# Pollution and Climate Change

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**Summary**

Childhood is a particularly sensitive time when it comes to pollution exposure. Allison Larr and Matthew Neidell focus on two atmospheric pollutants—ozone and particulate matter—that can harm children's health in many ways. Ozone irritates the lungs, causing various respiratory symptoms; it can also damage the lung lining or aggravate lung diseases such as asthma. Particulate matter affects both the lungs and the heart; like ozone, it can cause respiratory symptoms and aggravate asthma, but it can also induce heart attacks or irregular heartbeat. Beyond those immediate effects, childhood exposure to ozone and particulate matter can do long-term damage to children's health and reduce their ability to accumulate human capital. For example, frequent asthma attacks can cut into school attendance and academic performance, ultimately detracting from children's ability to earn a good living as adults.

Fossil fuel-burning power plants, which are a major source of carbon emissions that cause climate change, also emit high levels of nitrogen dioxide and sulfur dioxide, which play a role in forming ozone and particulate matter. We might assume, then, that policies to reduce climate change by cutting back on carbon emissions from power plants would automatically cut back on these other types of pollution. But it's not quite that simple—atmospheric concentrations of ozone and particulate matter are linked to heat and other climatic variables through complex, nonlinear relationships.

Taking those complex relationships into account and examining a variety of ways to model future air quality, Larr and Neidell project that policies to mitigate the emissions that produce climate change would indeed significantly reduce atmospheric ozone and particulate matter—at least in the United States, which has the most-complete data available to make such calculations. The drop in pollution would in turn produce significant improvements in child wellbeing. Children would be more likely to survive into adulthood, experience healthier childhoods, have more human capital, and be more productive as adults.

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We can expect climate change—and policies aimed at curbing it—to affect air quality, among other things. Exposure to pollution during childhood has numerous consequences for wellbeing. In the short term, it can affect health; for example, it can exacerbate children's asthma or even kill them. In the long term, it can alter their human capital (for example, how many years of school they complete) and their labor market productivity. This article spells out and quantifies some of those effects based on our understanding of the relationships between climate change and pollution and between childhood pollution exposure and wellbeing.

We focus on two ways that climate change and efforts to fight it may affect air quality. The first involves policies that aim to reduce the use of fossil fuels, which emit not only carbon dioxide ($CO_2$) but also many air pollutants that affect health. For example, power plants are major sources of $CO_2$, but they also emit high levels of sulfur dioxide and nitrogen dioxide, which lead to the formation of ozone and fine particulate matter (particles up to 2.5 microns in size, or $PM_{2.5}$). Therefore, any policies that reduce the use of fossil fuels would also reduce emissions that affect local air quality. (Geoengineering techniques such as carbon capture and sequestration don't generate improvements in local air quality because they don't reduce the amount of $CO_2$ produced.) The health effects of using less fossil fuel are often referred to as *cobenefits* of climate change policy.

The second way that climate change may affect air quality is through weather's role in determining pollution. For example, ozone forms when heat combines with volatile organic compounds and nitrogen oxides. Therefore, warmer temperatures are expected to increase ozone levels. The process is complex, however, and some predictions about climate change's net effect on air quality are ambiguous.

To understand how changes in ozone and $PM_{2.5}$ might affect child wellbeing, we review empirical estimates of the relationship, focusing solely on studies that use *quasi-experimental* research designs. We do so because pollution is not randomly assigned across children, and a third factor might cause both more exposure to pollution and worse health outcomes, skewing the results through what's called *omitted variable bias*. For example, because worse air quality is often reflected in lower housing prices, families with higher incomes are more likely to live in areas with less pollution. Those same families are also likely to invest more in their children's health and human capital. Failing to account for that correlation would lead to spurious estimates of pollution's effects. Quasi-experimental studies attempt to overcome that limitation by examining events that produce unexpected changes in air quality in some areas but not in others.

