STATE OF
GLOBAL AIR /2020

A SPECIAL REPORT ON GLOBAL EXPOSURE TO AIR POLLUTION AND ITS HEALTH IMPACTS

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WHAT IS THE STATE OF GLOBAL AIR?

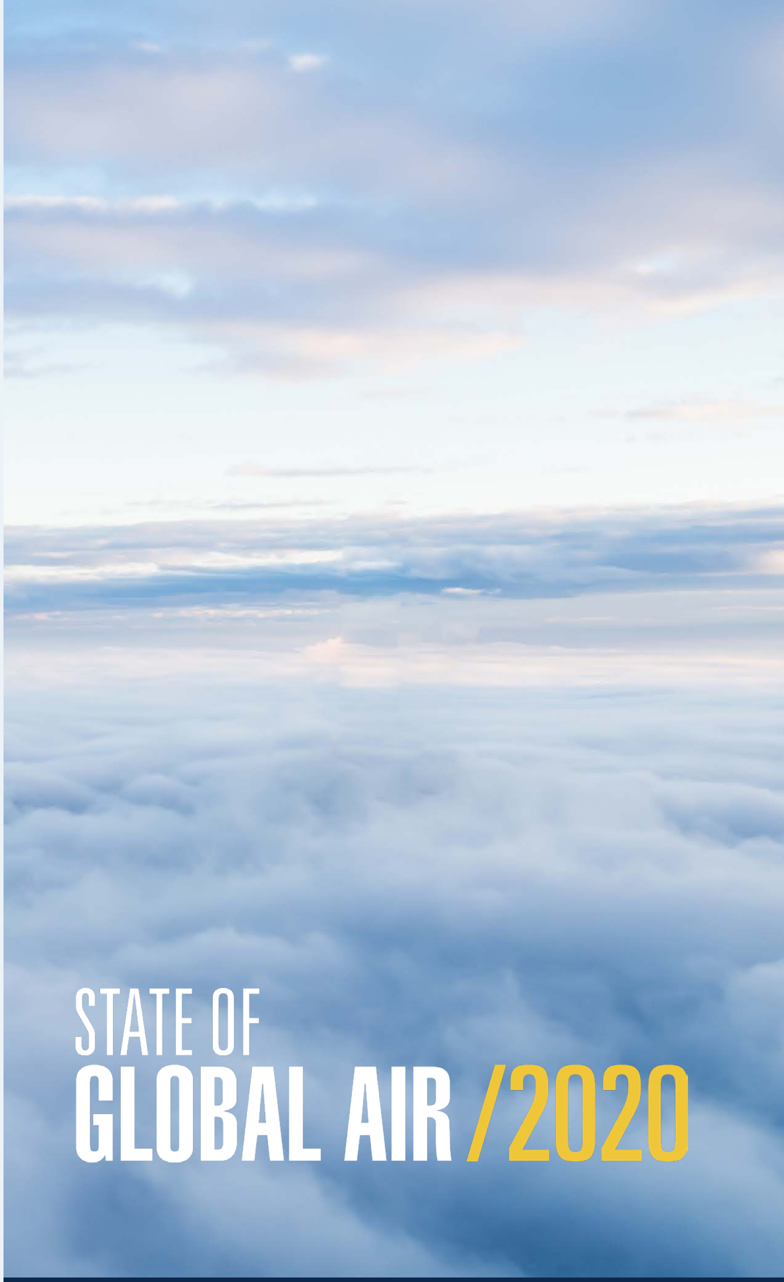
The *State of Global Air* report and interactive website bring into one place a comprehensive analysis of the levels and trends in air quality and health for every country in the world. They are produced annually by the Health Effects Institute and the Institute for Health Metrics and Evaluation's (IHME's) Global Burden of Disease (GBD) project and are a source of objective, high-quality, and comparable air quality data and information.

WHO IS IT FOR?

The report and website are designed to give citizens, journalists, policy makers, and scientists access to reliable, meaningful information about air pollution exposure and its health effects. These resources are free and available to the public.

HOW CAN I EXPLORE THE DATA?

This report has a companion interactive website with tools to explore, compare, and download data and graphics reflecting the latest air pollution levels and associated burden of disease. Anyone can use the website to access data for over 200 individual countries, territories, and regions, as well as track trends from 1990 to 2019. Find it at stateofglobalair.org.



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INTRODUCTION

As a result of the COVID-19 pandemic, public health has rocketed to the forefront of our collective concerns. We are continuing to learn about the damaging effects of COVID-19 infection, an invisible threat to our respiratory and cardiovascular health carried through the air we breathe. At the same time, the pandemic has brought renewed attention to another global airborne threat to public health, not entirely invisible, but one that continues to be ignored in many parts of the world — air pollution. While COVID-19's effects may appear in a few short weeks, the health consequences of air pollution may take years to manifest themselves in the form of chronic diseases. And yet, as we have learned in recent months, the underlying toll that air pollution has taken on respiratory and cardiovascular health over time has made individuals more vulnerable to the effects of COVID-19.

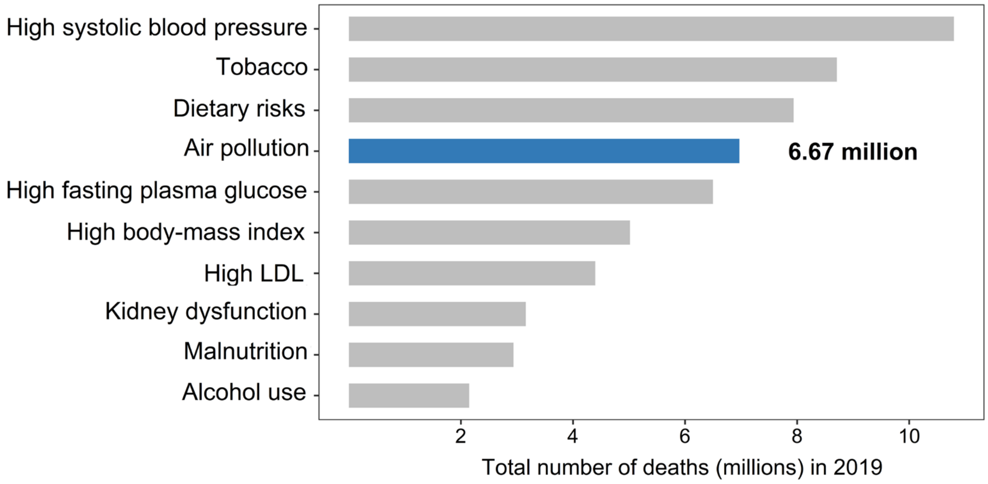
The drastic shifts that economic shutdowns required have made more visible the impacts of our own human activities on air pollution. Just as the COVID-19 crisis has demonstrated the need for multiple strategies to manage the pandemic, it has also provided an unexpected opportunity to understand what we can do better to address air pollution. Solutions to air pollution will require multifaceted ongoing efforts to bring attention to its health threats, to identify the policy changes necessary to control it, and to monitor progress over time.

The *State of Global Air* supports these efforts by providing a global report card on the current status of air pollution and health worldwide, the progress that has been made, and where problems persist or are getting worse. Since we first launched the *State of Global Air* nearly five years ago, air pollution has risen to the top of environmental concerns worldwide. In 2019, air pollution moved up from the 5th to the 4th leading risk factor for death globally, continuing to exceed the impacts of other widely recognized risk factors for chronic disease like obesity (high body-mass index), high cholesterol, and malnutrition (Figure 1). An important factor behind this shift is that the calculations now, for the first time, include air pollution's effects on the health of babies in their first month of life. And over the last several decades scientists have continued to build an extensive body of evidence on the risks that breathing poor-quality air poses to human health and our environment, perhaps the most extensive evidence that exists for any environmental risk factor.

Air pollution was the 4th leading risk factor for early death worldwide in 2019, surpassed only by high blood pressure, tobacco use, and poor diet.

Despite all that is known about the effects of air pollution on health, the findings in 2019 show that little or no progress has been made in many parts of the world. Major disparities continue to exist; air quality has improved in many high-income countries over the past

FIGURE 1 Global ranking of risk factors by total number of deaths from all causes in 2019.



several decades, while dangerous levels of air pollution persist in low- and middle-income countries. And evidence is mounting that air pollution can cause harm at much lower levels than previously thought, suggesting that even high-income countries need to continue their efforts to reduce exposure and to ensure that the progress achieved is not lost over time. Systematic and consistent efforts to track progress toward reducing air pollution and the impacts it has on human health remain essential.

What differentiates the *State of Global Air* from the near-daily updates on air pollution in the news? We work with the Institute for Health Metrics and Evaluation's (IHME's) Global Burden of Disease (GBD) project, a unique resource, where high-quality and internally consistent state-of-the-art methods have been applied to estimate current status and yearly trends in exposures and burden of disease from 87 risk factors or groups of factors in 204 countries and territories. Updated annually, this comparative risk assessment approach gives scientists, citizens, and policy makers the opportunity to understand both the absolute and relative importance of the multiple risks that contribute to burden on public health, putting air pollution into perspective.

This year's *State of Global Air* report focuses on key takeaways on the levels and trends in air pollution for the world's major regions and most populous countries. However, a much larger trove of data — with detailed statistics for every country in the world, tools for generating custom data tables and graphs, and factsheets for selected countries — is available at stateofglobalair.org.

WHAT'S NEW THIS YEAR?

Every year, the GBD project incorporates the latest scientific evidence and methods to refine estimates of the burden of disease — or impacts on population health — from air pollution and other risk factors. These are the primary updates for 2019:

Inclusion of air pollution's effects on adverse birth outcomes. Over the past decade, a growing body of scientific evidence has indicated that women who are chronically exposed to particulate air pollution are more likely to have babies born too small (low birth weight) or too early (preterm birth). These children are at greater risk of a range of health effects, which are now reflected in the health burden estimates for babies in their first month of life.

Improvements to $PM_{2.5}$ exposure estimates. The database of ground measurements of $PM_{2.5}$ (particles measuring less than 2.5 micrometers in aerodynamic diameter) has been expanded from 9,960 to 10,408 sites in 116 countries.

Exclusion of smoking studies from particulate matter exposure–response functions. In previous years, the integrated exposure–response functions for particulate matter and lung cancer, chronic obstructive pulmonary disease (COPD), lower-respiratory infections, type 2 diabetes, heart disease, and stroke had to rely on evidence from active smoking data to characterize risks at higher levels of exposure. With the availability of new studies of high air pollution conditions in China and South Asia and the new exposure–response modeling approach, the use of evidence from active smoking data is no longer necessary.

Revisions to exposure–response relationships. Using a methodology designed to improve the selection and modeling of all exposure–response relationships, GBD scientists revised the exposure–response functions for 10 risk–outcome pairs within air pollution: particulate matter pollution (ambient and household) and birthweight, preterm birth, lung cancer, COPD, lower-respiratory infections, type 2 diabetes, ischemic heart disease, and stroke; ozone and COPD; and household air pollution and cataracts.

Improvements to estimates of exposure to household air pollution. GBD scientists developed a new method to translate data on the proportion of households in a country using solid fuels for cooking into the proportion of individuals exposed to household $PM_{2.5}$ and their levels of exposure. This new method improves the ability to estimate the burden of disease attributable to household air pollution.

Improvements to ozone exposure estimates. The ozone exposure estimates were improved by doubling the number of monitoring sites from 4,400 to 8,800, combining their data with additional chemical transport models, and improving the spatial resolution of the estimates.

EXPOSURE TO AIR POLLUTION

The *State of Global Air* presents a comprehensive analysis of three types of air pollution known to impact human health: ambient (outdoor) fine particle pollution, ambient tropospheric ozone, and household air pollution. Drawing from the World Health Organization's city-level air quality monitoring database and other key sources, GBD scientists use a systematic approach to estimating exposure to air pollution that is internally consistent — making historical estimates comparable to today's — while taking advantage of the most recent data and advanced modeling and analysis methods. The results, reported here, offer both a comprehensive accounting of exposures and a foundation for informing decisions and actions toward a cleaner world.

The focus of this report is on long-term exposures to each of these air pollutants — exposures that occur over multiple years and that have been shown by studies to be the strongest determinants of the heavy burden from chronic diseases, diseases that persist for a long time and can take several years to develop.

Amit kg/shutterstock.com

Clean Air Collective, India

COVID-19

How Has COVID-19 Affected Air Quality?

The COVID-19 pandemic led to unprecedented restrictions that dramatically reduced global and local travel, shut down schools and businesses, and halted some industrial activity. While there have been significant societal and personal costs, many countries around the world have experienced blue skies and starry nights, often for the first time in many years. Satellite and ground-based air quality monitoring data have shown substantial reductions in concentrations of pollutants such as nitrogen dioxide (NO_2) and, in some cases, modest reductions for other pollutants such as $PM_{2.5}$. At the same time, levels of ozone appear to have increased, in part due to the reductions in NO_2 and changes in meteorological factors including temperature.

As evidence from some countries shows, these changes are only temporary. As restrictions have lifted, emissions have risen — quickly erasing any gains in air quality. Since air pollution's most substantial health burdens arise from chronic, long-term exposure, COVID-19 has offered only a temporary respite from air pollution.

Nonetheless, the blue skies have offered a reminder of what pollution takes away, and actions to restrict the spread of COVID-19 offered only a temporary solution, inspiring renewed demands for cleaner air in the longer term.

The sky in Rajpath, New Delhi, India, in 2018 and during the COVID-19 lockdown in 2020.

AMBIENT FINE PARTICLE AIR POLLUTION

Ambient fine particle air pollution refers to $PM_{2.5}$ (i.e., particles measuring less than 2.5 micrometers in aerodynamic diameter, and less than a 30th of the diameter of a human hair). These particles, as well as precursor chemicals that contribute to their secondary formation in the atmosphere, are emitted from vehicles, coal-burning power plants, industrial activities, waste burning, and many other human and natural sources. Although exposures to both smaller and larger airborne particles can also be harmful, studies have shown that exposure to high average concentrations of $PM_{2.5}$ over the course of several years has been the most consistent and robust predictor of mortality from cardiovascular, respiratory, and other types of diseases.

Ambient $PM_{2.5}$ concentrations are measured in micrograms of particulate matter per cubic meter of air, or µg/m^3. Understanding the concentrations individuals actually experience — their *exposure* — is crucial to estimating the burden of disease associated with $PM_{2.5}$ pollution. The GBD project estimates exposure at the country level as the *population-weighted annual average concentration,* the concentration to which most of a country's population is exposed. (See "How $PM_{2.5}$ Exposure Is Estimated" on page 8.)

Countries in Asia, Africa, and the Middle East continue to experience the highest levels of ambient $PM_{2.5}$.

