{2.5}$ levels and in the size, age, and disease rates of the populations exposed. These same countries and the EU all experienced decreases in age-standardized DALY rates and mortality rates. In China, India, Bangladesh, and Japan, increases in exposure, combined with increases in population growth and aging, resulted in net increases in attributable mortality. Decreases in exposure in Russia, Brazil, Indonesia, and Pakistan were offset by population growth and population aging, resulting in net increases in attributable mortality. In the United States and the European Union, reductions in exposure over the past 25 years have offset the contributions of population growth and aging, resulting in net decreases in $PM_{2.5}$-attributable mortality (by 17% and 22%, respectively). A similar pattern contributed to a net decrease of 34% in $PM_{2.5}$-attributable mortality in Nigeria, although the reductions in exposure were likely due to factors different from those in the United States and EU. Within the EU, this pattern held in all member countries except Italy, Greece, and Malta, where attributable mortality increased from 1990 to 2015.

As discussed earlier, DALYs grant additional insight into the burden of disease attributable to $PM_{2.5}$ exposure by providing a comprehensive measure of years of healthy life lost, due both to dying prematurely and to the years living with disability (see earlier text-box, "Understanding the Burden of Disease"). Many scientists prefer age-standardized DALY rates (DALYs/100,000 people) because they allow direct comparisons between populations of different sizes and age structures. The DALY rates attributable to $PM_{2.5}$ for the 10 most populous countries, the European Union, and the world are therefore presented in Figure 8.

Pakistan, Bangladesh, and India had $PM_{2.5}$-attributable DALY rates that were 5 to 10 times the lowest rates, which were found in the United States and Japan. Although the DALY rates within countries have been improving in general from 1990 to 2015, reflecting some improvements in underlying life expectancy and health, the large disparities across countries have persisted and even increased.

BURDEN OF DISEASE ATTRIBUTABLE TO OZONE EXPOSURES IN 2015 AND TRENDS

Ozone contributes to the global health burden through its impact on deaths and disability from COPD. In 2015, ambient ozone contributed to 254,000 deaths, making it the 33rd highest ranking risk factor globally for deaths in the GBD 2015 analyses (see Figure 1). Ozone also contributed to 4.1 million DALYs globally.

Globally there was a 60% increase in ozone-attributable deaths, with a striking 67% of this increase occurring in India.

Although the number of deaths attributable to ozone is smaller than that for $PM_{2.5}$, ozone-attributable mortality has increased proportionally more — up nearly 60% globally since 1990. In 2015, ozone was responsible for 8% of global mortality related to COPD, up from 5% in 1990. Higher contributions (~10%) were experienced in India and Bangladesh.

The disparities between countries in the ozone-attributable health burden are illustrated in Figure 9, which shows trends in the numbers of deaths from COPD attributable to exposure to ozone for the 10 most populous countries and the European Union from 1990 to 2015. As the most populous countries, India and China account for most of the ozone-attributable COPD deaths across all years, but India accounts for much (about 67%) of the global increase since 1990. Over the last 25 years, India experienced a nearly 150% increase in ozone-attributable deaths, while China's number remained about the same. The ozone-attributable COPD mortality rate decreased by about 1% over this time period in the United States and Indonesia, and remained relatively stable in Russia and the European Union.

As with $PM_{2.5}$-attributable mortality, the increases in deaths attributable to ozone exposure from 1990 to 2015 were driven by increases in concentrations of ozone throughout most of the globe (see Figure 6), by population aging, and by the increased rates of mortality from COPD, especially in South Asia.

Figure 9. Trends in numbers of deaths from COPD attributable to exposure to ozone for all ages and sexes.

Explore the data on the State of Global Air interactive site.

CONCLUSIONS

The GBD project plays a key role in identifying the factors that contribute most to disease and mortality — the first step toward identifying what can be done to improve public health. Among the 79 risk factors included in its comprehensive analysis, the GBD project reported that exposure to ambient air pollution from $PM_{2.5}$ ranked 5th globally in its contribution to mortality in 2015, accounting for over 4.2 million deaths, with an additional 254,000 attributable to exposure to ozone. The GBD project has also laid out the critical interplay between trends in population structure, underlying disease, and economic factors and trends in air pollution. Knowledge of these trends is essential to understanding patterns in the burden of disease experienced by the populations of different countries and regions and to helping to inform decision makers where policy action to reduce population exposure at the national or regional levels has the most potential to provide large benefits in improved health.

Progress in reducing the burden of disease attributable to air pollution will require continued tracking and analysis. This first annual State of Global Air report and the rich data resources found on the accompanying interactive website seek to build on GBD 2015 analyses to provide a deeper understanding of the regional and national patterns of $PM_{2.5}$ and ozone exposures and their contributions to death and disease. The State of Global Air site is the only source that makes available for exploration and downloading comprehensive air quality data for 1990 through 2015 (population-weighted, annual average air pollution levels), linked to health data (population estimates of attributable deaths and disease burden) for all countries and regions in the world.