We begin by describing how air pollution may affect child wellbeing. We then review estimates from models that project pollution changes under various climate change and mitigation scenarios. To gauge how climate change–induced pollution might affect child wellbeing, we then combine those pollution changes with estimates from quasi-experimental studies of how childhood pollution exposure affects various outcomes, including infant mortality, respiratory diseases, and labor market productivity. As with all research that projects the effects of climate change, our calculations involve many assumptions. Climate change is a long-term problem, and we need to make decisions in the present based on uncertain outcomes in the future; our estimates of the potential impacts offer suggestive evidence to help make those decisions.

Our projections suggest that mitigating the emissions that produce climate change would lead to significant improvements in child wellbeing. More children would experience healthier childhoods, survive into adulthood, have more human capital, and be more productive as adults. Those projected benefits arise whether we compare air quality under a mitigation scenario with today's air quality or with air quality in the future if no mitigation occurs.

Our calculations focus exclusively on the United States, not because we're interested only in this country but largely because we have sufficient US data, such as forecasts for ozone and $PM_{2.5}$ under various future climate scenarios. Although we can't explicitly quantify the relationship in other developed countries, we suspect that effects would be similar because of generally similar technologies, industrial activity, capacity to implement policy, and projected climate changes. Effects are likely to differ substantially in developing countries, however. For example, many developing countries, such as those in sub-Saharan Africa, already face much warmer temperatures today, and they differ in the likelihood that they would enact mitigation policies. Those and other factors could lead to vastly different air quality projections for developing countries. We'll discuss this topic as it relates to children to some degree, but the article by Rema Hanna and Paulina Oliva elsewhere in this issue analyzes climate change's effects on children in developing countries in depth.

## Biological and Behavioral Effects of Pollution

How do ozone and $PM_{2.5}$ affect child wellbeing?[1] Ozone affects the body primarily by irritating the lungs. It can cause various respiratory symptoms such as shortness of breath and coughing; it can inflame and damage the lung lining; and it can aggravate existing lung diseases such as asthma. Those effects can arise anytime from within a few hours of exposure to several days afterward, and they can be produced by quite low concentration levels.

$PM_{2.5}$ penetrates deep into the lungs and passes into the bloodstream, thereby affecting both the lungs and the heart. It can reduce lung function and increase respiratory symptoms such as airway irritation, difficulty breathing, and asthma. It can also induce heart attacks or irregular heartbeat. As with ozone, the effects can appear either quickly or several days after exposure, and they can arise at quite low concentration levels.

Children's rapid biological development suggests that childhood is a particularly sensitive time when it comes to pollution exposure. Children are believed to suffer greater effects from pollution than adults do, and younger children are more affected than older ones, which implies that the same dose of pollution has a greater effect the earlier in life it occurs.

Given the dynamic nature of health and how it interacts with human capital, exposure to these pollutants can harm wellbeing beyond immediate, direct health insults by affecting human capital accumulation and labor market outcomes later in life. For example, a child might experience asthma attacks that cut into her school attendance and academic performance, which later detracts from her performance in the workplace. Alternatively, children's human capital might be affected when their parents make investments to respond to a direct health shock—for example, by providing additional resources. The stream of events that flows from the initial insult through the life cycle represents an important component of childhood pollution exposure's total effects.

In addition to contemporaneous and life cycle effects, latent effects may appear years after pollution exposure. Evidence increasingly shows that the nine months in the womb and the first few years of life are critical periods for physiological development, when toxic exposures can have lasting impacts.[2] In particular, pollution may permanently alter the way genes function, and those epigenetic effects can damage intellectual growth and maturity later in life.[3] Latent effects may be accompanied by contemporaneous impacts as well, though they need not arise. For example, a person with latent epigenetic damage might appear to be in perfect health early in life only to experience observable health problems later on. Such latent effects constitute another important component of childhood exposure.

Sustained exposure to either ozone or $PM_{2.5}$ may also have cumulative long-run effects on child wellbeing. That relationship can be particularly important, but it is more complex and involves more uncertainty. We don't know of any quasi-experimental evidence on the subject, so we don't consider such cumulative effects in our review.

