Health and Economic Benefits of a 2ºC Climate Policy

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Our nation faces multiple challenges, including the ongoing climate emergency, poor health for many Americans along with enormous medical spending, unprecedented job losses and systemic inequality. Though seemingly disparate issues, these problems are all connected in many ways. In particular, the burning of fossil fuels that is the primary driver of climate change is also responsible for the majority of deadly air pollution in the US. Transitioning to alternative energy sources not only improves the environment but would create jobs and reduce the disproportionate suffering from climate change and air pollution that falls upon the most vulnerable and exacerbates inequalities.

In this testimony, I present the results of new research by my group at Duke University in cooperation with NASA colleagues on the health and economic benefits to Americans if the United States and the rest of the world mitigate climate change to meet the objectives of the Paris Climate Agreement and keep global warming below 2ºC. This new work is the first to incorporate advances in understanding of public health that have taken place up through this year in a consistent evaluation of the impacts of both the climate and air quality changes resulting from aggressive policies to mitigate climate change. These results show that the health benefits are much larger than those in prior studies. I can provide the Committee with results for all the contiguous 48 states and major metropolitan areas throughout the country. Here I focus on national totals. I will then present our findings on how the health and economic benefits develop over time and how much of the benefits come from US actions. Finally, I will discuss policies to achieve these benefits and briefly touch on how those affect jobs and other societal concerns.

We find that there would be enormous benefits to the health of Americans from adopting policies consistent with the world's 2ºC pledge. ***Over the next 50 years, keeping to the 2ºC pathway would prevent roughly 4.5 million premature deaths, about 3.5 million hospitalizations and emergency room visits, and approximately 300 million lost workdays in the US.*** These large impacts reflect our updated understanding of the severe toxicity of air pollution and the dangers of heat exposure. Although it does not appear on death certificates it is indirectly responsible for a substantial fraction of heart diseases, including strokes, and respiratory diseases, including lower respiratory infections and chronic obstructive pulmonary disease.

The economic value of these health and labor benefits is enormous. The avoided deaths are valued at more than $37 trillion[1]. The avoided health care spending due to reduced hospitalizations and emergency room visits exceeds $37 billion, and the increased labor productivity is valued at more than $75 billion. ***On average, this amounts to over $700 billion per year in benefits to the US from improved health and labor alone, far more than the cost of the energy transition.***

A key finding is that ***roughly 1.4 million lives could be saved from improved air quality during the next 20 years***. As we've seen with the coronavirus lockdowns in many places, air pollution responds immediately to emissions reductions. ***A rapid shift to a 2ºC pathway could reduce the toll of air pollution, which leads to nearly 250,000 premature deaths per year in the US, by 40% in just a decade. Our work shows that action now means benefits now.***

Context

Climate change is a planetary emergency, with global average temperatures at the Earth's surface already having risen by more than 1ºC since the industrial revolution. Thousands of scientific studies have provided compelling evidence of the enormous damages that will occur with further warming, prompting the nations of the world to agree to strive to keep the global temperature rise "well below 2ºC" (in the Paris Climate Agreement). Failure to meet this goal will lead to disastrous consequences, including crop failures, ever stronger storms, both severe flooding and exacerbated drought in different places, large rises in sea-level, shortages of fresh water in many parts of the world, and worsening heat waves.

Moving to a 2ºC pathway would therefore bring tremendous benefits from the reduction in climate change but importantly, would also provide many benefits from reductions in air pollution. This is because the same activities that drive carbon emissions, primarily burning fossil fuels, are also the main sources of the emissions that cause air pollution. Our research project is one of the few to include both these factors in a single set of analyses, with most prior work looking at either the effects of climate change or air quality alone and thus providing a valuable but partial picture of the overall economic and health impacts.

How We Do Our Research

We used NASA's model for long-term climate projections developed over many decades at the Goddard Institute for Space Studies. Projections of climate change made with this model more than 30 years ago, and presented to Congress in 1988, have been shown to have been highly accurate in capturing observed global warming[2]. A few years ago, my research group at Duke augmented the capabilities of this model to represent air pollution at relatively high resolution, making this model suitable for simultaneous studying the impact of climate and air quality[3]. The model has been extensively evaluated[4] against the fleet of Earth orbiting satellites launched by NASA and NOAA, as well as ground-based air pollution monitors, and is capable of providing reasonable estimates of future heat and pollution levels associated with different socio-economic scenarios.