Global Patterns in Ambient $PM_{2.5}$ Exposure

In 2019, over 90% of the world's population experienced annual average $PM_{2.5}$ concentrations that exceeded the WHO Air Quality Guideline of 10 µg/m^3. The highest annual average exposures were seen in Asia, Africa, and the Middle East (Figure 2). The 10 countries with the highest exposures worldwide are in these regions (Table 1), though given uncertainty in the estimates, the rankings are not absolute. The 10 countries with the lowest exposures (i.e., population-weighted annual average concentrations less than 8 µg/m^3) are Australia, Brunei Darussalam, Canada, Estonia, Finland, Iceland, New Zealand, Norway, Sweden, and the United States.

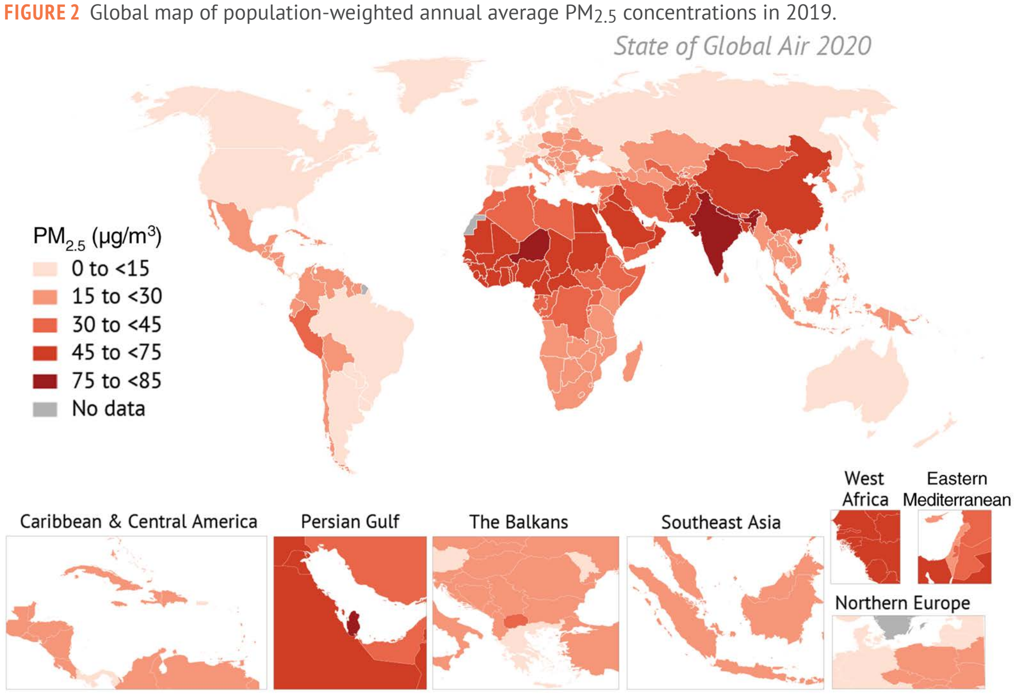
TABLE 1 Top 10 countries with the highest population-weighted annual average $PM_{2.5}$ exposures in 2019

Country	$PM_{2.5}$ Concentration (µg/m^3)	95% Uncertainty Intervals*
India	83.2	76.1 to 90.7
Nepal	83.1	62.9 to 107
Niger	80.1	42.2 to 145
Qatar	76.0	59.2 to 96.6
Nigeria	70.4	45.4 to 105
Egypt	67.9	47.8 to 92.8
Mauritania	66.8	37.6 to 108
Cameroon	64.5	43.8 to 92.6
Bangladesh	63.4	55.1 to 73.8
Pakistan	62.6	49.9 to 77.5

* The 95% uncertainty intervals are a measure of scientific uncertainty. They reflect a range of values, from the 2.5th to the 97.5th percentile of a possible distribution of values, within which the true concentration is likely to fall.

Because these population-weighted $PM_{2.5}$ concentrations represent annual averages across entire countries, they include, but do not represent, the considerably higher concentrations that may be observed day to day or in certain seasons, especially around cities or major pollution sources. Although short-term exposure spikes can affect health, it is long-term exposures that contribute most to the burden of disease and mortality from air pollution, and therefore are the focus of the GBD project.

FIGURE 2 Global map of population-weighted annual average $PM_{2.5}$ concentrations in 2019.



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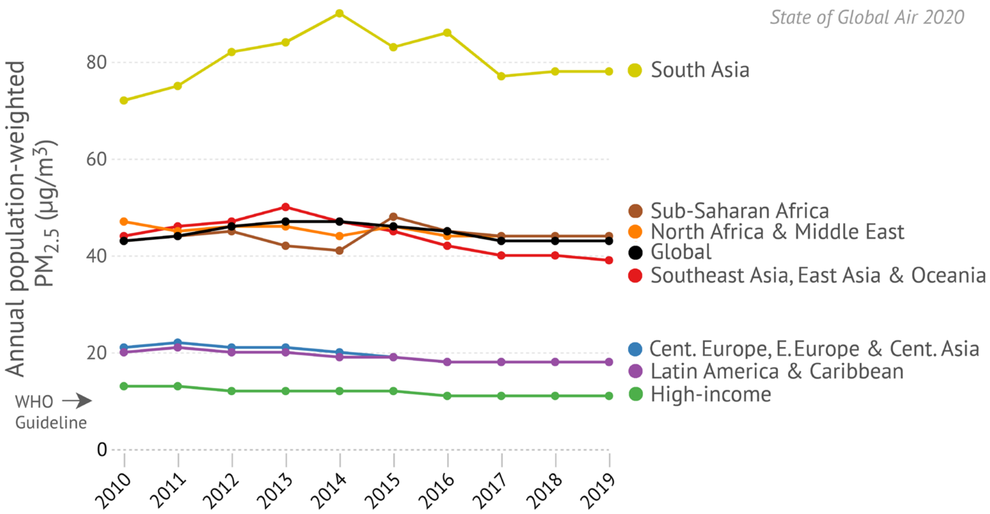
Trends in Ambient $PM_{2.5}$ Exposure

On average, global $PM_{2.5}$ exposures declined slightly from 2010 to 2019 but reflect very different experiences across the GBD Super Regions (countries grouped by similar cause-of-death patterns; Figure i). Some regions have seen improvements, notably Southeast Asia, East Asia, and Oceania, led by China, Vietnam, and Thailand. However, others — in particular North Africa, the Middle East, and sub-Saharan Africa — have experienced little or no progress or even have seen increases in exposures (Figure 3). The disparities in exposure to $PM_{2.5}$ across these regions have largely remained constant over the past decade, with South Asia consistently seeing the highest exposures. In large part, these regional trends track closely with socioeconomic development and national policy actions.

Although $PM_{2.5}$ levels have shown modest improvements in some regions, there has been little or no sustained progress in the most polluted regions.

With the exception of the High-Income Super Region, exposures in all regions continue to exceed the WHO guideline of 10 µg/m3. In fact, four of the seven Super Regions continue to experience $PM_{2.5}$ exposures that exceed even the least-stringent intermediate goal set by the WHO, Interim Target 1, which is 35 µg/m3.

FIGURE 3 Trends in population-weighted annual average $PM_{2.5}$ concentrations globally and in the GBD Super Regions, 2010–2019.



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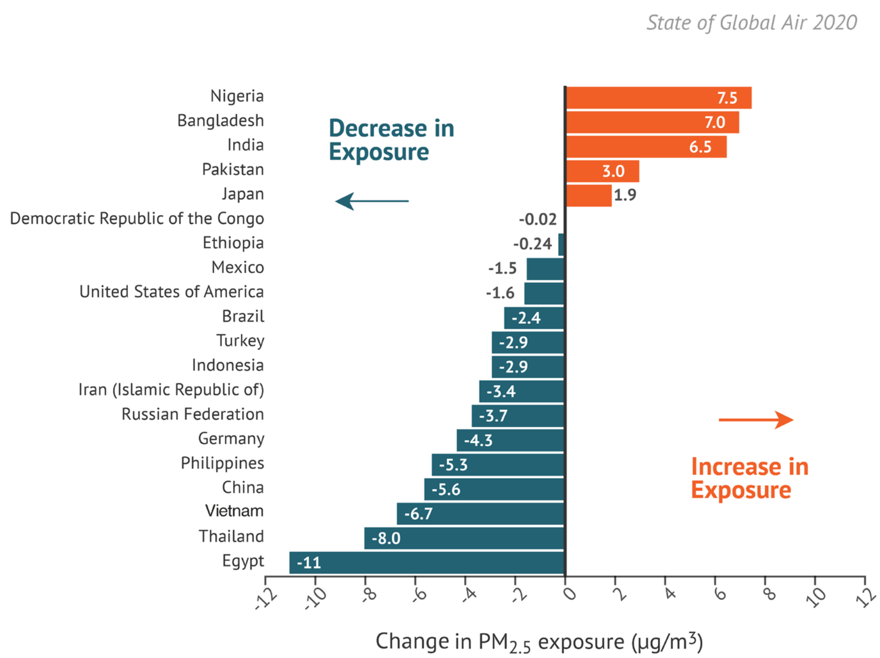
The world's 20 most populous countries collectively represent 70% of the world's population. The good news is that 14 of these 20 countries have seen declines in annual average $PM_{2.5}$ exposures, ranging from a slight decrease of 2.9 µg/m3 (from 22.3 to 19.4 µg/m3) in Indonesia to a substantial decline of 10.6 µg/m3 (from 78.5 to 67.9 µg/m3) in Egypt over the past decade (Figure 4). Germany and the United States, grouped within the High-Income Super Region, experienced modest reductions since 2010. Japan, another country in the High-Income Super Region, saw a modest increase in $PM_{2.5}$ levels (11.5 to 13.5 µg/m3), which may in part reflect increased emissions from power plants that burn fossil fuel, which replaced nuclear plants after the Fukushima nuclear accident in 2011.

At the other end of the spectrum, Nigeria experienced an increase of 7.5 µg/m3 in the level of $PM_{2.5}$, from 62.9 µg/m3 (95% uncertainty interval [UI]: 41.1 to 92.4) in 2010 to 70.4 µg/m3 (95% UI: 45.4 to 105.2) in 2019. Countries with some of the highest exposures in the world — India, Pakistan, and Bangladesh — continue to see increases.

FIGURE 4 Change in population-weighted annual average $PM_{2.5}$ exposure in the 20 most populous countries, 2010–2019.



How $PM_{2.5}$ Exposure Is Estimated

Many of the world's high- and middle-income countries measure $PM_{2.5}$ concentrations through extensive networks of reference-grade monitoring stations concentrated around urban areas. These stations offer a rich source of data that has served as the foundation for most studies of the health effects of air pollution and changes in air quality over time. In addition to these sources of data, GBD estimates incorporate data from the World Health Organization (WHO) air quality database, which serves as a repository for monitoring data for many individual cities around the world. In 2019, the GBD project added particulate matter measurements (PM_{10} and $PM_{2.5}$) from an additional 448 ground monitors, bringing the total to 10,408 ground monitors from 116 countries.

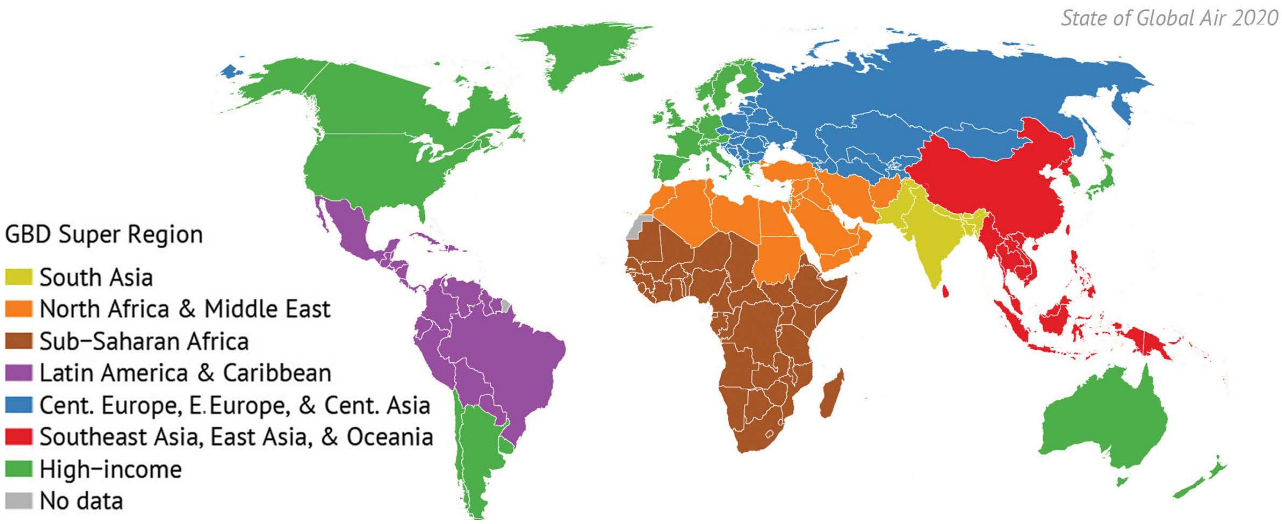
Although these data sources are valuable, on-the-ground air quality monitoring stations are few and far between in many regions of the world, particularly in countries at low and middle levels of development. To fill the gaps and to provide a consistent view of air pollution levels around the world, GBD scientists use sophisticated techniques to combine available ground measurements of particulate matter with observations from satellites and predictions from global chemical transport models. They update their estimates each year using improved methods and new ground-level and satellite measurements.

Extensive comparisons of these predictive methods (satellite and modeling approaches) with ground-level measurements demonstrate that they are reasonably accurate, and thus reliable indicators of $PM_{2.5}$ where ground monitors do not exist or data are not made publicly available.

Using this combined approach, GBD scientists systematically estimate annual average concentrations of $PM_{2.5}$, along with the 95% uncertainty interval (UI) for each estimate, across the entire globe divided into blocks, or grid cells, each covering 0.1° × 0.1° of longitude and latitude (approximately 11 × 11 kilometers at the equator). To estimate the annual average $PM_{2.5}$ exposures, or concentrations that a population in a specific country is more likely to come into contact with, GBD scientists link the concentrations in each block with the number of people living within each block to produce a *population-weighted annual average concentration*. Population-weighted annual average concentrations are better estimates of population exposures than simple averages across monitors, for example, because they give greater weight to the pollutant concentrations experienced where most people live. *Gridded data are available on request.*

Throughout the report, we present results for the GBD Super Regions — countries grouped by similar cause-of-death patterns (Figure i) — and the 20 most populous countries.

FIGURE i Countries included in the seven GBD Super Regions.