## Consequences of Climate Change

As we've said, climate change and mitigation of emissions are projected to affect air quality through two relatively distinct processes. First, weather directly influences the production of some pollutants. Though we don't know many of the net effects that changes in climate will have on pollution, the predicted effect on ozone is unambiguous. Ozone forms when nitrogen oxides and volatile organic compounds interact in the presence of heat and sunlight. Therefore, a warmer planet is likely to have more ozone. Second, policies that limit the use of fossil fuels that lead to climate change will also improve local air quality, because many of the sources that give rise to carbon emissions also give rise to air pollutants, such as sulfur dioxide and nitrogen dioxides, that help form ozone and $PM_{2.5}$. In this section, we focus on the direct effects of climate change; we discuss mitigation of emissions in the following section.

### Modeling Methods

To project future surface ozone and $PM_{2.5}$ levels requires a broad set of models and assumptions used to forecast future conditions. The models and assumptions involve carbon emissions, climate change projections, air quality models, and downscaling modeling techniques; we describe each of those below. Table 1 summarizes the methods used across the various studies we review.

*Carbon emissions.* To model how future emissions will affect climate change, researchers use different emissions assumptions under various future scenarios. For longer-term projections, most studies use one or several emissions scenarios that were developed by the Intergovernmental Panel on Climate Change (IPCC).[4] The scenarios are grouped into four families—A1, A2, B1, and B2—which are further broken down into

**Table 1.** Model Scenarios for Projecting Ozone and $PM_{2.5}$ under Climate Change

| Authors | Emissions scenario | Climate models and downscaling | Air quality models | Projection period |
|---|---|---|---|---|
| Chen et al. 2004 | IPCC A2 | PCM/MM5 | CMAQ/ MOZART-2 | 2045–54 |
| Hogrefe et al. 2004 | IPCC A2 | GISS GCM/ SMOKE/MM5 | CMAQ | 2053–57 |
| Avise et al. 2009 | IPCC A2 | PCM/MM5 | CMAQ | 2045–54 |
| Tao et al. 2007 | IPCC A1Fi and B1 | PCM/MM5 | SAQM | 2050 |
| Nolte et al. 2008 | IPCC A1B and current emissions | GISS GCM/MM5 | CMAQ | 2045–55 |
| Tagaris et al. 2007 | IPCC A1B and current emissions | GISS GCM/MM5 | CMAQ | 2049–51 |
| Trail et al. 2014 | RCP 4.5 | GISS GCM/WRF | CMAQ | 2048–52 |
| Penrod et al. 2014 | IPCC A1B | WRF | CMAQ | 2030 |

*Abbreviations:* CMAQ = Community Multiscale Air Quality Model; GISS GCM = Goddard Institute for Space Studies General Circulation Model; MM5 = fifth-generation Penn State/National Center for Atmospheric Research mesoscale model; MOZART-2 = Model for Ozone and Related Chemical Tracers; PCM = Parallel Climate Model; RCP = Representative Concentration Pathway; SAQM = San Joaquin Valley Air Quality Study/Atmospheric Utility Signatures, Predictions, and Experiments Study Regional Modeling Adaptation Project Air Quality Model; SMOKE = Sparse Matrix Operator Kernel Emissions model; WRF = Weather Research and Forecasting model.

a total of 40 unique scenarios. The scenarios differ based on the degree to which we might rely on fossil fuels, on patterns and sizes of economic and population growth, on the energy efficiency of future technology, and on patterns and rates of technological change. The favored scenarios in the studies we review below are the A1B scenario, which assumes rapid economic growth and more-balanced use of fossil fuels and renewable energy sources compared with present levels, and the A2 scenario, which assumes rapid population growth and consistent increases in $CO_2$ emissions.