We focus on a comparison over 2020 to 2070 between a baseline emission scenario including current policies alone and a scenario in which the world institutes ambitious policies starting next year that have a high likelihood of keeping global warming below 2ºC in accord with international commitments. Such policies include rapid and deep decarbonization of the energy sector, end-use electrification including of most vehicles, heating and industrial processes, improving the energy efficiency of buildings, appliances, and industry, and managing land-use to reduce carbon and methane emissions[5].

The health impacts of fine particles (small bits of smoke, soot, dust and other liquid and solid particles that are tiny enough to penetrate deeply into the lungs when inhaled), of ozone (a toxic molecule that is one of the primary components of smog), and of heat are then calculated from the projected changes in each quantity based on extensive medical studies that have characterized the increased risk of disease and death associated with changes in exposure to each of these environmental factors. These include studies tracking hundreds of thousands of patients over many years, or in some cases even millions of patients. We include several recent updates that use expanded datasets and reveal that air pollution is even more damaging to human health than previously believed[6,7]. Indeed, a recent report put out by both the National Academy of Sciences and the National Academy of Medicine (as well as foreign academies) reported that air pollution affects nearly every major organ in the body, damaging them from before birth through to old age[8]. The report states: "The scientific evidence is unequivocal: air pollution can harm health across the entire lifespan. It causes disease, disability and death, and impairs everyone's quality of life. It damages lungs, hearts, brains, skin and other organs … affecting virtually all systems in the human body." Many of these effects are clearly present but cannot yet be reliably quantified. Hence our study includes only the well-characterized effects. Among the health impacts of climate change we focus on deaths due to heat exposure as extreme heat kills more Americans each year than are killed by floods, storms, and wildfires combined. These results are based upon a nationwide analysis technique newly developed by my group[9]. By using the latest evidence for the impacts of both air pollution and heat to evaluate premature deaths we find impacts roughly double those that would have been obtained using older evidence. Nevertheless, by not including all health impacts of either air pollution or climate change, our estimates might be considered lower bounds. Uncertainties in our values stem primarily from those in the underlying epidemiological data, but also incorporate those in modeling air pollution and climate change. Uncertainties in impacts are roughly 25-35%, with values equally likely to be higher or lower than the best estimates provided here.

What We Found

Meeting the 2ºC target through reductions of fossil fuel use would produce a broad range of health benefits. In addition to those reported above, these include about 50,000 fewer hospital admissions for children due to asthma and about 2 million fewer cases of childhood bronchitis in the US. Older people are particularly vulnerable to both air pollution and heat exposure, as are the poor, and so the adverse impacts fall disproportionately on the most vulnerable within society. These non-fatal health effects all stem from improved air quality, and hence all are important during the next two decades as well as in the second half of the century.

Mitigating climate change requires action now, but the health benefits from lower temperatures than would otherwise have been seen take longer to appear because of the inertia of the climate system to response to emissions changes. During the 50-year period we study, keeping warming below 2ºC could prevent over 200,000 premature deaths of Americans from heat exposure. All of these occur during the latter half of the century, adding to the benefits from cleaner air that occur both before and during those years.

The impacts on lost workdays illustrate why it is so important to reduce both air pollution and climate change. Exposure to air pollution and heat not only sends people to the hospital or to their graves, but it keeps people from working productively or going to work at all[10]. People cannot work if they are directly affected by exposure to heat or dirty air, but also when they are caregivers for children or elderly made sick by their environment. Our analysis finds that following a 2ºC pathway leads to 235 million addition workdays that would have otherwise been lost due to air pollution, valued at $51 billion. Additional benefits from reduced labor losses due to extreme heat become apparent in the 2060s, with the cooler temperatures of a 2ºC pathway leading to about 80 million addition workdays that would have otherwise been lost, valued at $20 billion. Hence there would be direct benefits via labor productivity to American businesses averaging about $1.5 billion per year from the cleaner air and cooler temperatures resulting from decarbonization.