AMBIENT OZONE AIR POLLUTION

Ground-level, or *tropospheric*, ozone is a highly reactive pollutant that has adverse effects on human health, as well as on food crops and other vegetation. It is not released directly into the air but is formed in a complex chemical interaction between nitrogen oxides and volatile organic compounds in the presence of sunlight. Nitrogen oxides and volatile organic compounds are both produced by a variety of human activities. Nitrogen oxides are emitted from the burning of fossil fuels (oil, gas, and coal) in motor vehicles, power plants, industrial boilers, and home heating systems. Volatile organic compounds are also emitted by motor vehicles, as well as by oil and gas extraction and processing and other industrial activities. Certain types of volatile organic compounds can also be emitted from natural sources, such as trees.

Studies suggest that ozone levels today are 30% to 70% higher than they were 100 years ago. This increase reflects rising emissions of the chemicals that form ozone, as well as increases in global and local temperatures, which can accelerate ozone formation. Ozone is also a greenhouse gas, contributing to the warming on which it thrives. In urban areas, ozone levels can vary widely within and around cities depending on local and regional sources. In addition, ozone is an important regional pollutant, traveling long distances to suburban and rural areas and across national boundaries, leading to high ozone levels far from the emission sources that contribute to its formation.

Ozone pollution is accelerated by — and contributes to — climate change.

Ozone concentrations are measured in parts per billion (ppb). When assessing human exposure to ozone, GBD scientists focus on measurements taken in the warm season in each region, when ozone concentrations tend to peak in the mid-latitudes (where most epidemiological studies have been conducted to date). The GBD assessment evaluates human exposure in terms of the *average seasonal 8-hour daily maximum concentrations*, the measure of long-term exposure in the most recent epidemiological studies of ozone's health effects. Season is defined by the six-month period with the highest average ozone concentrations. Like $PM_{2.5}$ exposures, ozone exposures are estimated for each country as *population-weighted concentrations*. (See "How Ozone Exposure Is Estimated" on page 11.)

Tracking ozone concentrations systematically around the world and over time is vital to measuring progress and evaluating this pollutant's implications for human health and the environment. The GBD is continually improving the scientific basis for this tracking, bolstered by the addition of data from a large number of new monitoring sites, many in China; by improvements in the models used to estimate ozone concentrations where data are lacking; and in the statistical methods used to combine the information from monitors and models to improve confidence in the final estimates over geographical areas and over time.

Trends in Pollution Policy: How Do Key Countries Compare?

China implemented the first comprehensive five-year plan to improve air quality between 2013 and 2017 and subsequent plans have continued to address air pollution. Between 2010 and 2019, outdoor $PM_{2.5}$ levels in China decreased by 30%, largely due to actions undertaken in the past 5 to 7 years, including a shift from coal to gas in residential and industrial sectors and a reduction in industrial emissions. However, there are fears that the recent economic slowdown and related increases in coal-burning capacity will continue to pose challenges with respect to air pollution control.

India released its National Clean Air Programme in 2019 with a view to reducing outdoor $PM_{2.5}$ levels by 2024. While the program has been criticized for its lack of a legal mandate and its narrow focus on cities, it has led to increased engagement on the issue of air pollution at the state and local levels. In April 2020, the country initiated a switch to Bharat Stage VI (BS-VI) vehicle emission standards, which is likely to bring benefits over the next few years. However, the COVID-19 pandemic has raised concerns that the full implementation of the switch might be delayed.

Nigeria saw a 7% increase in outdoor $PM_{2.5}$ levels between 2010 and 2019. In 2019, the National Short-Lived Climate Pollutant Plan was launched, which aims to reduce $PM_{2.5}$ emissions by 75% by 2030. Among a list of 22 key measures, the actions to address $PM_{2.5}$ include regulation and enforcement of vehicle emission standards, switching to cleaner fuels for cooking, eliminating gas flaring, and reducing emissions from crop burning and livestock.

Pakistan lacks a coordinated national action plan on air pollution, although air quality is broadly addressed within the Pakistan Environmental Protection Act. Recent efforts, some of which are mandated through orders from the Supreme Court, have been focused on control of emissions from brick kilns, agricultural burning, and industry. The country still relies on Euro-II vehicle emissions norms, and emissions from large as well as smaller, informal industries are not regulated. Regional action plans (e.g., Punjab Clean Air Action Plan) have been announced, but progress is unclear.

Bangladesh released the draft Clean Air Bill in 2019, which sets the stage for preparation of the National Air Quality Management Plan as well as identification of critical air quality areas, among other measures. The country also undertook an extensive program (Clean Air and Sustainable Environment project) to address air pollution from brick kilns and the transportation sector between 2009 and 2019.

Global Patterns in Ozone Exposure

Global ozone exposures vary from a low of about 12.2 ppb to a high of 67.2 ppb across the globe (Figure 5). The 10 countries with the highest average ozone exposures in 2019 were in Asia and the Middle East (Table 2), although from the uncertainty intervals, the differences in the rankings are not always significant. Small island states, such as Micronesia and Papua New Guinea, were among the countries with the lowest concentrations.

How do these exposure levels compare with health-based standards? The WHO set a guideline for daily maximum 8-hour exposure to ozone at 50 ppb, a level exceeded by all of the top 10 countries. The U.S. National Ambient Air Quality Standard is 70 ppb and is calculated as the annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years. Neither is measured in exactly the same way as the GBD ozone levels; however, the steady increase in ozone levels in the last several decades is bringing them closer to levels of concern for public health in many regions of the world.

Global levels of ozone exposure have been slowly but steadily increasing over the past decade.

Trends in Ozone Exposure

On average, global exposure to ozone increased from about 47.3 ppb in 2010 to 49.5 ppb in 2019, although patterns across the GBD Super Regions vary (Figure 6). Countries in South Asia saw the steepest increase, while some countries in the High-Income, Central Europe, Eastern Europe, Central Asia and East Asia Regions experienced modest declines.

Figure 7 plots the absolute changes in population-weighted average seasonal 8-hour maximum ozone concentrations for the

FIGURE 5 Global map of population-weighted average seasonal 8-hour daily maximum ozone concentrations in 2019.

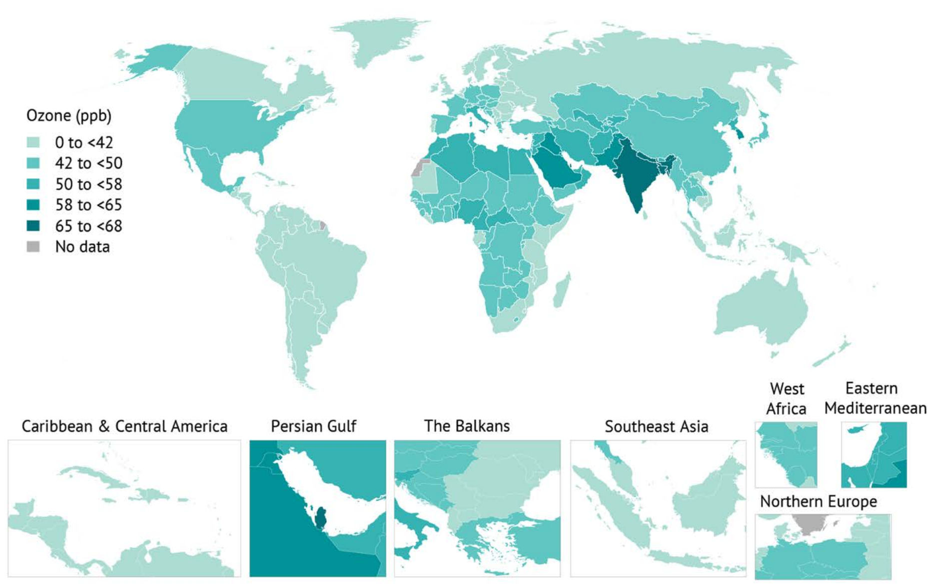


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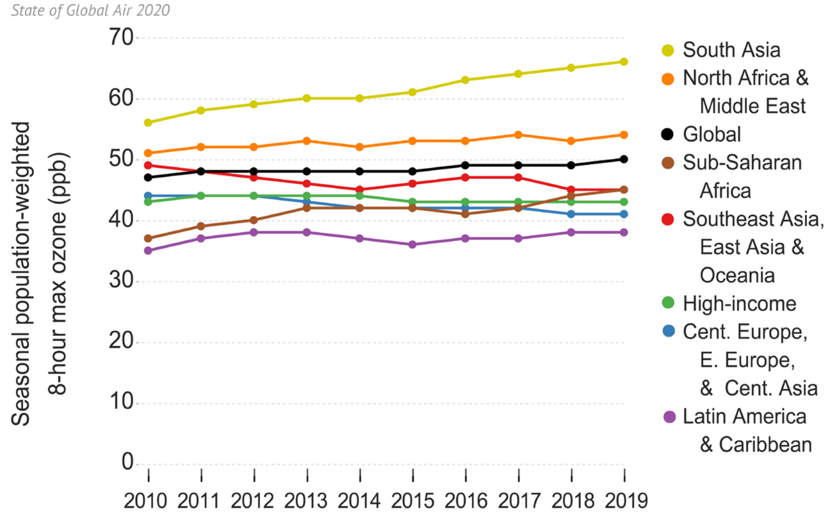
TABLE 2 Top 10 countries with the highest ozone exposures globally in 2019.

Country	Tropospheric Ozone (ppb)	95% Uncertainty Intervals*
Qatar	67.2	62.3 to 72.4
Nepal	67.0	65.5 to 68.6
India	66.2	66.0 to 66.3
Bangladesh	64.6	63.9 to 65.3
Bahrain	64.0	51.7 to 75.9
Pakistan	63.3	62.8 to 63.8
Kuwait	62.1	57.6 to 67.1
Iraq (Islamic Republic of)	59.5	58.8 to 60.2
Republic of Korea	57.9	56.4 to 59.3
Saudi Arabia	58.2	57.7 to 58.6

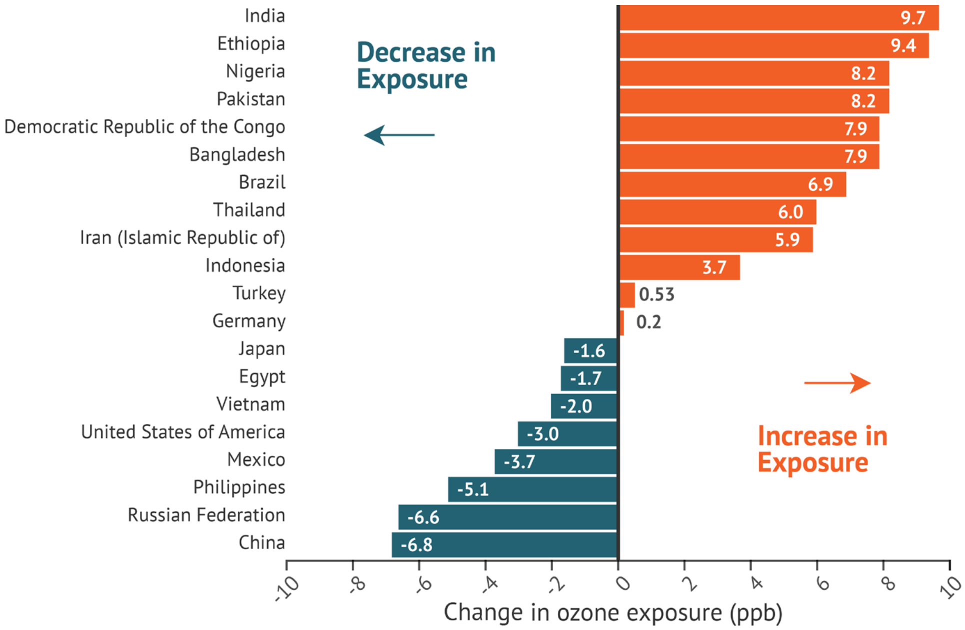
* The 95% uncertainty intervals are a measure of scientific uncertainty. They reflect a range of values, from the 2.5th to the 97.5th percentile of a possible distribution of values, within which the true concentration is likely to fall.

FIGURE 6 Trends in population-weighted average seasonal 8-hour maximum ozone concentration globally and in the GBD Super Regions, 2010–2019.



20 most populous countries from 2010 to 2019. Ethiopia, Nigeria, the Democratic Republic of the Congo, and Brazil experienced increases in ozone concentrations over this time frame. Ethiopia, for example, experienced a steep increase of 27% — from 34.9 ppb (95% UI: 34.5 to 35.3) in 2010 to 44.3 ppb (95% UI: 43.8 to 44.6) in 2019. Several of the most populous countries that already had the highest ozone concentrations in 2010 — India, Pakistan, and Bangladesh — have also seen some of the greatest increases. India, for example, experienced an increase of about 17% — from 56.5 ppb (95% UI: 56.3 to 56.6) in 2010 to 66.2 ppb (95% UI: 66.0 to 66.3) in 2019. Eight of the 20 countries saw a reduction in ozone levels over the past decade, ranging from a 1.6 ppb drop in Japan to a 6.8 ppb drop in China.

FIGURE 7 Change in population-weighted average seasonal 8-hour maximum ozone concentrations in the 20 most populous countries, 2010–2019.



OZONE

How Ozone Exposure Is Estimated

Like $PM_{2.5}$, ozone concentrations are measured in more-developed countries using extensive monitoring networks, but many parts of the world do not have such networks or have not made their data openly available to scientists. To characterize ozone concentrations and trends in a consistent way around the world — particularly for regions where monitoring data are sparse — scientists combine data from monitoring networks with outputs from atmospheric transport models. Using both approaches enables scientists to correct for differences between observed and modeled values and to estimate uncertainty in the model predictions.

This year the GBD project improved its methods for estimating ozone concentrations in several important ways. For the first time, in addition to data from the international scientific collaboration on ozone (see the Tropospheric Ozone Assessment Report [TOAR]), GBD scientists were able to obtain data from 1,565 surface ozone monitoring stations from the China National Environmental Monitoring Center network for the years 2013 to 2017, filling an important gap in global monitoring data. Along with the addition of other new stations globally, this network increased the number of observation locations from 4,400 to more than 8,800. Second, they expanded the combination of global atmospheric models used in their analysis from six to nine. Third, the team used improved methods to fuse, or combine statistically, the monitor observations and model results over both space and time, including for each year from 1990 to 2017. Finally, ozone concentrations were modeled at a finer spatial scale than in previous years. Together, these data and approaches led to greater confidence in the model predictions and estimates of human exposures. The annual trends were then extrapolated to the years 2018 and 2019.