FUTURE UPDATES

This year's State of Global Air report and interactive website are only the beginning. Both will be updated each year as a companion to the annual release of the GBD results, adding pollutants and health outcomes as they meet the rigorous inclusion criteria of the larger GBD project. For example, the links between long-term and acute exposure to air pollution and a number of diseases other than those discussed in this year's report (e.g., asthma, various adverse birth outcomes, diabetes, and neurological disorders) have been suggested by a number of studies. However, to date, the evidence has not been considered sufficient to be included in the GBD project. Other updates on the state of global air to be included in future years will focus on understanding important sources of air pollution and health impact, both at the global and national level. Household burning of coal, biomass, and other solid fuels is one such example (see the textbox "How Household Burning of Solid Fuels Affects Public Health" on page 13). Another will be the GBD MAPS study in India that is forthcoming in 2017. Because national averages can obscure important local differences, we plan further analysis of air pollution and health burden for provincial and other subnational units as data for them become available. Finally, next year's report will highlight examples of cities and countries that have successfully improved air quality and public health and will share information on the actions they took to accomplish those improvements.

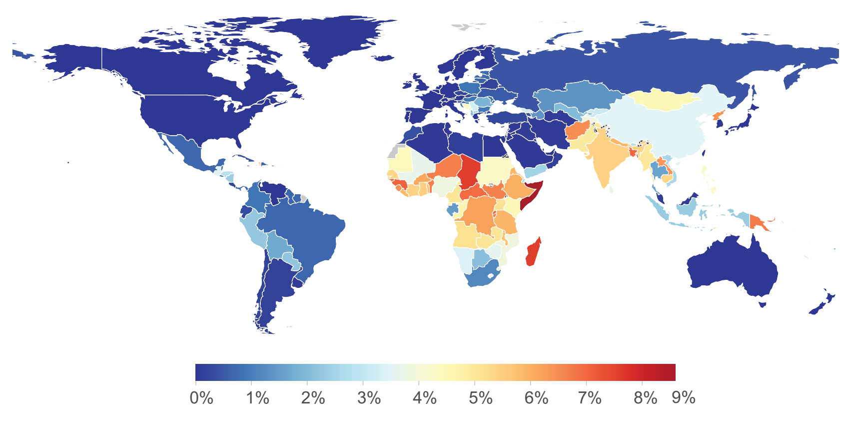
How Household Burning of Solid Fuels Affects Public Health

In many parts of the world, household burning of solid fuels—including coal, wood, charcoal, dung, and other agricultural residues for cooking and heating—can contribute to high levels of pollution exposure and to substantial impacts on mortality and health. Figure 1 in the main text shows that, worldwide, household air pollution ranks 10th among risk factors for mortality, contributing to approximately 2.85 million deaths in 2015 from cardiovascular disease, COPD, LRIs, and lung cancer. Among children less than 5 years old, it is the 7th leading risk factor for death due to its impact on acute respiratory infections such as pneumonia. In South Asia, household air pollution is the 4th leading mortality risk factor. Among countries considered "low income" by the World Bank, household air pollution ranks even higher; it is the 2nd leading mortality risk factor for that population.

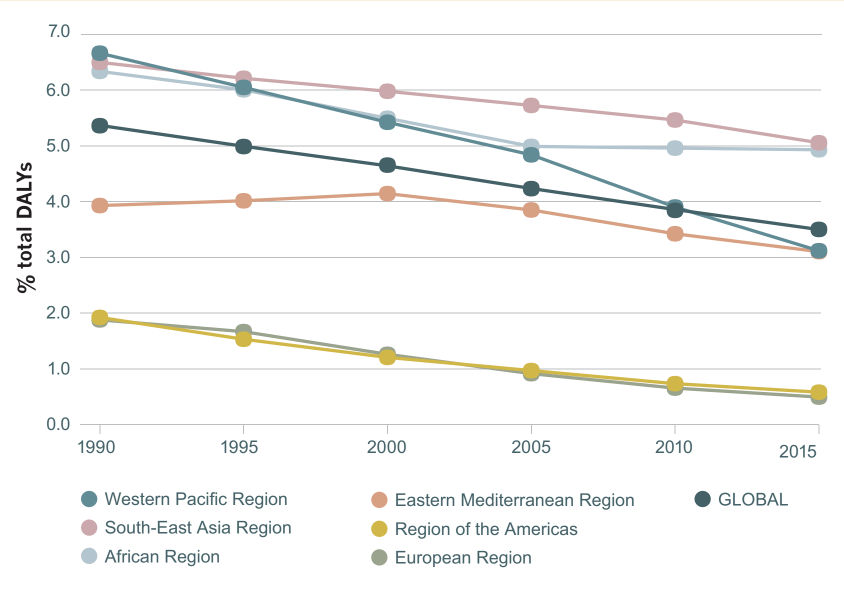
The burden of increased mortality and disease from household air pollution falls most heavily on countries in Africa and in Asia where solid fuels are more extensively used (see the global map in this textbox, showing health burden measured by the percentage of all DALYs in a country). Although still responsible for a substantial impact on global disease burden, the trends in percentage of all DALYs attributable to household air pollution are encouraging across all regions (see line graph in this textbox). Since 1990 there has been a 15.5% decrease globally in total deaths (a 39% decrease in death rates) and a 37% decrease in total DALYs (a 55% decrease in DALY rates) associated with household air pollution exposures.