*Climate change projections.* The process of modeling climate change typically starts with the results of a general circulation model of physical processes in the atmosphere, in the ocean, and on land, which comprises all of the variables that affect climate on a global scale. Many research teams develop and maintain their own general circulation models, which take into account many variables that affect global climate. Those variables include but aren't limited to temperature, precipitation, wind, sea level rise, and radiative forcing—that is, the difference between the solar energy Earth absorbs and the energy it radiates back to space. One commonly used general circulation model was developed by NASA's Goddard Institute for Space Studies. Researchers may input various greenhouse gas emissions scenarios into the model, whether they come from the IPCC or elsewhere.[5] General circulation models are structured so that the results they produce appear at coarse levels of spatial resolution: each output may correspond to an area that can be as large as hundreds of square kilometers in size. To obtain more-fine-grained results, researchers use downscaling methods, which we describe below.

*Air quality.* As we've said, air quality is a function of meteorological conditions and emissions. Using the assumptions and results from the models described above, researchers project changes in air quality that are likely to occur under future conditions. One frequently used model is the Environmental Protection Agency's (EPA's) Community Multi-Scale Air Quality model, which simulates the chemical and physical processes involved when chemicals travel through the atmosphere. Developed to help communities project future air quality conditions, it is highly flexible in both space and time.[6]

*Downscaling.* To generate results for smaller levels of spatial resolution, most if not all climate models require downscaling.[7] Through downscaling, large-scale results are further analyzed to characterize smaller spatial regions—for instance, a state or region of the United States. As with general circulation models and air quality models, researchers have many downscaling methods and techniques at their disposal.

Many methods are available for each step in the modeling process, and many possible combinations of assumptions and modeling techniques can affect the results, all of which contributes to uncertainty when we compare results across studies. However, the general framework for modeling future air quality follows the process outlined above.

Unabated climate change is projected to diminish air quality in the United States both overall and, to a great extent, by region, although projections vary by research team and depend on the assumptions and models a team uses to generate results. Even though projected changes in ozone concentrations across the United States are relatively well documented both regionally and nationally, projections of $PM_{2.5}$ in the context of climate change are comparatively sparse.

## Projections of 2050 US Ozone Levels—Regional and National

Given the way ozone forms, many studies focus on ozone levels during the summer months—when temperatures are higher—looking specifically at the daily maximum eight-hour ozone level, which is the measure through which ozone is regulated under the Clean Air Act. The most comprehensive review of 2050 ozone levels under different climate change scenarios comes from the EPA, whose projections summarize the results of six studies that analyzed how climate change would affect US air quality in areas of various sizes.[8] The EPA projects that if emissions don't decrease, most regions of the country will see higher mean daily eight-hour average ozone levels, though some regions will see little to no change and a few will see ozone levels fall. The studies used a variety of emissions reduction scenarios, which contributed to uncertainty regarding future ozone levels.

It's difficult to accurately synthesize the results of projections by different research teams.[9] The methods teams use differ in a number of ways, which contributes to uncertainty in analyzing the combined results. For instance, a review of studies that projected ozone and $PM_{2.5}$ levels found that of the eight that focused on North America, only three produced results across the United States, and only one team used the same set of assumptions and methods to project both $PM_{2.5}$ and ozone levels and the corresponding health effects. Because of such difficulties, we focus on results from Efthimios Tagaris's team, which projected both ozone and $PM_{2.5}$ under two scenarios—business as usual, defined as emissions conditions under historical 2001 conditions, and a scenario of planned climate change mitigation—thus establishing a baseline set of assumptions that underlie projections for each measure of air quality.[10]

Under the 2001 emissions scenario, climate change was expected to affect atmospheric ozone concentrations variably by region, ranging from a decrease of 1.4 parts per billion in the Midwest to an increase of up to 1.6 parts per billion in the Northeast. Averaging across the United States, however, the team saw no increase in ozone. In contrast, under the decreased-emissions scenario, ozone levels were projected to fall across all regions, by approximately eight parts per billion overall.

## Consequences of Mitigating Climate Change

### Reducing Emissions

At the federal level, proposed policies aim to fight climate change both directly and indirectly. The policies fall into three broad categories.