Our Duke/NASA research also allows us to differentiate between the health benefits the US will realize if the world acts together to keep warming below 2ºC and those that the US will realize if we act alone. An apt analogy might be that climate change is like the coronavirus – we cannot close our borders and keep out this catastrophe. Air pollution is different, however. While concerted global action will reduce air pollution in the United States more than domestic action alone – and hence save more lives and produce more health benefits – the United States can realize a large proportion of the benefits from reducing air pollution even if it acts alone. We found that US action alone would bring us more than two-thirds of the health benefits of worldwide action over the next 15 years, with roughly half the total over the entire 50-year period analyzed. Hence ***while it is unquestionably true that tackling climate change requires the nations of the world to work together, it is also true that the bulk of the near-term benefits we stand to receive from taking action will come from our own policies.***

What's Good for the Environment is Good for the Economy

Though our study attempted to be comprehensive in health and economic impacts we could reliably quantify, climate change causes many additional profound damages. I live in North Carolina, and we've been hit by multiple hurricanes in the last couple years, with terrible flooding and damage. Our beautiful barrier islands are being drowned by the rising seas. We might not be able to stop these things, but we can slow down the losses and reduce the severity of hurricanes, wildfires, and heatwaves. The toll of billion-dollar disasters has been rising rapidly, with costs of more than $100 billion per year over the last 5 years[11] and will continue to do so if we don't take prompt action. All of these add to the economic case for action, which is clearly less expensive than failing to act.

It is sometimes claimed that we face a choice between the environment and the economy. This is false. Ask a delivery truck driver how easy is it to get their job done when it's 108 degrees Fahrenheit. Find a construction worker hammering down a roof in the blazing sun in Texas and ask them how well they work when it's 110 and humid. Ask a worker on a farm or on a giant factory floor too large to be air conditioned how many breaks they'll need when temperatures rise even more in the summertime. Adding in the impacts of breathing dirty air, these productivity losses cost American businesses billions each year. The environmental costs of climate change and air pollution are also passed on to all businesses who pay in their higher health and damage insurance costs. Hence it's not a question of choosing the environment or the economy – it's choosing a healthy environment and a strong economy or a polluted environment and a weaker economy.

Furthermore, renewable electricity sources such as solar and wind power and energy efficiency programs create far more jobs per unit of energy produced or saved than fossil fuels, making the transition better for workers too (though obviously compensation and training for current fossil fuel sector employees would be a necessary part of a clean energy transition). In fact, clean energy employment has grown far more rapidly than coal jobs have been lost, and 2020 data show that it now accounts for more than 40 percent of America's entire energy workforce[12]. New clean energy jobs are especially important now when new jobs are so desperately needed due to the economic slowdown caused the coronavirus pandemic.

Our research quantifies how when heat waves reduce labor productivity in construction, agriculture and other outdoor jobs, there are real costs paid by businesses. It evaluated how, when increased asthma keeps kids home from school, and therefore their parents stay home from work, that too leads to large costs. These indirect economic effects are analogous to those caused by the coronavirus pandemic, in which the effect of that change in our environment extends far beyond the direct impacts on individuals who need healthcare themselves. Similarly, when everyone's insurance and health care premiums rise due to climate change and air pollution, we all pay these costs. Recognizing the magnitude of these costs is critical to making the best decisions for all. By picking up the tab for the costs of environmental and health damages from fossil fuel use, we are effectively subsidizing an extremely profitable industry, and in doing so, are paying for our own ill-health. Overall, we find that the health and labor benefits of reaching a 2ºC pathway far outweigh the associated costs, especially given the newer, larger benefits reported here[13].

What We Can Do

We have solutions and can reap the enormous gains in health, jobs, productivity, and agricultural yield while in many cases saving consumers and businesses money. Solar or wind energy are now cheaper electricity sources than fossil fuels in most of the country, often cheaper even when including battery storage[14] which is going some way to solving the intermittency challenge of wind and solar that are otherwise not always available when desired. This applies not only to new generation capacity, but even to existing infrastructure. For example, most coal-fired power plants in the US could be shut down and replaced with renewables at a net cost savings[15]. And unlike fossil fuel systems, the cost of renewable power is continuing to decline, prompting widespread worry about stranded assets associated with any further spending on fossil fuels along with widespread optimism that future energy-intensive businesses will be more competitive in those parts of America powered by clean energy. The immediate pivot away from fossil fuels required to meet aggressive climate change mitigation targets would thus provide great benefits for both the health of Americans and their pocketbooks, whereas any new construction of fossil fuel infrastructure is now viewed as both an economically risky and ethically dubious investment by many.