Although household air pollution is tracked as an independent risk factor, it is also an important source of outdoor air pollution, so reducing household air pollution has added benefits for public health that are not reflected in these statistics.

Percentage of total DALYs in each country attributable to household air pollution in 2015.



Trends in percentage of total DALYs attributable to household air pollution by region, 1990–2015, using WHO-defined regions.



ADDITIONAL RESOURCES

GBD 2015

Details on the methods used to estimate $PM_{2.5}$ and ozone exposures and to estimate deaths and disability adjusted life years (DALYs) for the GBD 2015 analyses can be found in these studies and their related references:

GBD 2015 Risk Factors Collaborators. 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. Lancet 388:1659–1724.

Shaddick G, Thomas ML, Jobling A, Brauer M, van Donkelaar A, Burnett R, et al. Data integration model for air quality: a hierarchical approach to the global estimation of exposures to ambient air pollution. Available: *https://arxiv.org/abs/1609.00141* [accessed 24 January 2017].

Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, et al. 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet; doi:10.1016/S0140-6736(17)30505-6 [Online 10 April 2017].

At the GBD Compare website, data on mortality and disease burden for air pollution, as well as other risk factors, may be further explored and downloaded.

$PM_{2.5}$ AND OZONE HEALTH EFFECTS

For comprehensive reviews of the scientific evidence on the health effects associated with exposures to $PM_{2.5}$ and ozone from WHO, IARC, and the U.S. Environmental Protection Agency, see the following:

International Agency for Research on Cancer. 2016. Outdoor air pollution. IARC Monogr Eval Carcinog Risk Hum 109:1–488. Available: *http://monographs.iarc.fr/ENG/Monographs/vol109/mono109.pdf* [accessed 24 January 2017].

U. S. EPA. 2009. Final Report: Integrated Science Assessment for Particulate Matter. EPA/600/R-08/139F, 2009. Washington, DC:U. S. Environmental Protection Agency. Available: *http://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=216546* [accessed 11 January 2017].

U.S. EPA. 2013. Final Report: Integrated Science Assessment for Ozone and Related Photochemical Oxidants. EPA/600/R-10/076F, 2013. Washington, DC:U.S. Environmental Protection Agency. Available: *https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=247492* [accessed 11 January 2017].

World Health Organization. 2015. Air Quality Guidelines: Global Update 2005. WHO Reg Off Eur [online 22 December 2015]. Available: *www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/* [accessed 11 January 2017].

NUMBERS, NUMBERS EVERYWHERE

Listed below are the reports and papers referred to in the textbox "Numbers, Numbers Everywhere" on page 2:

International Energy Agency. 2016. Energy and Air Pollution: World Energy Outlook Special Report. Paris, France:International Energy Agency. Available: *www.iea.org/publications/freepublications/publication/weo-2016-special-report-energy-and-air-pollution.html* [accessed 11 January 2017].

Organization of Economic Cooperation and Development. 2014. The Cost of Air Pollution: Health Impacts of Road Transport. Paris:OECD Publishing. Available: *http://dx.doi.org/10.1787/9789264210448-en* [accessed 11 January 2017].

World Health Organization. 2016. Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. Geneva:World Health Organization. Available: *http://apps.who.int/iris/bitstream/10665/250141/1/9789241511353-eng.pdf?ua=1* [accessed January 24 2017].

World Bank and Institute for Health Metrics and Evaluation. 2016. The Cost of Air Pollution: Strengthening the Economic Case for Action. Washington, DC: World Bank. Available: *http://documents.worldbank.org/curated/en/781521473177013155/pdf/108141-REVISED-Cost-of-PollutionWebCORRECTEDfile.pdf* [accessed 24 January 2017].

World Health Organization. WHO Global Urban Ambient Air Pollution Database (Update 2016). Available: *www.who.int/phe/health_topics/outdoorair/databases/cities/en/* [accessed 11 January 2017].

CONTRIBUTORS AND FUNDING

CONTRIBUTORS

Health Effects Institute: HEI is an independent global health and air pollution research institute, a leader of the air pollution analysis within the Global Burden of Disease (GBD) project, and the producer, most recently, of the GBD Major Air Pollution Sources (GBD MAPS) report on China and the upcoming India report. HEI is the primary developer of the State of Global Air report, host and manager for the related website, coordinator of input from all other members of the team, and facilitator of contact with media partners.

The Institute for Health Metrics and Evaluation: IHME is an independent global health research center at the University of Washington, which provides rigorous and comparable measurement — through the GBD project — of the world's most important health problems and the risk factors that contribute to them, and which evaluates the strategies used to address them. A key collaborator, IHME provides the underlying air pollution and health data and other critical support for this project.

University of British Columbia: Professor Michael Brauer of the School of Population and Public Health at UBC is a critical external expert advising on this project. Dr. Brauer is a long-time principal collaborator on the air pollution assessment for the GBD project and led the effort to define the project's global air pollution exposure assessment methodology.

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Glossary

For a glossary of terms, see the State of Global Air website.

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