- Policies to reduce greenhouse gas emissions by requiring or encouraging greater energy or fuel efficiency standards in vehicles, buildings, and appliances.
- Policies to reduce emissions from power plants, which are the greatest sources of carbon emissions in the United States.[11]
- Policies to encourage the use of renewable and less-carbon-intensive energy sources, including but not limited to wind, solar, and hydropower. These policies aim to mitigate climate change indirectly by displacing emissions-heavy energy sources such as coal, oil, and natural gas.

The EPA's Clean Power Plan is one example of a supply-side policy targeting the power sector. Finalized on August 3, 2015, the Clean Power Plan will mitigate climate change by cutting power plants' carbon emissions to 70 percent of 2005 levels by 2030, using a state-based framework that sets a $CO_2$ mitigation target for each state. Along with substantially decreasing carbon dioxide emissions, the policy will also decrease emissions of particulate matter, nitrogen oxides, and sulfur dioxide. Thus mitigation policies that seek to reduce emissions are especially important for air quality. Reducing carbon emissions is nearly always associated with reductions in other emissions that directly harm human health or that react in chemical pathways that produce harmful agents.

### Projections of 2050 $PM_{2.5}$ Levels—Regional and National

To date, one study has comprehensively analyzed how climate change and climate change mitigation will affect future $PM_{2.5}$ levels in the United States compared with a no-mitigation scenario. Three more studies have compared projected with historical $PM_{2.5}$ levels.

Jeremy Avise and colleagues projected how climate change mitigation policies will affect $PM_{2.5}$ levels in the United States.[12] They characterized $PM_{2.5}$ forecasts in 2050 under six different scenarios. The scenarios that examined only climate change, maintaining current emissions levels, projected that $PM_{2.5}$ would decrease overall in the United States by 0.9 micrograms per cubic meter, with decreases or no change in each region except the Northeast, which was projected to experience an increase in $PM_{2.5}$ of 0.2 micrograms per cubic meter. When they took into account future changes in emissions, land use, and climate change together, however, the researchers projected that $PM_{2.5}$ would increase across all regions by 2 micrograms per cubic meter overall in the United States (a 25 percent increase) and by up to 4 micrograms per cubic meter in the Northeast (a 44 percent increase).

Tagaris and colleagues, in the study we described earlier, projected changes in $PM_{2.5}$ levels in conjunction with ozone levels under two different climate change scenarios. If emissions are reduced compared with 2001 levels, they projected, summer $PM_{2.5}$ would decrease by 2.9 micrograms per cubic meter on average across the United States, with the highest decrease in the Southeast at 6.2 micrograms per cubic meter.

Another team of researchers compared current ozone levels with future summertime ozone concentrations for the United States using a climate change scenario that corresponds to global emissions of greenhouse gases and land use changes that produce a $CO_2$-equivalent atmospheric greenhouse gas concentration of 650 parts per million by 2100, compared with 481 parts per million in 2014.[13] ($CO_2$-equivalent atmospheric greenhouse gas concentration is a measure of the aggregate concentration of all atmospheric greenhouse gases, expressed in terms of the amount of $CO_2$ alone that would be required to produce the same amount of radiative forcing.) In addition to their climate change assumption, the group assumed future air quality conditions that would result if the IPCC's A1B scenario were combined with passing and implementing a number of policies to improve air quality. The group projected pollution levels in 2050 compared with levels for 2006–10 and found that once emissions and climate change were taken into account, air quality would improve over much of the country, including decreases in ozone and $PM_{2.5}$. When they examined the impact of climate change alone, however, they found that pollution policies' effects on ozone and $PM_{2.5}$ levels were muted, suggesting that climate change would make air quality improvement measures less effective. Although this study is helpful for comparative purposes, it doesn't provide regionally specific results in units we can use for our projections.