Electric vehicles now have long ranges and both they and more fuel-efficient vehicles save consumers money on fuel costs over the lifetime of the car. Electric vehicles and more fuel-efficient vehicles also save lives by reducing air pollution. Those benefits are well-known but have been underestimated in prior analyses. The economic gains from switching to electric vehicles are likely to grow as battery costs continue their decline and electric vehicles reach parity with internal combustion engines in the next few years (their lifetime costs, including fuel and maintenance, are already lower than internal combustion vehicles in many cases). Supporting electric vehicle charging infrastructure, more fuel-efficient cars, mass transit and active transit are all ways to reduce emissions from transportation. Another part of addressing climate change is energy efficiency improvements, which typically pay for themselves while putting people to work.

In addition to transitioning away from fossil fuel use, there is a compelling need to reduce emissions of methane, the second most important driver of human-made climate change after carbon dioxide. Fortunately, many solutions are available to reduce emissions of methane, and even better a large fraction of them more than pay for themselves as captured methane from landfills or fossil fuel infrastructure is a valuable product (methane is the main component of natural gas). Since methane is one of the emissions that leads to ozone production, reductions not only reduce climate change but also reduce air pollution, as with decarbonization. Within the fossil fuel and waste sectors, roughly half of US methane could likely be reduced at a net cost savings even without accounting for environmental damages. When accounting for the health and economic benefits of the improved air quality and avoided climate change, nearly two-thirds of our emissions could be eliminated at a net economic gain through technological changes. The remainder are largely from agriculture. Decreasing emissions from that sector would require reduced consumption of cattle-based foods, which for most people would be a healthy choice that happens to also help the planet by reducing methane emissions. Hence there are many reasons to follow a 2ºC pathway in addition to environmental impacts. The Climate and Clean Air Coalition, of which the US is a founding partner, works to achieve substantive reductions in emissions, including methane, in order to simultaneously mitigate climate change and improve air quality. US leadership in this area would be likely to inspire additional action elsewhere, benefiting us all.

I would like to close by acknowledging my NASA GISS and Columbia University colleagues and my research group at Duke, whom I note are mostly students, without whom this work would not have been possible. Together our research has shown that we do not need to choose between the economy or the environment, but rather that mitigating climate change helps American businesses that would see increased worker productivity and lower health and damage insurance premiums, improves the health of Americans suffering from heat exposure and air pollution, increases the number of jobs, and reduces systemic inequality and injustice for the most vulnerable who are disproportionately affected by both air pollution and climate change –

the poor, children, the elderly and people of color. We can thus gain both a stronger economy and a healthier environment by transitioning now to clean energy and a 2ºC pathway.

Research Team

The work presented here represents the efforts of a large team of researchers, though they are not responsible for the statements expressed here. No statements should be construed to imply that NASA endorses these policy suggestions.
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Appendix: Methods

Model Setup

Our health and economic impact evaluation is based upon the results of computer simulations of the effect of future emissions of carbon dioxide and other greenhouse gases along with associated pollutants such as ozone and particulate matter under two sets of scenarios. The first set examined the effects of a transition across all sectors and all countries to a 2ºC pathway relative to a reference scenario that leads to approximately 4ºC warming by the end of the century.

The second set of scenarios compared three scenarios: (1) decarbonizing the entire world's power sector; (2) decarbonizing only the US power sector; and (3) maintaining current policies along with projected changes in energy demand, but not taking further action to reduce burning of fossil fuels for energy production. In the decarbonization scenarios, the rate of decarbonization of the power sector was assumed to be consistent with keeping warming below 1.5ºC.

These simulations were performed using the latest version of NASA's global climate model developed at the Goddard Institute for Space Studies (version: GISS-E2.1-G[4]). That model includes representations of the physical and chemical processes that govern Earth's climate and the composition of the atmosphere, has been widely used in climate research over the past several decades, and has been shown to realistically capture many of the physical quantities and trends that have been observed by the fleet of NASA and NOAA Earth-observing satellites (e.g. [16]). Note that the newer E2.1 version (used for GISS submissions to phase 6 of the Coupled Model Intercomparison Project (CMIP6)) includes an improved representation of surface ozone concentrations relative to prior versions that showed a substantial positive bias.