Using this combined approach, the scientists are able to systematically estimate seasonal 8-hour maximum concentrations of ozone across the entire globe divided into blocks, or grid cells, each covering 0.1° × 0.1° of longitude and latitude (approximately 11 × 11 kilometers at the equator). To estimate the exposures, or concentrations, that a population in a specific country is more likely to come into contact with, GBD scientists link the average seasonal 8-hour maximum concentrations in each block with the number of people living within each block to produce a *population-weighted average seasonal 8-hour maximum ozone concentration*. Population-weighted concentrations are better estimates of population exposures than simple averages because they give greater weight to the pollutant concentrations experienced where most people live. *Gridded data are available upon request.*

HOUSEHOLD AIR POLLUTION

Household air pollution results from the burning of various fuels (coal, charcoal, wood, agricultural residue, animal dung, and kerosene, among others) for heating or for cooking using open fires or cookstoves with limited ventilation. Burning these fuels produces an array of pollutants that may harm human health, including fine particulate matter ($PM_{2.5}$), black carbon, and carbon monoxide. The GBD focuses only on the role of burning solid fuels for cooking in its estimates of exposure to household air pollution. These exposures in homes are estimated in terms of $PM_{2.5}$ concentrations based on the proportion of a country's population that relies on solid fuel for cooking, combined with evidence from household and personal exposure measurement studies. (See "How Household Air Pollution Is Estimated" on page 14.) These estimates are likely to understate the total exposure and health burden in some locations because they do not include exposures related to use of solid fuels for heating and for hot water, or exposures from burning of liquid fuels such as kerosene.

Although this analysis focuses on the exposures experienced in the home only, household air pollution is a major contributor to ambient $PM_{2.5}$, and as we have reported elsewhere, it is sometimes a dominant source. However, these exposures are accounted for as part of exposures to ambient $PM_{2.5}$ presented in the previous section.

Global Patterns in Household Air Pollution Exposure

Exposures to household air pollution are most widespread in sub-Saharan Africa and in parts of Asia (Figure 8). The 10 countries with the highest proportion of households cooking with solid fuels are the Central African Republic, South Sudan, Rwanda, Burundi, Niger, Mali, Madagascar, Tanzania, Uganda, and Guinea-Bissau; in each, more than 97% of the country's population uses solid fuels for cooking.

Most people who rely on solid fuels for cooking live in Africa and Asia.

Trends in Household Air Pollution Exposure

Since 2010, the use of solid fuels has fallen slowly and steadily in most regions, in particular in South Asia and in the Southeast Asia, East Asia, and Oceania Super Regions (Figure 9). Progress has been slower in sub-Saharan Africa. Declines in solid fuel use — reflecting years of efforts to move to cleaner energy sources as well as broader development and urbanization that have made that process easier — have led to an 11% overall reduction in the percentage of the global population relying on solid fuels for cooking. However, that still leaves 49% of the world's population — about 3.8 billion people — exposed to household air pollution from the burning of solid fuels. Most of them live in just 17 countries — those with over 50 million people and more than 10% of the population relying on solid fuels for cooking.

FIGURE 8 Global map of the proportion of each country's population cooking with solid fuels in 2019.

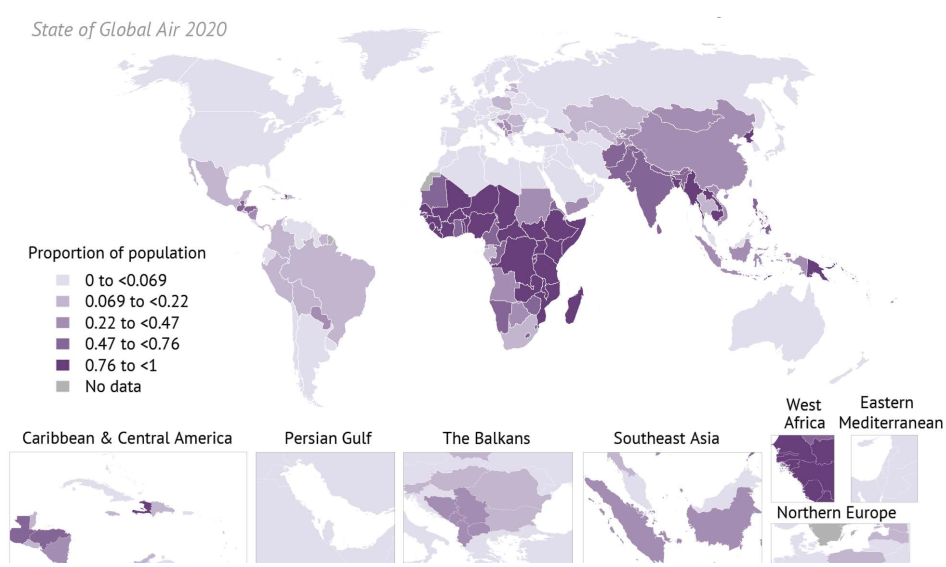


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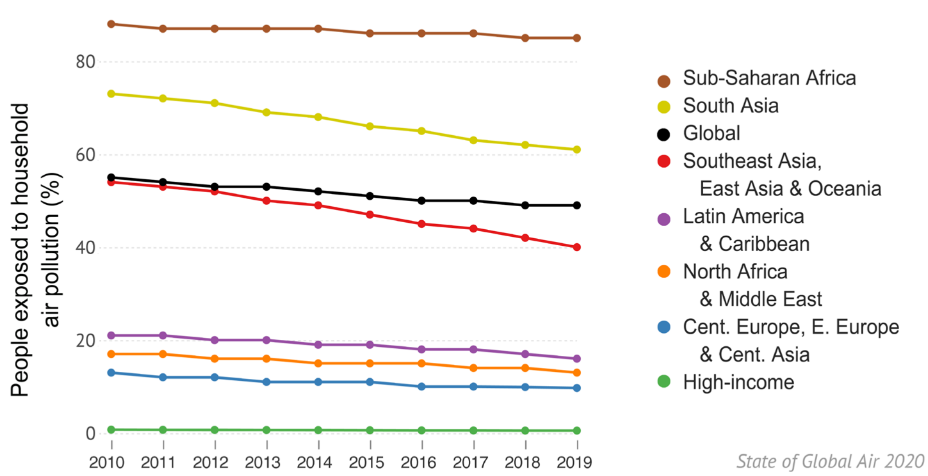
FIGURE 9 Trends in the proportion of population cooking with solid fuels globally and in the GBD Super Regions, 2010–2019.

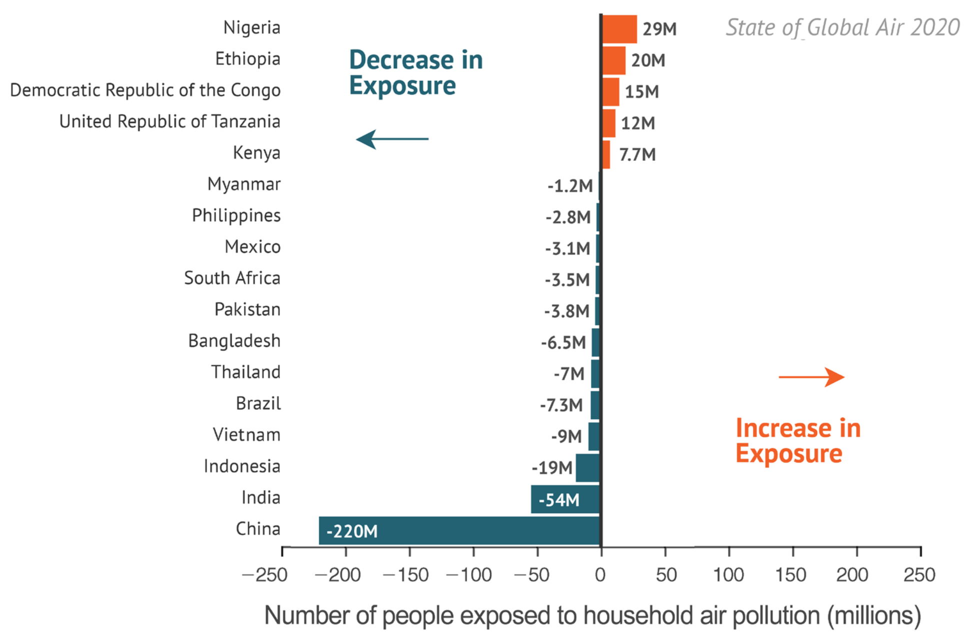


The reduction in exposures to household air pollution is a growing success story, but half of the world's population remains exposed.

The global average reductions in the percentage of populations exposed to household air pollution from 2010 to 2019 mask important differences among individual countries. The impact on the numbers of people affected is clearly dominated by countries in South and East Asia, most notably in India and China, where there have been aggressive campaigns encouraging a switch to cleaner fuels (Figure 10). China reduced the percentage of its population exposed to household air pollution from 54% to 36%, while India reduced its percentage from 73% to 61% over the decade.

Several countries in Africa with fast-growing populations actually experienced net increases in the numbers of people exposed to household air pollution, despite reductions in the percentages of their populations using solid fuels for cooking. Nigeria, for example, reduced the percentage of its population using solid fuels from 82% to 77%, but population growth meant that 29 million people remained exposed. Increases in the numbers of people exposed occurred in countries such as Ethiopia and the Democratic Republic of the Congo where 96% and 93% of the populations, respectively, continue to rely on solid fuels for cooking.

FIGURE 10 Change in the number of people exposed to household air pollution in the 17 countries with over 50 million people and at least 10% of their population cooking with solid fuels, 2010–2019.



AIR POLLUTION AND DEVELOPMENT

Disparities in socioeconomic development contribute to disparities in exposure and health. To capture different facets of development that are relevant to health outcomes, the GBD project uses a metric called the *sociodemographic index* (SDI). A country's SDI is calculated based on average income per person, educational attainment, and total fertility rate (number of children per woman). It varies from zero to one, with zero indicating the lowest income and educational attainment but the highest fertility rate — indicative of low sociodemographic development — and one indicating the opposite. An analysis of SDI and air pollution exposures reveals patterns for household air pollution and ambient $PM_{2.5}$, with no strong pattern evident for ozone (Figure 11).

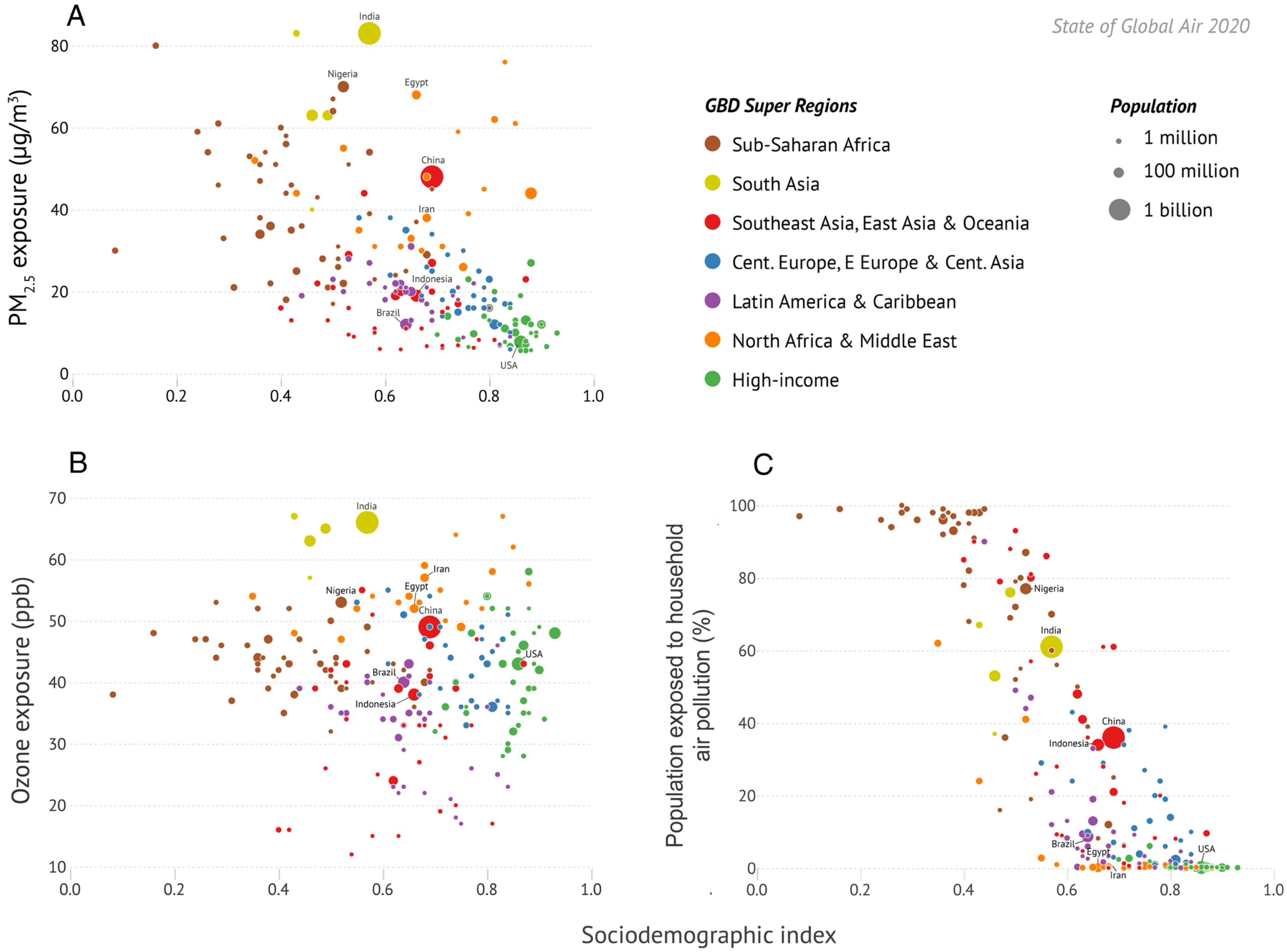
The least-developed countries suffer the worst air quality

Exposure patterns for ambient $PM_{2.5}$ suggest that lower sociodemographic development tends to be associated with higher exposures to $PM_{2.5}$. Countries in sub-Saharan Africa generally have the lowest SDI and the highest $PM_{2.5}$ levels, while high-income countries experience the lowest $PM_{2.5}$ exposure. However, the correlation between SDI and $PM_{2.5}$ is only moderate. Some variation is likely because $PM_{2.5}$ is a regional pollutant that can be carried long distances, affecting neighboring countries regardless of their levels of development. Higher $PM_{2.5}$ exposures in some more-developed countries in North Africa and the Middle East may also reflect impacts from local dust sources as well as wind-blown dust from the Sahara, which would not be expected to be associated with SDI.

Exposure patterns for ozone reveal no consistent relationship between SDI and exposures. However, limited regional patterns suggest some of the highest ozone levels occur in the higher SDI countries of North Africa and the Middle East (see orange dots in Figure 11), particularly in Kuwait, Saudi Arabia, Bahrain, and Iraq. These higher levels may reflect regional sources of ozone precursors due to oil production and related industries, as well as local meteorology.

Exposure patterns for household air pollution reveal a clear relationship between SDI and the proportion of households using solid fuels. Countries with lower SDI have higher rates of reliance on solid fuels that may be either subsidized or easily gathered locally; often, these countries also lack the infrastructure to provide clean energy. Household air pollution exposure declines sharply in countries with higher levels of SDI.