A fourth team projected changes in ozone and $PM_{2.5}$ in 2026–30 under the IPCC A1B scenario for the contiguous United States only. The researchers didn't compare a future business-as-usual simulation with that projection; instead, they compared their results with current ozone levels.[14] They found that summer ozone levels would fall across almost the entire country, with the exception of large urban areas. A drop in ozone precursor emissions, such as nitrogen dioxides, would be the leading cause of the drop in summer ozone concentrations. The study predicted that summer $PM_{2.5}$ would fall the most in the central and eastern United States; several areas in the Southwest and the Great Lakes region would actually see increased levels of $PM_{2.5}$.

## Geoengineering

Some strategies to mitigate climate change—in particular, geoengineering techniques such as carbon capture and storage—won't improve local air quality. Geoengineering in general encompasses strategies to reduce climate change by managing solar radiation. Carbon capture and storage involves capturing $CO_2$ at the point of emission and storing it to prevent it from entering the atmosphere. Because geoengineering approaches don't reduce the amount of pollutants other than carbon released into the atmosphere, they don't affect local air quality.

One example of a geoengineering strategy in action is the Boundary Dam Integrated Carbon Capture and Storage Demonstration Project at a coal-fired power plant in Saskatchewan. A recent assessment of the project found that its carbon capture operation would reduce greenhouse gas emissions by 63 percent.[15] But whether local air quality also improves depends greatly on the type of mitigation and not simply on whether mitigation takes place.

## Empirical Problems

When we try to identify the causal effects of pollution exposure, the primary problem we run into is called *residential sorting*.[16] Sorting occurs when people vote with their feet by choosing where to live based on such characteristics as school quality, crime rates, and—most relevant here—pollution levels. For such sorting to occur, people need not be directly aware of pollution concentrations; they need only choose where to live based on factors correlated with pollution levels, such as proximity to major roads and industrial production. Major roads and factories are drawbacks by themselves, but they are also major sources of pollution.

*High-income families tend to move away from highly polluted areas.*

Evidence increasingly suggests that sorting based on environmental quality indeed plays an important role in determining where people live. Researchers have found that high-income families tend to move away from highly polluted areas and that when an area's environmental quality improves, the proportion of pregnant women in that area who are white and college educated increases.[17] Furthermore, areas with higher pollution levels also have lower housing prices.[18]

As a result of this kind of sorting, areas with more pollution may also have other, unobserved characteristics correlated with health, suggesting that omitted variable bias is likely to skew estimates. For example, a more polluted area may also be a more impoverished area, and children there may have less access to medical care. Failing to account for that lack of access can lead to spurious estimates of the relationship between pollution and health. In this example, not accounting for access to care would lead to overestimating the true relationship, but other factors might lead to underestimates. For example, urban and suburban areas typically have greater access to care but also more pollution than do rural areas. Given the way sorting can skew estimates, we focus here on quasi-experimental studies that directly attempt to confront sorting.

A secondary empirical problem stems from avoidance behavior. If people act to protect their children's health when pollution is high, those actions will lead to nonrandom pollution exposure. Such actions require knowledge of pollution levels. Many large cities disseminate pollution information to the public, often accompanied by recommended strategies to avoid pollution, such as staying indoors or shifting activities to times of day when pollution is expected to be lower. Because such avoidance behavior occurs in response to pollution levels, omitting it from analyses doesn't bias estimates per se. Rather, omitting avoidance behavior affects how the estimated relationships are interpreted. Estimates that control for avoidance behavior uncover the direct biological effect of pollution on health. Estimates that don't control for avoidance behavior measure pollution's net effect on health, which consists of the biological effect plus the degree to which avoidance behavior is successful in reducing health effects. Avoidance behavior is an important component of pollution's total welfare cost because avoiding pollution is costly.[19]

## Quasi-Experimental Evidence

So that we can project calculations based on climate–pollution forecasts in the next section, we limit ourselves to studies that directly examine ozone and $PM_{2.5}$, though we note that other studies examine emissions that may lead to those pollutants.[20] Most notably, we omit studies that focus on carbon monoxide, another pollutant linked with many measures of wellbeing. Though carbon monoxide is highly correlated with $PM_{2.5}$, it comes predominantly from automobiles rather than from power plants; power plants are the major sources of $CO_2$ emissions that mitigation policies target.