As an example of the model's performance, our simulations produce a 2020 population-weighted concentration of particulate matter with a diameter less than 2.5 microns ($PM_{2.5}$) across the contiguous US of 8.9 µg m^{-3} (reporting the 2016-2025 average). For comparison, the comparable population-weighted concentration calculated from a widely-used dataset produced by using satellite observations of aerosol to adjust a global model's simulated concentration is 9.3 µg m^{-3} for 2014-2016, the latest years available[17], and the value estimated by US EPA scientists using a data fusion of surface monitoring and a high resolution regional model was 8.4 µg m^{-3} for 2014 (the most recent year analyzed[18]).

Impacts: Introduction

The climate and air pollution conditions derived from the modeling were then used to quantify impacts on human health (mortality and morbidity) due to pollution and heat exposure, and on worker productivity due to air pollution and heat exposure. Impacts of exposure to both pollution and climate change were calculated for each set of scenarios worldwide, but here we focus on results in the United States. Impacts were evaluated on a grid of approximately 50 x 50 km (33 x 33 miles). This relatively high-resolution simulation allows the model to capture pollutant exposures in urban areas, as documented in prior publications using similar methodology[3].

The health impacts analysis used the most up-to-date epidemiological relationships based on decades of public health data on air-pollution related deaths, heat-related deaths, and nonfatal (morbidity) impacts of exposure. In such studies, the health of hundreds of thousands or even millions of people are tracked over time, allowing a statistical relationship between exposure and health effects to be established. This is similar to research relating cigarette smoking to health impacts. Exposure to air pollution has been clearly linked to increased risk of heart disease, stroke, chronic obstructive pulmonary disease, lower respiratory infection, lung cancer, pneumonia, and diabetes, all of which can lead to premature death. The increased risk due to exposure is combined with data on baseline public health and population distributions, along with projected changes in those factors over the coming decades, to evaluate overall health burdens on the US population.

Our analysis includes projected changes in population and baseline health conditions. Population projections are from the socio-economic modeling associated with the Shared Socio-economic Pathways (SSP), a community-wide project to provide plausible alternative projections of various futures including 'sustainability' (SSP1) and 'regional rivalry' (SSP3)[19]. These population projections are applied at the country-level using the year 2015 distribution of population in the US (CIESIN, https://sedac.ciesin.columbia.edu/data/collection/gpw-v3) but also accounting for the slight increase from 85% to 94% for the urban share of population from 2020 to 2070 in the projections. The projected US population varies greatly across the scenarios, even as to the direction of change relative to the current (2020) population of about 340 million. Under SSP1, the US population rises to 440 million whereas under SSP3 it decreases to 315 million. As our standard reference case is SSP3, this means that all climate policy cases (which use the other SSPs) have higher population, thereby reducing the health benefits when evaluated in terms of total numbers. In particular, the benefits of the lowest warming scenarios which are under SSP1 are realized by a population 43% larger than that projected under the reference case SSP3 in 2070, greatly reducing their apparent value when viewed in terms of total burdens. These populations projections are applied for both mortality and morbidity calculations.

The projections of future baseline mortality including cardiopulmonary disease, respiratory disease and malignant neoplasms are from the International Futures (IF;[20] Hughes et al., 2011) model version 7.45 base scenario (http://pardee.du.edu/access-ifs, accessed September 23, 2019). This model projects cause- and country-specific baseline mortality rates through 2100. For each country and underlying disease, we calculate the baseline mortality rate changes between the future year (e.g. 2050) and 2015 and then we apply this relative change to the 2015 Global Burden of Disease (GBD) baseline mortality[21]. GBD baseline mortality rates were mapped to best match the current International Classification of Diseases (ICD) codes for respiratory (ICD-10 Codes: J00-J98; GBD Codes: B.3, A.2.3, A.2.4) and cardiovascular (ICD-10 Codes: I20-I25, I30-I51, I60-I69, I70; GBD Codes: B.2.2, B.2.3, B.2.8, B.2.9, B.2.10) related deaths for which significant impacts were found in the epidemiological study[22]. For ozone-related impacts, the IF cardiovascular and respiratory changes were mapped to those impacts. In the case of impacts for which the epidemiology has provided links to broader mortality rates, we apply the nearest match from the IF data: all-cause except accidents is matched to non-communicable plus communicable diseases for heat exposure and non-communicable diseases plus lower respiratory infections is used for the all-cause impacts of $PM_{2.5}$ (consistent with the epidemiological study[23]).