FIGURE 11 Exposures in countries with different levels of sociodemographic development: **(A)** $PM_{2.5}$, **(B)** ozone, and **(C)** household air pollution. Dots represent individual countries, color-coded according to GBD Super Region. Dot size reflects population size. Higher SDI indicates a greater level of sociodemographic development.



How Household Air Pollution Is Estimated

In the GBD project, exposure to $PM_{2.5}$ related to household air pollution is estimated using a multi-step process, beginning with information on the proportion of populations that burn solid fuels for cooking. The proportion of households using solid fuels for cooking is estimated based on data from numerous international and national surveys, databases, and individual studies, updated each year from 1980 to 2019. This information is used together with demographic data on household composition to estimate the percentage of men, women, and children of different ages who are potentially exposed to pollution as a result of cooking with solid fuels in each country. These percentages are then translated into $PM_{2.5}$ levels to which individuals are exposed based on data from the WHO Global Household Measurements Database and other key studies (for a total of 75 studies in 43 countries). This translation process relies on a mathematical model that takes into account the type of fuel (solid or non-solid), type of air pollution measurement (e.g., kitchen versus personal), duration of the measurement, whose exposure was measured (men, women, or children), and the sociodemographic index for the location and year.

To make sure that the estimated exposure to $PM_{2.5}$ for each location and year represents household exposures only, GBD scientists subtract the ambient $PM_{2.5}$ concentration for each study location at the time of measurement. In this way, the analysis provides independent estimates of exposures to household pollution and to ambient $PM_{2.5}$.

BURDEN OF DISEASE FROM AIR POLLUTION

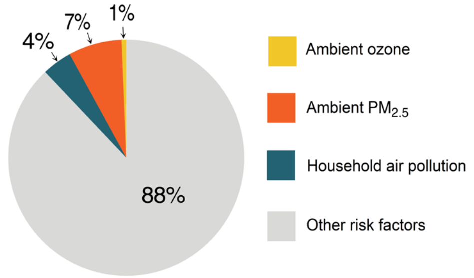
Exposure to air pollution has serious health consequences. Understanding these consequences — the risks faced by particular groups, the impacts of different pollutants, and the changes over time — is key to informing air quality interventions and saving lives.

Understanding the burden of disease that air pollution places on society begins with the scientific evidence for its effects on health. An extensive body of scientific evidence has been amassed over several decades, including studies from many countries of the world. Short-term exposures to air pollution can harm health; for example, high-pollution days can trigger asthma symptoms and cause a local spike in hospitalizations or even deaths related to respiratory and cardiovascular diseases. There is broad scientific consensus that long-term exposures to air pollution contribute to increased risk of illness and death from ischemic heart disease, lung cancer, chronic obstructive pulmonary disease (COPD), lower-respiratory infections (e.g., pneumonia), stroke, type 2 diabetes, and, more recently, adverse birth outcomes, and that the public health burden from these exposures is much larger than that from short-term exposures. The GBD project relies on epidemiological studies and other evidence to estimate the burden of disease from air pollution in terms of the deaths and years of healthy life lost borne by populations as a whole in every country of the globe. (See "How Burden of Disease Is Estimated" on page 22.) Ongoing studies continue to explore air pollution's role in the development of asthma, cognitive disorders, and other effects (e.g., chronic kidney disorders) which, as evidence accumulates, will be considered for inclusion in the GBD project in future years.

In 2019, air pollution is estimated to have contributed to 6.67 million deaths (95% UI: 5.90 to 7.49 million) worldwide, nearly 12% of the global total (Figure 12). Air pollution is the leading environmental risk factor for early death, with its total impact exceeded only by high blood pressure (10.8 million, 95% UI: 9.51 to 12.1 million), tobacco use (8.71 million, 95% UI: 8.1 to 9.3 million), and dietary risks (7.94 million, 95% UI: 6.5 to 9.8 million) (Figure 1). Every year, far more people worldwide die as a result of air pollution exposure than die from traffic collisions, a number estimated at 1.28 million in 2019.

In 2019, air pollution contributed to 6.67 million deaths worldwide.

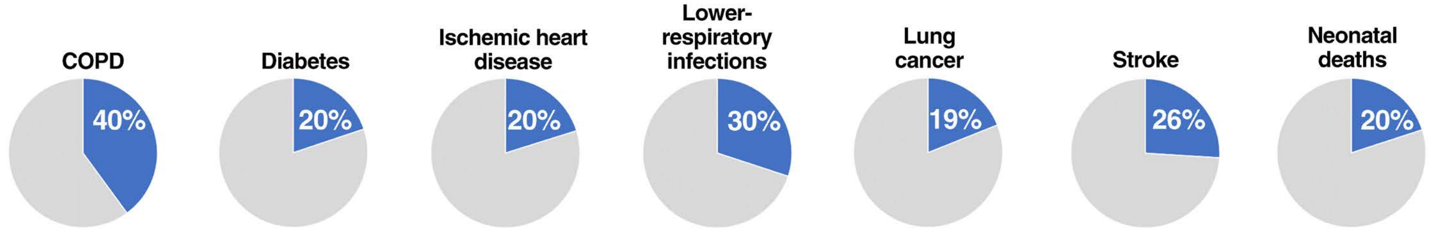
FIGURE 12 Percentage of global deaths attributable to individual pollutants.



This large burden of disease reflects the substantial contribution that long-term exposures to air pollution make to chronic noncommunicable disease and, more specifically, to some of the world's leading causes of death in 2019 (Figure 13). About 80% of air pollution's burden is attributed to noncommunicable diseases. For example, $PM_{2.5}$, household air pollution, and ozone together contribute as much as 40% of deaths from COPD, a highly debilitating lung disease. Air pollution also contributes to as much as 30% of lower-respiratory infection as well as 20% of infant mortality in the first month of life.

The air pollution–attributable burden from each of these diseases is not borne equally across the world. For example, while the contribution of air pollution to ischemic heart disease is 20% on average globally, that includes a range from 5% in higher income regions of the world to over 30% in sub-Saharan Africa and South Asia regions. These variations reflect not only exposures but other social, economic, and demographic factors that affect the underlying health and vulnerability of populations to air pollution in those regions. To reduce the burden of disease attributable to each of these diseases and for each air pollutant, each country will need to explore and understand its own data. Some of these data (e.g., exposures and mortality/DALY rates) are available on the State of Global Air website, while additional data may be found on the Global Burden of Disease website.

FIGURE 13 Percentage of global deaths from specific causes attributable to total air pollution.



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A BURDEN BORNE BY THE YOUNG AND OLD

The burden of disease attributable to air pollution does not fall evenly across age groups. Throughout the world, children and the elderly are most acutely affected.

Figure 14 shows a peak in pollution-related deaths among babies in the early (0 to 6 days) and the late (7 to 27 days) neonatal groups, reflecting the influence of particulate matter on adverse birth outcomes and lower-respiratory infections, while the second, larger peak in the older age groups reflects air pollution's contributions to lower-respiratory infections and major noncommunicable diseases that develop over time — ischemic heart disease, stroke, COPD, lung cancer, and type 2 diabetes. DALYs follow a similar pattern as total deaths, though the first peak is much higher for the younger age groups, reflecting the lifetime of years lost for the youngest babies.

FIGURE 14 Distribution of global deaths in 2019 attributable to $PM_{2.5}$, ozone, and household air pollution by age (years, except early neonatal [0 to 6 days] and late neonatal [7 to 27 days]).

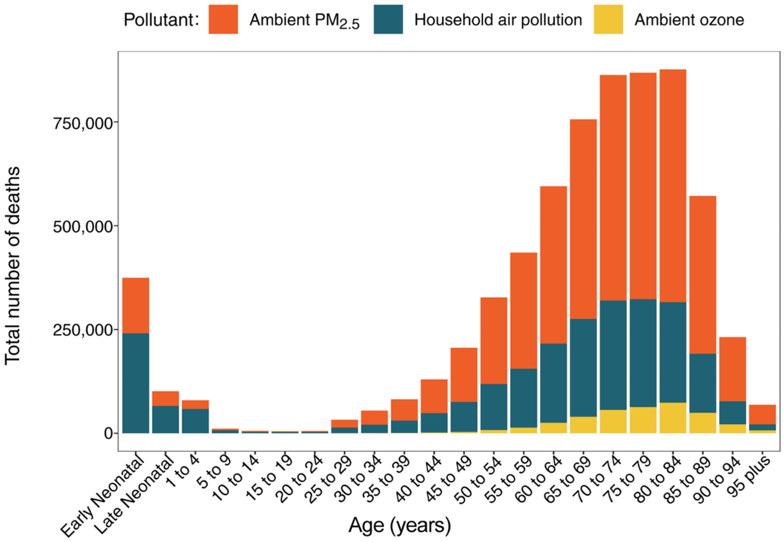


Figure 14 also provides insights into how the three types of air pollution affect different age groups. Ambient $PM_{2.5}$ and household air pollution are the largest contributors to mortality and years of healthy life lost across age groups. Because COPD takes years to develop and is the only health outcome included in the analysis for ozone, the effects of ozone are seen only in adults.

Does Air Quality Affect COVID-19 Susceptibility?

Extensive evidence links exposure to air pollution with higher rates of respiratory and cardiovascular diseases, including lower-respiratory infections. Could air pollution also increase a person's risk of developing a COVID-19 respiratory infection or suffering its most severe complications?

There is reason to believe it could. SARS-CoV-2, the coronavirus that causes COVID-19, is a respiratory virus that can affect the lungs, blood vessels, and many other parts of the body. Exposure to air pollution has been shown to affect the body's immune defense, making an individual more susceptible to respiratory and other infections. In addition, many of the health conditions that have been associated with increased vulnerability to COVID-19 — such as diabetes, cardiovascular disease, and chronic obstructive lung diseases — are also caused by long-term exposure to air pollution.

What we learned from the SARS-CoV-1 outbreak in 2002–2004 offers some insight into the interaction between air pollution and the effects of COVID-19. Several studies reported an association between higher air pollution concentrations and higher than expected death rates from SARS-CoV-1. A handful of early studies of COVID-19 appear to suggest that areas with higher air pollution concentrations — $PM_{2.5}$ or NO_2 in particular— might similarly experience either higher infection rates or higher case fatality rates. Investigators around the world are hard at work trying to understand fully the linkages between COVID-19 and air pollution, and how exposure to air pollution might affect rates of COVID-19 infection, the severity of disease, or the likelihood of dying.

IStock/life in shots

Delhi, India.

BURDEN OF DISEASE FROM AMBIENT FINE PARTICLE AIR POLLUTION

In 2019, long-term exposures to ambient particulate matter ($PM_{2.5}$) pollution contributed to 4.14 million deaths [95% UI: 3.45 to 4.80] and 118 million lost DALYs [95% UI: 95.9 to 138], accounting for 62% of all air pollution–attributable deaths and 55% of DALYs, respectively. Among 69 risk factors included in the GBD analysis that are considered to be potentially modifiable, ambient $PM_{2.5}$ ranks 6th behind high blood pressure, smoking, and high blood sugar, among others. It is the leading risk factor among all environmental and occupational risks.

Global Patterns in $PM_{2.5}$ Burden of Disease

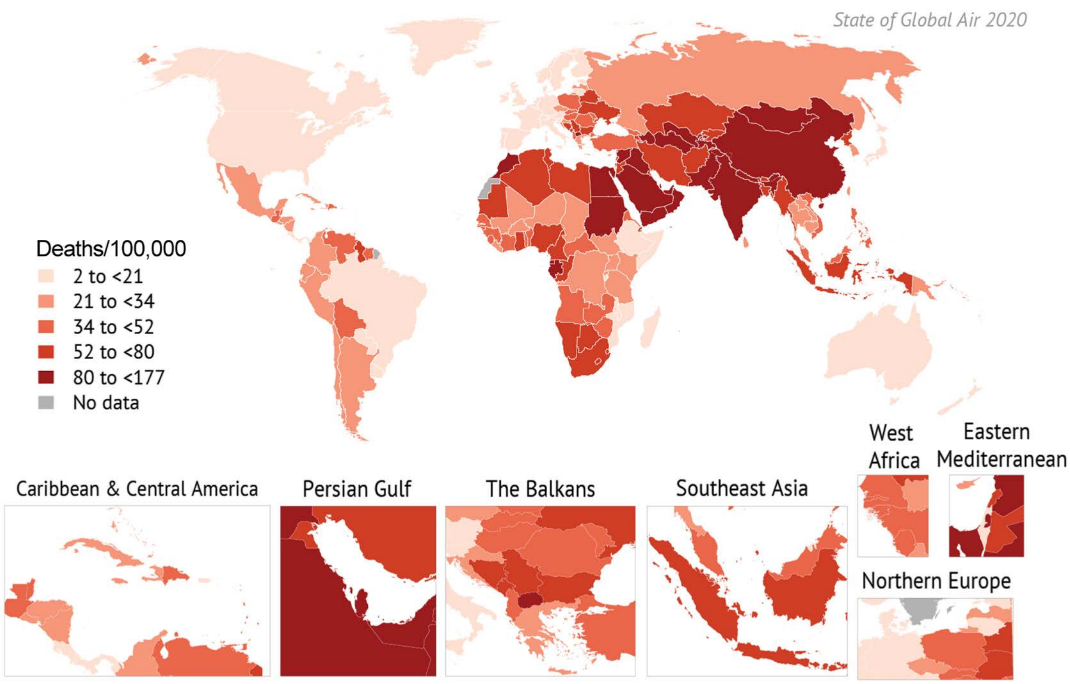
The burden attributable to $PM_{2.5}$ varies widely around the globe, reflecting variation in exposures and underlying prevalence of disease and other population susceptibilities (Figure 15). Globally, countries in Asia and Africa experience the highest age-standardized rates of death and DALYs attributable to $PM_{2.5}$: for example, India (96 deaths/100,000 population, 95% UI: 75 to 116); China (81 deaths/100,000, 95% UI: 67 to 96); Egypt (157/100,000, 95% UI: 117 to 200); Iran (63/100,000, 95% UI: 55 to 71); and Nigeria (59/100,000, 95% UI: 37 to 85). Countries in the GBD High-Income Region have rates that are far lower: Germany (13/100,000, 95% UI: 9.7 to 16); United Kingdom (11/100,000, 95% UI: 7.3 to 14); the United States (8.5/100,000, 95% UI: 4.7 to 13); Canada (5.4/100,000, 95% UI: 2.6 to 8.5); and Norway (3.8/100,000, 95% UI: 1.5 to 6.5).

Ambient $PM_{2.5}$ is the largest driver of air pollution's burden of disease worldwide.

Although age-standardized rates of death are important for comparing the health burden among countries, total numbers of deaths are useful for identifying where the most people are affected. Globally, the $PM_{2.5}$-attributable mortality burden continues to be dominated by the most populous countries in the world — China, which saw 1.42 million $PM_{2.5}$-attributable deaths (95% UI: 1.17 to 1.69 million) and India, which saw 980,000 $PM_{2.5}$-attributable deaths (95% UI: 0.77 to 1.19 million). Together, these two countries account for 58% of worldwide deaths attributed to $PM_{2.5}$ in 2019.