Because $PM_{2.5}$ has been monitored for a much shorter time than ozone has, we also include studies that look at larger particles—specifically, $PM_{10}$ (particles up to 10 microns in size) and total suspended particles (equivalent to $PM_{100}$)—which have been monitored longer. Many of these studies capture the effects of all particles, of which $PM_{2.5}$ particles are a subset. In fact, the only available evidence on long-run effects comes from studies using total suspended particles. For future projections, we provide a crude approximation by scaling our estimates according to the estimated fraction of particles included in either $PM_{10}$ or total suspended particles that are small enough to be considered $PM_{2.5}$.[21]

### Short-Run Effects—Infant Health

The health of newborns is a crucial place to start. Two landmark studies that focused on the effects of air pollution pioneered research designs used by many researchers ever since. The first examined the recession of the early 1980s in the United States.[22] Manufacturing is a key source of emissions, so an economic slowdown can produce far-reaching changes in pollution. Furthermore, manufacturing is not spread evenly throughout the United States, so the shocks to manufacturing from the 1980s recession induced considerable spatial variation in pollution—specifically, in total suspended particles. Because those changes in total suspended particles were caused by a global economic phenomenon, they were unlikely to be related to other factors affecting health. The study found that a decline of 1 microgram per cubic meter in total suspended particles reduced infant deaths by four to seven per 100,000 births.

The second landmark study used the 1970 Clean Air Act Amendments as a source of quasi-experimental variation in pollution. Counties that were out of compliance with pollution thresholds established by the Clean Air Act Amendments were required to lower pollution, whereas counties with pollution levels just below the thresholds were unaffected. By comparing affected and unaffected counties, the researchers estimated that a decline of 1 microgram per cubic meter in total suspended particles led to five to eight fewer infant deaths per 100,000 live births.

Using the same design based on the Clean Air Act Amendments, other researchers examined the effects of pollution on sex ratios at birth.[23] Because male fetuses are thought to be more fragile than female fetuses, a decrease in the ratio of male live births to female live births suggests an increase in fetal deaths. Consistent with that hypothesis, researchers found that a reduction in pollution increases the fraction of male fetuses.

Another way to confront sorting is to use *fixed effects* models, which compare changes in pollution in a set of geographic areas over time with changes in health outcomes in the same areas. That approach thereby controls for all of an area's characteristics that don't vary over time, such as access to health care and underlying health status (if they are in fact constant over time). For example, one study used the primary unit of local government as a fixed effect to examine the relationship between pollution levels in Great Britain from 1998 to 2005 and the deaths of children under 15 years old.[24] It estimated that reducing $PM_{10}$ by 10 micrograms per cubic meter was associated with four fewer deaths per 100,000 children.

Another study used California traffic congestion data as a source of variation in pollution levels, with fixed effects by ZIP code.[25] Traffic congestion temporarily raises pollution levels in a way that isn't correlated with other factors affecting child health. The authors found that reducing $PM_{10}$ levels by 1 microgram per cubic meter led to 18 fewer infant deaths per 100,000 live births. It's important to note that unlike the pioneering studies of the 1980s recession and the 1970 Clean Air Act Amendments, this study focused on the 1990s—a more recent time period.

Only a few studies of pollution and child health have examined less-developed countries. One team of researchers looked at pollution and infant mortality in Mexico.[26] The team used thermal inversions—which trap pollution near the ground—as a source of variation in daily pollution; their model included fixed effects by municipality. The researchers found that an increase in $PM_{10}$ of 1 microgram per cubic meter produced a statistically significant 0.24 more weekly infant deaths per 100,000 births, which is quite comparable to estimates for the United States.