Premature Deaths

In the case of particulate matter, these epidemiological relationships come from a comprehensive report released in 2018 by 54 of the world's leading experts on small particle air pollution[23]. That analysis is based upon the results of a meta-analysis including 41 cohort studies from around the world, including the US. Among other findings, that study concluded that the all-cause impact of $PM_{2.5}$ exposure was on the order of 30% greater than the sum of the response to the five previously established specific causes of death (ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and lower respiratory infections). Deaths are evaluated for adults older than 25 based on the response to modeled exposures obtained with the Global Exposure Mortality Model described in the meta-analysis study.

In the case of ozone, these epidemiological relationships come from a 2016 study that updates the prior analyses by the same team that is the basis of standard US and international health analyses[22]. This analysis is based upon the responses reported in one of the largest studies to date that uses the American Cancer Society Cancer Prevention Study-II cohort. It calculated cause-specific deaths attributable to incremental changes in the maximum daily 8 h average ozone concentration using a version of this cohort that spans 22 years of follow-up and included 669,046 subjects who experienced 237,201 deaths.

The Environmental Protection Agency uses a program called BenMAP to calculate the number of air pollution-related deaths and illnesses[24]. BenMAP, however, incorporates older versions of the epidemiological relationships between air pollution and deaths and illnesses that were developed in 2009 for ozone and 2014 for particulates. The estimates presented in this briefing use the latest epidemiological relationships developed by the researchers in 2016 for ozone and 2018 of particulates. We point out that both the exposure-response relationships in EPA's BenMAP and those used in the estimates presented in this briefing are derived from the work of the same leading researchers. These updated epidemiological relationships show that both types of pollution are more lethal than previously understood.

For example, BenMAP estimates that exposure to particulate matter caused 121,000 premature deaths in 2014 in the United States[17]. The more recent work by the leading small particulate experts estimates that exposure to particulate matter caused 213,000 premature deaths in 2015 in the United States and Canada[23]. This is very similar to our 2020 value which is 191,000 annual premature deaths in the US using the latest exposure-response function, with the slightly larger value in the other study seeming to correspond well to the inclusion of Canada and the slightly earlier year for their analysis. For ozone, using observed concentrations and the older 2009 epidemiology produces estimated deaths in the United States of 17,000 per year whereas using the newer 2016 epidemiology produces estimates of 51,000 per year[25].

In the case of heat exposure, we use the generalized risk function covering the US for hot temperatures above the local optimum temperature derived in a prior study[26]:

$$RR = 1 - 0.0014 \times (SMT - 30.9)T^2 + 0.005 \times (SMT - 26.7)T$$

where RR is relative risk, SMT is the local summer mean temperature (June–August) and T is the local daily temperature in °C above the optimum temperature where the latter is represented by each location's 84th percentile temperature[27]. For US conditions, this relationship implies a stronger increase in RR at the highest temperatures in cooler locations, consistent with the underlying epidemiological data used to derive the generalized function[26,28]. This generalized risk function has been shown to capture the observed shape of the exposure-response curve in each of the 10 US cities that were used in prior evaluation of its performance[26]. As with other impacts, mortalities are estimated using:

$$\Delta Mort = y_0 \times AF \times Population$$

where the attributable fraction AF is defined as (RR-1)/1, y_0 is the all-cause baseline mortality rate and Population is the all-age local population. Potential adaptation to heat is also evaluated using a variety of plausible assumptions[26].