Total mortality is also high in many of the same countries where age-standardized death rates are high. In North Africa and the Middle East, the 10 countries with the highest numbers of $PM_{2.5}$-attributable deaths are Egypt, which had 91,000 such deaths (95% UI: 67,000 to 117,000), followed closely by Iran, Turkey, Morocco, Iraq, Algeria, Saudi Arabia, Yemen, Syria, and Tunisia. In sub-Saharan Africa, the top 10 countries with the highest burden are led by Nigeria (68,500 deaths, 95% UI: 41,000 to 102,000) followed more distantly by South Africa, Ghana, the Democratic Republic of the Congo, Cameroon, Ethiopia, Côte d'Ivoire, Tanzania, Angola, and Kenya. In South Asia, three countries account for most of the $PM_{2.5}$-attributable deaths: India (980,000, 955 UI: 770,000 to 1,192,000), Pakistan (114,000, 95% UI: 78,500 to 151,000), and Bangladesh (74,000, 95% UI: 48,000 to 102,000).

FIGURE 15 Global map of age-standardized rates of death attributable to $PM_{2.5}$ in 2019.



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Trends in $PM_{2.5}$ Burden of Disease

Over the past decade, the number of deaths attributable to ambient $PM_{2.5}$ globally increased by 23.3% (95% UI: 13.9 to 34.4) even as attributable death rates declined by about 4% (−3.9%, 95% UI: −10.8 to 4.9). Similarly, the numbers of ambient $PM_{2.5}$-attributable DALYs have increased by 17.1% despite declines in DALY rates. The difference in these trends hints at the competing factors that influence overall burden of disease from $PM_{2.5}$. Declining age-standardized rates attributable to air pollution reflect improvements in treatment of, and survival from, underlying diseases to which air pollution contributes. Given the relatively stable global $PM_{2.5}$ exposures, increase in deaths or DALYS despite the declining rates points to the substantial impact of the growth and aging of the global population.

These trends are strikingly different across GBD Super Regions (Figure 16). South Asia and Southeast Asia, East Asia, and Oceania saw steep increases in total deaths attributable to $PM_{2.5}$, while more modest increases were seen in sub-Saharan Africa and in North Africa and the Middle East. Together, the increases in these regions vastly outweigh the modest decreases in the High-Income and the Central Europe, Eastern Europe, and Central Asia Regions.

A closer look at the 20 most populous countries provides some insights into where some of the major changes in $PM_{2.5}$-attributable mortality burden have taken place (Figure 17). Over the past decade, 16 of these countries experienced increases in $PM_{2.5}$-attributable deaths, ranging from 2,350 deaths (a 6% increase) in Turkey to 373,000 in India, an increase of 61%. China experienced a 20% increase, about 238,000 deaths. Although they did not have the largest burden overall, Bangladesh and the Democratic Republic of the Congo experienced the highest percentage increases in burden over this time period. Decreases in deaths attributable to $PM_{2.5}$ ranged from a reduction of over 900 deaths (a 2% decrease) in Brazil to over 48,000 in the Russian Federation (a decrease of 39.6%).

What's driving these changes? Several factors can contribute, sometimes with opposite effects. Air pollution exposures may rise or fall. Reductions in mortality rates for the diseases associated with air pollution — for example, through the availability of better treatments — can also reduce pollution-attributable death rates. Because socioeconomic development can be tied to both air pollution exposures and the availability of health care, changes in a country's level of development can also influence the burden of disease over time.

Even as exposures to $PM_{2.5}$ level off, the attributable burden of disease continues to rise as populations grow and age.

Overall, changes in population size and age structure sometimes have the largest impacts on these trends. Even if exposures to air pollution are decreasing, the overall attributable burden of disease can 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 develop, and are more susceptible to, diseases linked with air pollution. Together, population growth and aging of the global population are estimated to account for more than half of the increased deaths attributed to $PM_{2.5}$ exposure over the past decade.

FIGURE 16 Trends in total deaths attributable to $PM_{2.5}$ in the GBD Super Regions.

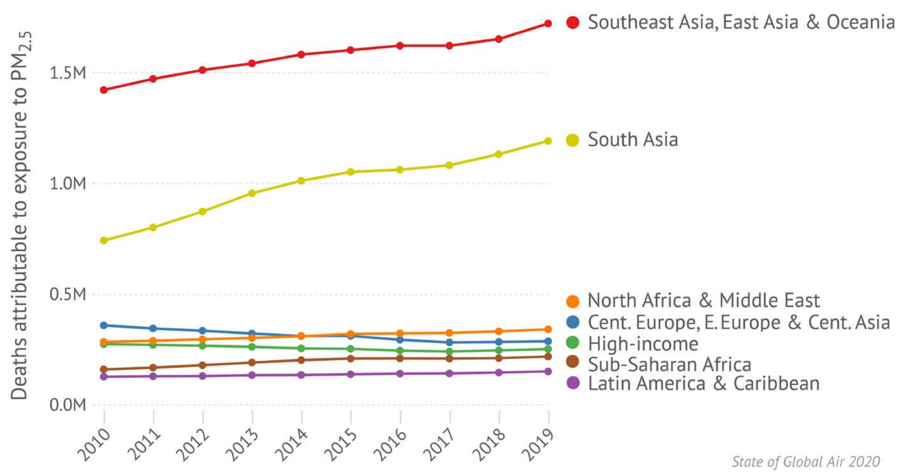

FIGURE 17 Change in total deaths attributable to $PM_{2.5}$ in the 20 most populous countries, 2010–2019.

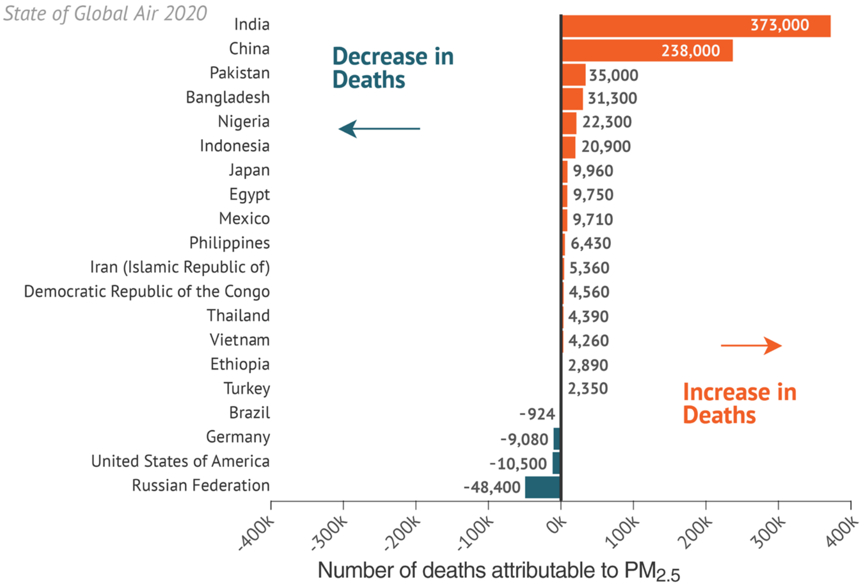

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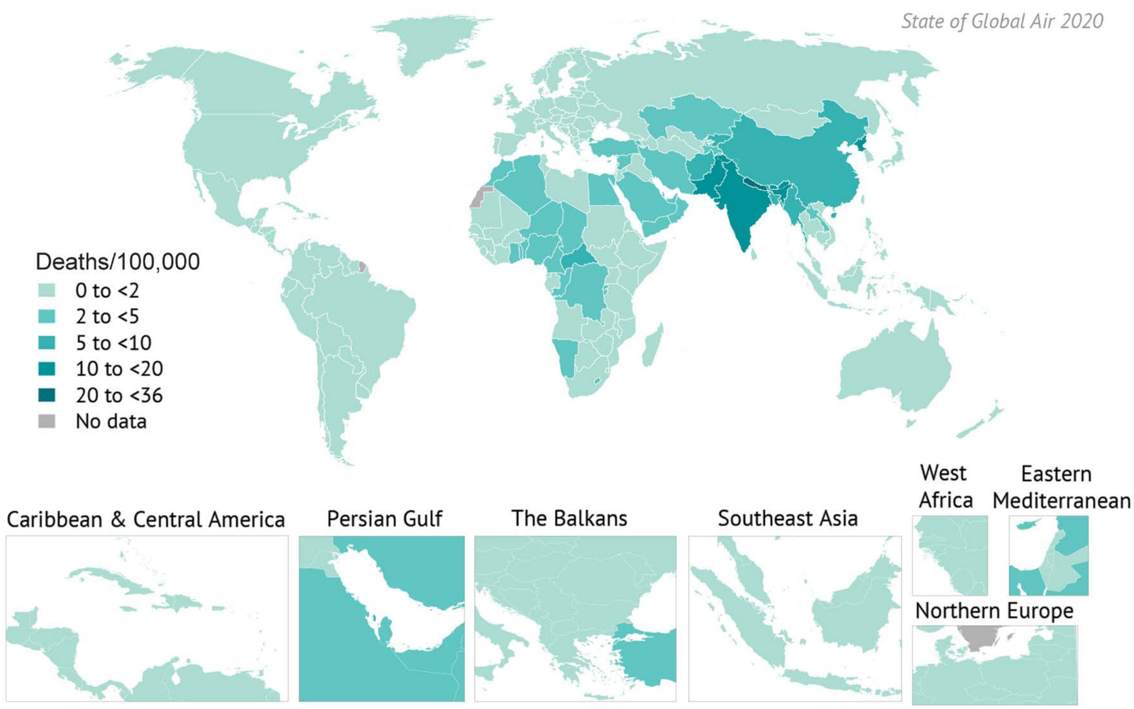
FIGURE 18 Global map of age-standardized rates of death attributable to ozone in 2019.



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BURDEN OF DISEASE FROM AMBIENT OZONE AIR POLLUTION

In 2019, long-term exposures to ozone contributed to an estimated 365,000 deaths (95% UI: 175,000 to 564,000) from COPD worldwide, accounting for 11.1% (95% UI: 5.32 to 17) of all COPD deaths globally. This premature loss of life equates to 6.21 million (95% UI: 2.99 to 9.63 million) DALYs from COPD across the world.

Ozone exposure accounts for 1 out of every 9 deaths from COPD globally.

Global Patterns in Ozone

The highest age-standardized rates of death attributable to ozone occurred in countries in Asia — in particular, India (18/100,000, 95% UI: 8.9 to 28), Pakistan (14/100,000, 95% UI: 6.7 to 21), and Bangladesh (8.8/100,000, 95% UI: 4.1 to 16) compared with 4.7/100,000 globally (Figure 18). China's rate was lower at 5.9/100,000 (95% UI: 2.7 to 9.6). India and China, which have quite different rates of ozone-attributable deaths but large populations, had the highest overall numbers of ozone-attributable deaths worldwide, with 168,000 (95% UI: 82,000 to 262,000) deaths occurring in India and 93,300 (95% UI: 42,700 to 151,000) occurring in China. The United States has a lower overall rate of ozone-attributable deaths (2.1/100,000, 95% UI: 0.93 to 3.6) compared with these countries, but one that is higher than most other countries in the High-Income Super Region. Given its sizeable population, the United States saw 13,000 (95% UI: 5,600 to 21,000) ozone-attributable deaths, again more than any other country in the High-Income Super Region.

Trends in Ozone's Burden of Disease

Although global mortality rates from COPD attributable to ozone have declined by nearly 13% (95% UI: −20.3 to −4.9) over the past decade, the overall number of associated deaths increased by 16.1% (95% UI: 5.8 to 26.7). Trends in DALYs show the same pattern.

As with $PM_{2.5}$, the regional trends in total mortality burden attributable to ozone vary widely (Figure 19) given regional differences in ozone exposures, as well as underlying health and population characteristics. In general, exposures to ozone have risen at a lower rate than their associated health burdens over the same time period, despite declines in mortality rates from COPD in major regions like Southeast Asia, East Asia, and Oceania. Mortality rates from COPD in South Asia have remained relatively constant. Thus, the increase in burden in these and similar locations is driven largely by growth and aging of their populations. The overall global increase in the number of ozone-attributable deaths from COPD is strongly influenced by the trends in the large populations in the South Asia and the Southeast Asia, East Asia, and Oceania regions. Mortality burden in the High-Income Region is also trending slightly upward. Because COPD typically takes many years to develop as a result of long-term exposure to ozone and other irritants, it takes its toll primarily in older adults and is therefore most prevalent in countries with aging populations.

Changes in ozone-attributable deaths among the world's 20 most populous countries (Figure 20) show that 15 of these countries experienced increases in burden ranging from about 140 deaths in Mexico (a 6.5% increase) to over 76,000 in India (an 84% increase). Decreases in ozone-attributable mortality ranged from a reduction of about 70 deaths (a 5% decrease) in Vietnam to a reduction of about 52,000 in China, a decrease of 36%. The largest proportional increases were seen in Brazil (which saw a 191% increase in ozone-attributable deaths), Ethiopia (171%), the Democratic Republic of the Congo (97%), and Indonesia (89%). Given that these countries experienced only small increases in ozone exposure during the same time period, and COPD mortality rates have been largely stagnant over this time period, the increases largely reflect the growing numbers of older adults in the population.

The largest declines in the burden of disease from air pollution stem from reductions in exposure to household air pollution.

FIGURE 19 Trends in total deaths attributable to ozone in the GBD Super Regions.

State of Global Air 2020

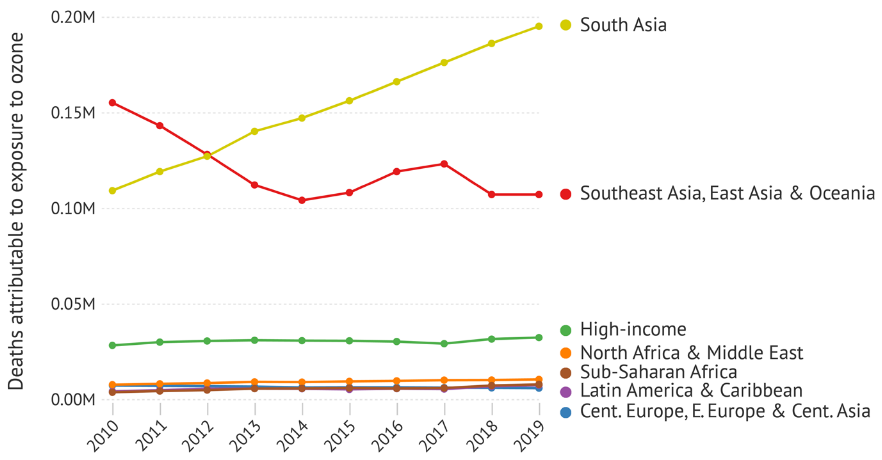

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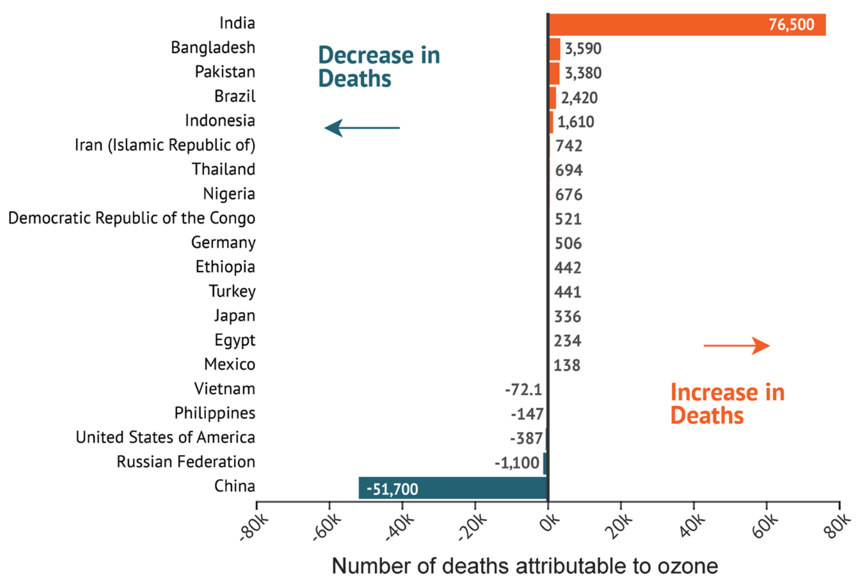
FIGURE 20 Change in total deaths attributable to ozone in the 20 most populous countries, 2010–2019.

State of Global Air 2020



BURDEN OF DISEASE FROM HOUSEHOLD AIR POLLUTION

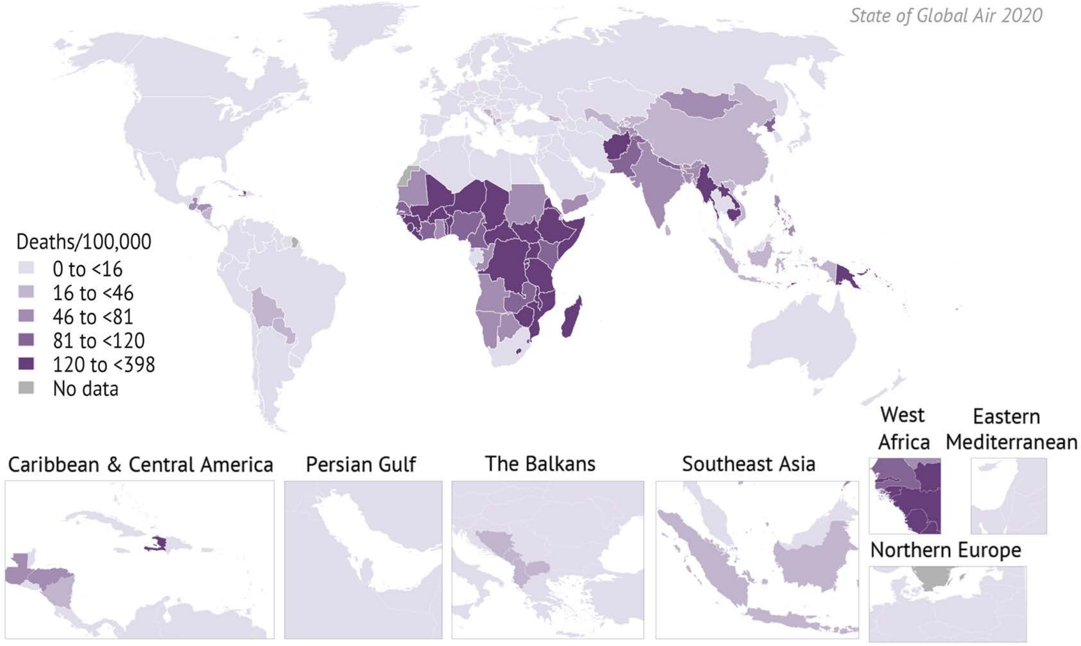
In 2019, long-term exposure to household air pollution from the burning of solid fuels for cooking contributed to 2.31 million (95% UI: 1.63 to 3.12) deaths and 91.5 million (95% UI: 67.0 to 119) DALYs. More than 90% of the DALYs were accounted for by years of life lost with the remainder due to years lived with disability. Household air pollution accounts for 4.1% of all global deaths and 3.6% of DALYs.

Among 69 risk factors included in the GBD that are considered to be potentially modifiable, household air pollution ranks 9th in the number of attributable global deaths. Although this is a decrease from its ranking of 7th in 2010 and reflects important progress in reducing this risk, this position underscores the continuing importance of household air pollution not only among environmental risk factors, but also compared with diet, lifestyle, and other factors.

Global Patterns in Household Air Pollution's Burden of Disease

The age-standardized rates of deaths attributable to household air pollution follow similar regional patterns as exposure to household air pollution (Figure 21). The highest age-standardized rates of death attributable to household air pollution are clearly visible in sub-Saharan Africa where household air pollution-related death rates are close to 200/100,000 in several countries (e.g., Niger, Chad, Mali, and Burkina Faso). The mortality rate of Nigeria, one of the most populous countries in the region, is 83/100,000 (95% UI: 57 to 111), lower but still more than twice the global average of 30/100,000. In South Asia, India has among the lowest rates

FIGURE 21 Global map of age-standardized rates of death attributable to household air pollution in 2019.



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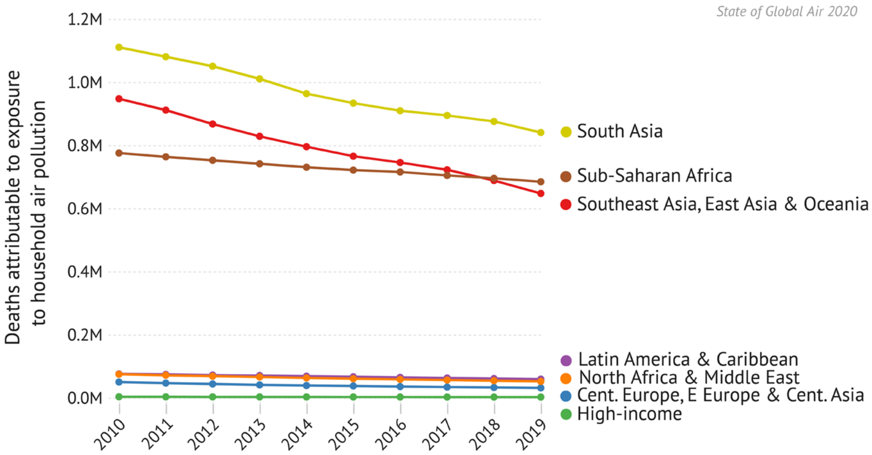
(60/100,000, 95% UI: 38 to 84) compared with Nepal (113/100,000, 95% UI: 69 to 166), Pakistan (93/100,000, 95% UI: 59 to 130), and Bangladesh (79/100,000, 95% UI: 51 to 113). In East Asia, the highest rates were reported for the Democratic Republic of Korea (107/100,000, 95% UI: 70 to 146), with the lowest for China (21/100,000, 95% UI: 10 to 35) and Taiwan (1.2/100,000, 95% UI: 0.28 to 3.4). For comparison, most countries in the High-Income Region, have household air pollution–attributable death rates well less than 1/100,000.

FIGURE 22 Trends in total deaths attributable to household air pollution in the GBD Super Regions.



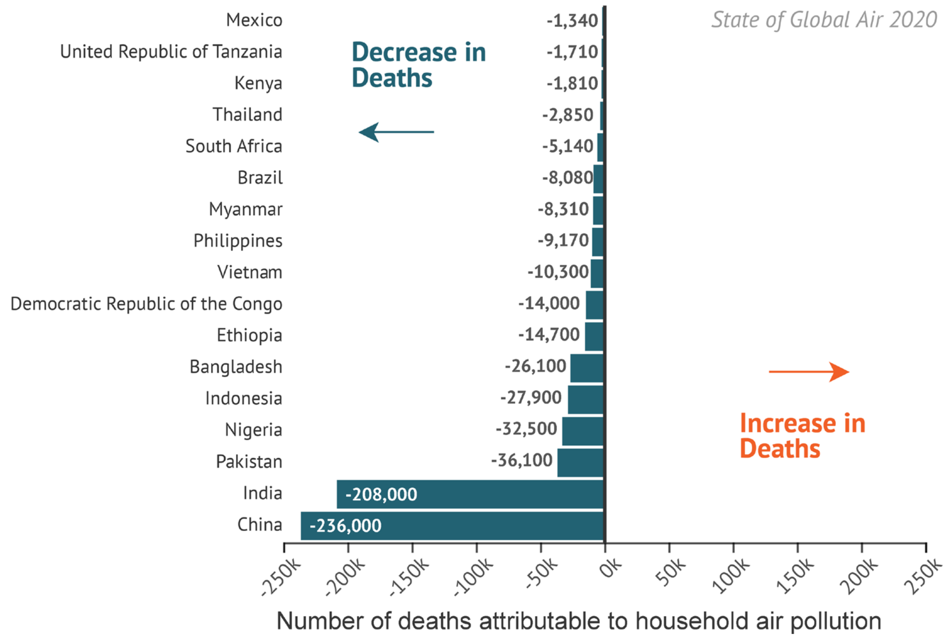
Trends in Household Air Pollution's Burden of Disease

The global burden of disease from household air pollution has decreased steadily over the past decade. Total deaths attributable to household air pollution fell by 23.8% (95% UI: −32.3 to −15.5), while the age-standardized mortality rates dropped by 37.5% (95% UI: −44.0 to −31.1). Total DALYs as well as age-standardized DALY rates attributable to household air pollution have dropped by similar percentages. Most of these declines have occurred in GBD Super Regions where the proportion of the populations using solid fuels and the related mortality rates are highest (Figure 22) — sub-Saharan Africa, South Asia, and Southeast Asia, East Asia, and Oceania.

Among the 17 countries with over 50 million people and where at least 10% of the population relied on solid fuels in 2010, all have seen substantial reductions in the burden of disease attributable to household air pollution in the past decade (Figure 23). By far the greatest gains have been made in China, where large-scale efforts have focused on replacement of coal cookstoves and led to dramatic reductions in exposure to household air pollution, and in India, where access to clean fuels (i.e., liquefied petroleum gas [LPG]) has been dramatically expanded across the country.

As for the other pollutants, these trends reflect not only reductions in exposures, but also declining mortality rates from improved treatment of and survival from air pollution–attributable diseases. In the case of household air pollution, those two factors have, on average, more than offset increases in population size and the aging of populations, even in countries like Nigeria and Ethiopia where the actual numbers of people exposed to household air pollution increased (Figure 10).

FIGURE 23 Change in the number of deaths attributable to household air pollution in the 17 countries with over 50 million people and at least 10% of their population cooking with solid fuels, 2010–2019.



How Burden of Disease Is Estimated

The GBD project's estimation of the burden of disease begins with a systematic evaluation of the scientific evidence and whether it is strong enough to attribute a given health outcome or cause of death to a particular pollutant. Every risk–outcome pair included in the GBD has undergone this rigorous evaluation.

For those outcomes linked through this process to individual pollutants, the GBD project then calculates air pollution's burden of disease in each country using:

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

The results of these calculations are expressed for the population in every country in a number of ways. In the *State of Global Air*, we focus on four:

- **Total number of deaths:** The number of deaths in a given year attributable to air pollution that likely occurred earlier than would be expected in the absence of air pollution.
- **Disability-adjusted life-years (DALYs):** The sum of the years of life lost from those early deaths plus the years lived with a disability, such as paralysis from a stroke related to air pollution exposure. Because DALYs reflect both the overall number of people affected and the age at which death or disability occurs, they better represent the total burden on society by capturing the years in which individuals are prevented from participating fully in life and the economy. Given the set of diseases currently attributed to air pollution in GBD, most of the DALY burden stems from early deaths rather than years of life with disability; for this reason, the *State of Global Air* focuses largely on mortality.
- **Age-standardized rates:** The total number of deaths or DALYs per 100,000 people, calculated based on a standard distribution of population across age categories. Age-standardized rates allow direct comparison of the health burden among countries with very different population sizes and distribution of ages in the population (e.g., older or younger). Higher air pollution–attributable age-standardized rates of disease reflect a combination of higher air pollution levels and/or sicker populations.
- **Loss of life expectancy at birth**: The difference in years between a person's expected lifespan and the length of life that would be expected if air pollution were not present.

Estimates of scientific uncertainty are provided for every value in the form of 95% uncertainty intervals (UIs), representing the range between the 2.5th and 97.5th percentiles of the distribution of possible values.

Numbers, Numbers! Estimates of the burden of disease attributed to air pollution have been proliferating at a rapid pace in recent years. In addition to the GBD estimates, among the most influential are those reported by the World Health Organization (WHO), which published its most recent estimates in 2016. Since that time, the WHO and the GBD approaches to estimating air pollution burden of disease have increasingly converged, and the differences between their estimates are diminishing. In 2018, the WHO and IHME signed a memorandum of understanding to collaborate on the development of burden of disease estimates in general, a step that may lead to closer collaboration on air pollution in particular.

AIR POLLUTION'S YOUNGEST VICTIMS

For the first time in 2019, the GBD analysis accounts for the impacts of particulate matter pollution (ambient $PM_{2.5}$ and household air pollution) exposures on infants' health and survival in their first month of life (ages 0 to 27 days). Relying on a growing body of evidence linking mothers' exposures during pregnancy to air pollution with the increased risk of their infants being born too small (low birth weight) or too early (preterm birth), the GBD estimated that 476,000 newborns worldwide died in 2019 as a result of air pollution exposure.

In 2019, air pollution contributed to nearly 500,000 deaths among infants in their first month of life.

A Fragile Stage

Low birth weight is typically defined as weighing less than 2,500 grams (5.5 pounds) at birth, while preterm birth is defined as being born before 37 weeks of gestation, the period that the child is carried in the mother's womb (full term is 38 to 40 weeks). These conditions, which are related because babies born too early are often small, make infants more susceptible to a range of diseases that carry a high rate of death or higher risks of long-term disabilities. For example, they are linked to a higher risk of lower-respiratory infections, diarrheal diseases, and other serious infections as well as brain damage and inflammation, blood disorders, and jaundice.

Air pollution accounts for 20% of newborn deaths worldwide, most related to complications of low birth weight and preterm birth.