Morbidity Outcomes

Morbidity impacts of $PM_{2.5}$ are based on a systematic review and meta-analysis of literature describing responses for hospital admissions (HA), asthma-related emergency room visits (ERV), and childhood bronchitis cases. Briefly, in the meta-analysis for HA, we separate impacts into those associated with cardiovascular disease and those related to respiratory disease. Cardiovascular diseases are defined as either codes 390–459 based on the International Classification of Diseases, Ninth Revision (ICD-9), or I00-I99 based on the Tenth Revision (ICD-10). For the latter revision, these include cardiovascular diseases (CVD-ICD I00-I99, except I88), arrhythmia (ICD10: I46-I49), cardiac diseases (ICD10: I00-I59, I97.1, I98.1), cardiac failure (ICD10: I50); ischemic heart disease (ICD10: I20, I21, I22, I24, I25.2), myocardial infarction (ICD10: I21, I22) and stroke (ICD10: I60-I66, I67 (except I67.0, I67.3), I68 (except I68.0), I69). Similarly, respiratory impacts are defined as hospital admissions classified with codes 460–519 in ICD-9 or codes J00-99 in ICD-10. For ICD-10, these include the broad category diseases of the respiratory system (J00-J99), which in turn encompass acute upper respiratory infections (J00-J06), pneumonia (J12-J18), chronic obstructive pulmonary disease (J41-J44), and asthma (J45-J46), among others. We did not include studies that only focused on specific causes within the above groups. In other words, we are reviewing the increased risk in "all-cause" cardiovascular and respiratory hospital admissions.

The exposure-response function (ERF) for the relationship between $PM_{2.5}$ exposure and cardiovascular HA is based upon 32 studies, with separate ERFs for the all-age population and for the population older than 65 years of age. Our ERF for the relationship between $PM_{2.5}$ exposure and respiratory HA is based upon 41 studies, with a single all-age ERF as no significant differences were observed for different population subgroups. The ERF for asthma-related ERV is based upon 27 observations reported in 17 studies. Among those, 9 observations were focused on child asthma ERV but statistical tests did not indicate a significant difference between the effects on children and those on adults. We thus constructed an ERF for the all-age population based on the pooled results of all the studies.

For each morbidity endpoint, we constructed both log-linear and non-linear ERFs. The log-linear exposure-response model is described by:

$$HR = \exp{(\beta x)}$$

where HR is the hazard ratio, β is the coefficient of the exposure-response effect, and x is the exposure to $PM_{2.5}$. By definition, the logarithm of the HR increases at a constant rate β with increasing exposure. The non-linear ERF has two additional parameters, μ and τ, to allow curvature and location of the ERF to change across the range of exposure. This modeling approach was applied in reference 23. This ERF is expressed as:

$$HR = \exp\,(\theta \mathrm{T}(\mathrm{x}))$$

where

$$T(x) = \mathrm{f}(\mathrm{x})\omega(\mathrm{x})$$
$$f(x) = \mathrm{x}, \text{ or } f(x) = \log\,(\mathrm{x} + 1)$$
$$\omega(\mathrm{x}) = 1/(1 + \exp\{-(\mathrm{x} - \mu)/(\tau \mathrm{r})\})$$

where θ is the regression coefficient, (μ, τ) are parameters, x is the exposure and r is the 5^{th}-95^{th} percentile range of exposures in the underlying studies. The two forms of $f(x)$ allow this ERF to behave as either a log model (when $f(x) = \log\,(\mathrm{x} + 1)$, $HR = \exp\,(\theta \log(\mathrm{x} + 1)\, \omega(\mathrm{x}))$) or as a log-linear model (when $f(x) = \mathrm{x}$, $HR = \exp\,(\theta\, \mathrm{x}\omega(\mathrm{x}))$). Note that when ω(x)=1 and $f(x) = \mathrm{x}$, this functional form becomes identical to the log-linear model above (i.e. $HR = \exp\,(\theta \mathrm{x})$). The function ω(x) is a logistic weighting function, where μ and τ control the shape. As such, the effect size becomes a non-linear function of x, instead of being constant across the range of x.

Finally, the HR calculated from the ERFs above is then used to derive AF:

$$AF = 1 - 1/HR$$

where AF is the fraction of total morbidity burdens at a specific location attributable to the $PM_{2.5}$ exposure, such that similar to mortality:

$$\Delta Morbidity = y_0 \times AF \times Population$$

where y_0 is the baseline morbidity rate of each endpoint for the US, and population is the total population in the age groups applicable for a given morbidity endpoint.