The smaller the baby or the earlier she is born, the higher the risk of complications. If these babies survive infancy, they remain at a higher risk for not only lower-respiratory infections and other infectious diseases throughout early childhood but also for major chronic diseases throughout life.

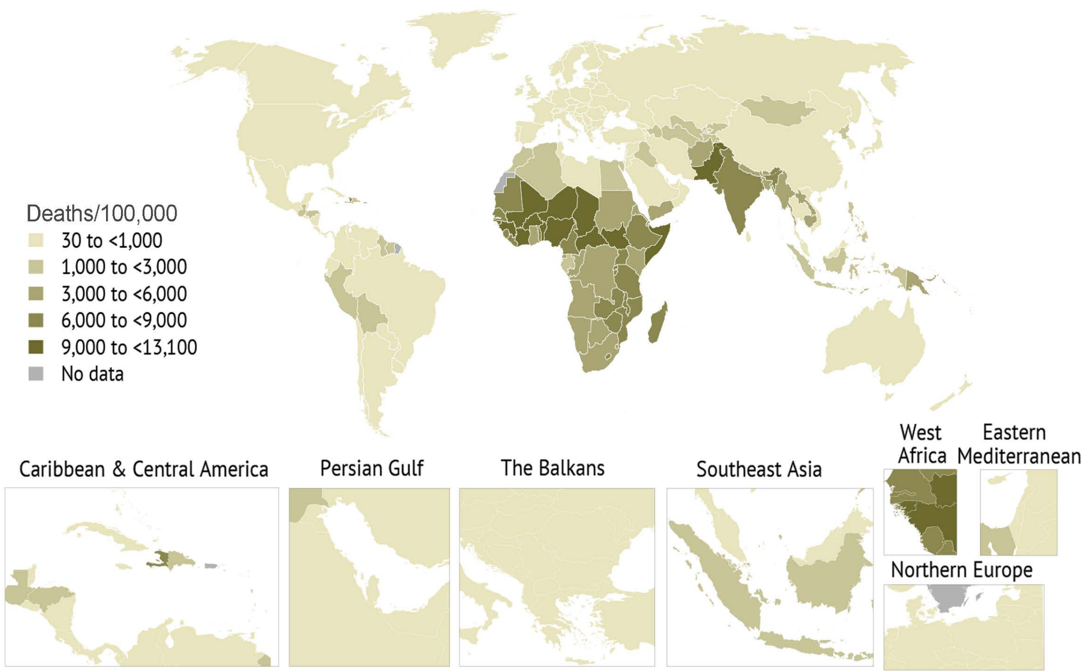
In 2019, about 2.42 million newborns died in the first 0 to 27 days of life from all causes. Of these, low birth weight and preterm births, combined with the health conditions that can often follow them, accounted for about 1.78 million deaths. A number of factors can contribute to low birth weight and preterm birth, including being pregnant with more than one baby (e.g., twins or triplets), and various aspects of a mother's health, including chronic health conditions, malnutrition, and tobacco use. Many of these risk factors are influenced by some of the same sociodemographic factors that increase a woman's risk of being exposed to high levels of air pollution. As a result, women in countries with low levels of sociodemographic development are especially at risk for adverse birth outcomes, with the related consequences for their children.

Impacts of Air Pollution

A growing body of both epidemiological and toxicological research links air pollution with increased risks of low birth weight and preterm birth. Although the biological reasons for this linkage are

FIGURE 24 Global map of neonatal death rates attributable to air pollution in 2019.

State of Global Air 2020



Of neonatal deaths attributable to air pollution, nearly two-thirds are related to household air pollution. Babies born in sub-Saharan Africa and South Asia face the highest risk.

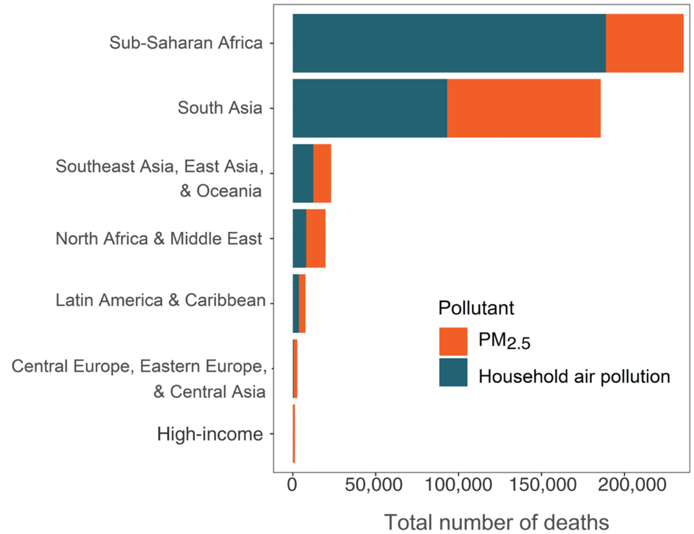
not fully known, it is thought that air pollution may affect a pregnant woman, her developing fetus, or both through pathways similar to those of tobacco smoking, which is a well-known risk factor for low birth weight and preterm birth. One plausible mechanism is that pollution particles or their components may move across the membranes of the lungs and be carried to other parts of the body, affecting placental function and the fetus. Another is that pollutants may initiate systemic inflammation or oxidative stress that affects the health of both the pregnant woman and her baby. Further research is likely to shed more light on possible biological mechanisms.

In previous years, GBD scientists have assessed air pollution's burden of disease for only one health outcome affecting babies: lower-respiratory infections. The inclusion of a broader suite of health effects — those mediated by low birth weight and preterm birth — represents a significant expansion in our understanding of how air pollution affects its youngest victims.

Global Patterns in Infant Deaths

Infants born in sub-Saharan Africa and South Asia have the highest rates of neonatal death attributable to air pollution, from 9,000 to 13,100 per 100,000 live births (Figure 24). High rates of pollution-attributable infant death are also seen in other parts of Asia, North Africa, and the Middle East, where $PM_{2.5}$ exposures are relatively high.

FIGURE 25 Deaths attributable to particulate matter in 2019 among babies in their first month of life in the GBD Super Regions.



Both indoor and outdoor pollution can be harmful to mothers and babies, but on a global scale, exposures to household air pollution are particularly dominant. Of all neonatal deaths attributable to air pollution, household air pollution (from burning solid fuels for cooking) accounts for about 64%, while the rest are attributable to ambient $PM_{2.5}$ (Figure 25). The highest percentage of deaths attributable to household air pollution (80%) was in the sub-Saharan region, while the lowest was in High-Income Region (<2%).

How Burden of Disease Is Estimated for Adverse Birth Outcomes

To assess air pollution's impact on infant health, GBD scientists conducted a systematic review of the scientific evidence. This review included over 70 epidemiological studies that examine the relationships between $PM_{2.5}$ or household air pollution and two fundamental indicators of risk in newborns:

- **Birth weight**, assessed based on continuous data (e.g., a baby's weight at birth) or threshold-based data (e.g., categorizing a newborn as either low birth weight or not, based on a cutoff weight of 2,500 grams); and
- **Gestational age**, assessed based on continuous data (total weeks of gestation up to 37 weeks) or threshold-based data (categorizing babies born before 37 weeks of gestation as "preterm" and those born before 32 weeks of gestation as "very preterm").

In assessing these studies, scientists took steps to distinguish between the effects of air pollution and those of other maternal risk factors that could affect birth outcomes, such as having twins or smoking during pregnancy. Based on the available evidence, scientists developed mathematical functions for estimating the proportion of neonatal deaths in a population accounted for by air pollution in two ways:

- **Direct effects** of air pollution as seen in lower-respiratory infections in babies 0 to 27 days old, and
- **Indirect effects** of air pollution as seen in low birth weight or preterm birth and the range of diseases linked with these outcomes. The functions for these indirect effects use continuous distributions between exposure and outcome to account for the increasing risk to babies the lower their birth weight or the earlier they are born (e.g., a month early versus a week early) relative to the ideal.

Because lower-respiratory infections can result from air pollution directly as well as indirectly as an effect of low birth weight or preterm birth, the calculations of total burden of disease from lower-respiratory infections include steps to avoid double counting.

CONCLUSIONS

The GBD project offers the most comprehensive and comparative analysis of the major risk factors that contribute to disease and early death worldwide — a crucial foundation for setting priorities to improve public health. Each year, the *State of Global Air* reports on air pollution's position within this comparative framework and on pollution levels and trends around the world. Knowledge of these trends is essential to understanding patterns in the burden of disease across countries and regions and vital to informing actions to reduce pollution in ways that have the greatest potential to benefit health.

Air pollution — comprising ambient $PM_{2.5}$, ozone, and household air pollution — is an increasingly important risk factor contributing to death and disability worldwide. In 2019, air pollution ranked 4th among major mortality risk factors globally, accounting for nearly 6.75 million early deaths and 213 million years of healthy life lost. Ambient $PM_{2.5}$ accounted for 4.14 million deaths (118 million years of healthy life lost); household air pollution accounted for 2.31 million deaths (91.5 million years of healthy life lost), and ozone accounted for about 365,000 early deaths (6.21 million years of healthy life lost). Taken together, these forms of air pollution accounted for more than 1 in 9 deaths worldwide in 2019.

As science advances, GBD scientists adjust their methods to account for the latest understanding of the ways in which air pollution affects human health. This year, the inclusion of adverse birth outcomes in the analysis brings a more complete picture of air pollution's burden of disease for infants in their first month of life. In 2019, particulate matter air pollution — ambient $PM_{2.5}$ and household air pollution — contributed to the deaths of nearly 500,000 infants in this age group.

The reality is that despite the explosion in data in recent years that have brought intense focus on air pollution, little or no progress has been made toward reducing air pollution and its associated health burden in many regions of the world. Over the last decade, levels of $PM_{2.5}$ exposure have remained high or increasing particularly in parts of Asia, Africa, and the Middle East. East Asia has seen marked regional reductions in pollution levels, driven primarily by major declines in $PM_{2.5}$ in China.

Ozone levels continue to creep upward, reflecting growing emissions of its precursor chemicals and a warming climate that helps accelerate ozone's formation. Countries in South Asia, which already have some of the highest ozone exposures in the world, have experienced the largest increases in exposure and burden over the past decade, while some countries in the High-Income, Central Europe, Eastern Europe, Central Asia and East Asia Regions saw modest declines in exposure, but not necessarily in burden.

Some of the largest improvements in air quality in the past decade stem from a shift away from the use of solid fuels for cooking. Of the three pollutants the GBD project studies, household air pollution is most closely linked to socioeconomic and demographic development. Improvements in sociodemographic indicators, coupled with major investments in clean energy for cooking by countries like China and India, have driven significant declines in exposure to global household air pollution and its associated burden of disease. However, much work remains to be done; roughly half the world's population continues to rely on solid fuels for cooking. The rate of solid fuel use remains highest in sub-Saharan Africa and several countries in Asia, home to the majority of the world's global poor.

Marked disparities in air quality among regions have barely changed over the last decade.

The marked disparities in air quality among regions have barely changed over the last decade; with few exceptions, the low- and middle-income regions remain the dirtiest, and high-income regions remain clean or are getting cleaner. The result is that millions of people every year have borne an avoidable burden from air pollution–related disease and premature mortality.

Reducing the burden of disease from air pollution poses an increasing challenge even where levels of exposure are leveling off or declining. Populations that are growing, and especially populations with an increasing number of older individuals, can see a rising number of people affected by air pollution even with the same exposure levels, since many of the chronic conditions associated with air pollution take years to develop and thus have a greater impact on health as populations age.

Communication of these patterns and trends forces recognition of the magnitude of the problem and whether or not we're making progress toward cleaner air and healthier communities. However, progress requires actions — actions that must be grounded in an understanding of the sources and drivers of air pollution and other risk factors at regional, national, and local levels; that take advantage of known solutions to sources of air pollution; and that address the economic, educational, and social disparities in resources necessary to make and sustain progress on air pollution and health.

This year, the emergence of a global pandemic and the subsequent closure of economies around the world have given us a stark reminder of the value of clean air. The air cleared in many places, opening vistas not seen in decades. At the same time, this global health emergency has laid bare vulnerabilities and disparities in our states of health, our health care systems, and our communities — conditions that may indeed have been worsened by disparities in both current exposures and years of prior exposure to air pollution. Understanding the interplay between air pollution and the COVID-19 pandemic will require much more careful research. The pandemic has nonetheless strengthened the case for accelerating efforts to achieve the lasting reductions in air pollution needed to remove it as one of the major risk factors for early death and disability around the world.

KEY RESOURCES

GLOBAL BURDEN OF DISEASE 2019 METHODS

These references provide background details on the latest GBD methods used to estimate $PM_{2.5}$, ozone, and household air pollution exposures and to estimate the premature deaths and disability-adjusted life-years (DALYs) reported in the State of Global Air *this year.*

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Explore and download additional information and data on mortality and disease burden for air pollution, as well as other risk factors, at the IHME GBD Compare site.

The exposure estimates included in the Global Burden of Disease and State of Global Air incorporate city-level measurement data reported by countries to the World Health Organization and Open AQ, among many other sources. Explore, visualize, and download city-level data from the WHO Ambient Air Quality database and OpenAQ.

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Explore information on monitoring and management of air pollution on the C40 Knowledge Hub.

CONTRIBUTORS AND FUNDING

Health Effects Institute

HEI is an independent global health and air research institute. It is the primary developer of the *State of Global Air* report, the host and manager for this website, the coordinator of input from all other members of the team, and the facilitator of contact with media partners. Key HEI contributors include Katy Walker, principal scientist; Pallavi Pant, staff scientist; Joanna Keel and Lee Ann Adelsheim, research assistants; Hilary Selby Polk, managing editor; Sofia Chang-DePuy, digital communications manager; Hope Green, editorial project manager; Aaron Cohen, consulting scientist at HEI and affiliate professor of Global Health at IHME; Bob O'Keefe, vice president; and Dan Greenbaum, president.

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Other Contributors

ZevRoss Spatial Analytics provided data visualization support and developed the interactive features of the site. Metropolis Creative designed the website; Charles River Web developed the website; Creative Science Writing provided writing support for the report and website; StoryMine produced the video.; and Cameographics composed the report.

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University of California, Berkeley.

(1947–2020)

The Legacy of Kirk Smith

Kirk R. Smith, MPH, PhD, was both a consummate scientist and a passionate advocate advancing the cause of reducing exposure — especially of mothers and children — to harmful household burning of solid fuels. Among his many other contributions, including to the development of WHO Air Quality Guidelines and UN Sustainable Development Goals, Kirk was a Global Burden of Disease pioneer. He led the first assessments for household air pollution and made seminal contributions to the development of methods for air pollution burden estimation. His knowledge and vision will be sorely missed, but his legacy is likely to live on in the many scientists and others he trained and inspired — and in the slow but steady decline in these exposures that has been happening worldwide, in no small part due to Kirk's work.