In addition, we evaluated the effects of both air pollution and heat exposure on labor productivity. Labor losses due to exposure to extreme heat are evaluated using previously established exposure-response functions for the US[29]. In that study, nationally representative survey data from 2003 to 2006 and daily weather observations from roughly 8,000 weather stations were used to investigate how Americans allocate their work and leisure time as a function of ambient temperatures. They found a statistically significant approximately linear decrease in the time allocated to labor with increasing temperatures for high-risk sectors when value exceeded a threshold of about 29°C. This relationship has been widely used recently [30, 31]. In our calculations, the value of time lost is calculated using county-level annual employment (covering working ages 15-64 years old) and annual average weekly wages from the Quarterly Census of Employment and Wages, US Bureau of Labor Statistics. We use the North American Industry Classification System to determine the number of workers in high-risk industries/sectors (largely those that cannot readily be air-conditioned): agriculture, forestry, fishing and hunting, construction, manufacturing, mining, transportation, and utilities. The 2016 fraction of workers in high-risk industries is used for each county. National average wages range from \$19.0 $hour^{-1}$ for agriculture to \$44.9 $hour^{-1}$ for utilities and are spatially heterogeneous across the US. The analysis covers the contiguous US. Surface temperature changes are based upon the daily temperature values modeled in the simulations, with results reported averaging lost hours over at minimum 10 years to reduce the noise inherent in daily temperature values.

The effects of exposure to $PM_{2.5}$ on labor are evaluated based on a study relating such exposure to work loss days in the US for 1976-1981[32]. As in similar analyses performed by the US EPA[24], we calculate the HR as the average across years weighted by the variance of β each year, finding a mean of 1.047 per 10 μg m^{-3} and a 5%-95% confidence interval of 1.04 to 1.05. These apply to the working age population defined as persons aged 15-64.

Valuation of Impacts

Monetized benefits associated with avoided mortality are evaluated using a willingness-to-pay (WTP) measure of the value societies place upon reduced risk of premature death. This measure is often referred to as the value of a statistical life (VSL) though it is in fact an expression of the value that people affix to small changes in mortality risks in monetary terms rather than the value of any individual's life. Such valuations can be derived from empirical data, for example on the increased wages offered for occupations with a higher risk of death or expenditures on transportation safety measures. Health literature often uses disability adjusted life years, which are arguably more informative since they incorporate the age of the affected individuals, but for monetization VSL is a better-established metric in the economics. We base our WTP on the mean of 26 peer-reviewed studies evaluated by the United States Environmental Protection Agency[33] and used by that agency to derive its official recommended VSL of $7.4 million in 2006$. That value is then inflated to represent the year 2018 using an economic growth rate of 2.6% yr^{-1} and an elasticity for WTP with income growth of 0.4.

For morbidity, the value of avoided hospital admission is based on the Healthcare Cost and Utilization Project, a US government-run health data project with a comprehensive dataset for inpatients[34]. Values range from $11,900 per visit for respiratory illness to $16,400 per visit for cardiovascular disease in persons over 65 and to $18,900 per visit for cardiovascular disease in persons under 65 years of age. Valuation of avoided asthma ERVs is based on ref. 35 and is $91 per visit. Valuation of work loss days due to air pollution and of childhood bronchitis is based on the Carbon Reduction Benefits on Health calculation tool produced by the World Health Organization[36], adjusted to US conditions, and are $216 per day and $1057 per case, respectively. Work losses due to air pollution are assumed to affect all sectors of the economy.

To estimate the value associated with labor losses from heat, which do not affect all sectors, we use 2016 county-level annual employment (working ages 15-64 years old) and annual average weekly wages from the Quarterly Census of Employment and Wages, US Bureau of Labor Statistics (https://www.bls.gov/cew/datatoc.htm, accessed Jan 10, 2019). We use the following North American Industry Classification System (NAICS) codes to determine the number of workers in high-risk industries/sectors that are affected by heat exposure: NAICS 11 for agriculture, forestry, fishing and hunting; NAICS 23 for construction; NAICS 31-33 for manufacturing; NAICS 21 for mining; NAICS 48-49 for transportation, and NAICS 22 for utilities (https://data.bls.gov/cew/doc/titles/industry/industry_titles.htm, accessed Jan 10, 2019). The 2016 fraction of workers in high-risk industries is used for each county. National average wages range from $19.0 $hour^{-1}$ for agriculture to $44.9 $hour^{-1}$ for utilities, and these are spatially heterogeneous across the US.

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