## Short-Run Effects—Childhood Health and Human Capital

Beyond its effects on infants, exposure to pollution throughout childhood can also significantly affect health and human capital—for example, by causing respiratory diseases or reducing performance in school. To explore the relationship between ozone and respiratory-related hospitalizations, one researcher confronted sorting by studying military personnel.[27] The relocation of military personnel is based entirely on the needs of the armed forces and not on personal preferences; thus variations in pollution exposure among military families are similar to random assignment. Furthermore, all military families are covered by identical health insurance plans, so access to care isn't a factor. The study found that a 15 percent decrease in annual ground-level ozone exposure decreased the probability of respiratory hospitalizations among children aged 2 to 5 years by 8 to 23 percent.

As we've said, people may take actions to reduce their exposure to harmful pollutants by, say, making changes in daily activities or even moving to a new home in a different area. If people act to lessen their exposure, then estimations that don't take those actions into account may understate pollution's effects. One of the authors of this article, Matthew Neidell, used fixed effects by ZIP code to exploit naturally occurring daily variation in ozone pollution.[28] He accounted for avoidance behavior by controlling for smog alerts—an important source of information about pollution and health. Without taking smog alerts into account, he found that when five-day ozone levels increased by 12.8 percent, child hospital admissions rose by 1.09 percent; when he controlled for smog alerts, the estimate rose to 2.88 percent.

Two researchers studied monthly variations in ozone exposure by following a large cohort of English children over time.[29] Like the children in military families, the English children all had the same access to health care—in this case, via the United Kingdom's universal National Health Service. To avoid skewing the estimates, the researchers used a child fixed effects model, controlling for all of the children's characteristics that didn't vary over time. They found that increases in ozone were associated with statistically significant increases in respiratory treatments among children aged 2 to 6 years. Specifically, a 10 percent increase in a month's ozone levels increased by 2.5 to 3.3 percent the probability that a child would undergo respiratory treatment in that month.

We've seen that exposure to pollution may affect not only children's health but also their performance in school—whether directly through harm to the brain or indirectly through such channels as asthma attacks that cause them to miss school. A study using annual classroom-level performance data from California showed that higher pollution levels affected scores on annual achievement tests.[30] Because unobserved differences in student populations could be correlated with both pollution and lower test scores, the researchers included in their analysis school fixed effects as well as observable student and family characteristics. They found that when ambient levels of $PM_{2.5}$ fell by 10 percent, students' scores rose by 0.34 percent on standardized math tests and by 0.21 percent on standardized reading tests.

Another study examined whether daily exposure to pollution could affect student performance on high-stakes high school tests.[31] The researchers followed Israeli students over time as they took multiple tests, which allowed the researchers to control for all of the students' time-invariant characteristics. An increase in $PM_{2.5}$ of 1 microgram per cubic meter was associated with a 0.65-point decrease in the students' test scores. Looking further ahead, the researchers also found that the decrease in test scores caused by higher levels of $PM_{2.5}$ affected important college outcomes.

## Long-Run Effects

Because we don't have a lot of data that would let us link childhood pollution exposure to later outcomes, only a handful of studies have looked at long-run effects from any pollutant.[32] Two focus on particulate matter, but only for total suspended particles; again, we scale the estimates based on total suspended particles to approximate the projected effects of $PM_{2.5}$. Despite the limited evidence, a consensus is growing that early pollution exposure has significant long-run consequences.

One recent study built on earlier work by using quasi-experimental variation in pollution during the 1980s recession and examining how children who were in the womb when the recession occurred performed on high school tests many years later.[33] Unfortunately, the researcher wasn't able to identify where the women were living when their children were born, so he was forced to assume that the children were born in the same place they attended high school. Despite that potential source of measurement error, which would likely bias his estimates toward no effect, he found that a 21.9 percent decrease in total suspended particles around the time of birth increased high school test scores by 10.3 percent.

Similarly, another team of researchers interested in long-run outcomes recently returned to the 1970 Clean Air Act Amendments as a source of variation in pollution.[34] Unlike the study of children who were in the womb during the 1980s recession, these researchers were able to obtain children's counties and dates of birth. Comparing children born in counties just below the threshold for action under the amendments with those born in counties just above, they found that each 10-unit decrease in total suspended particles during pregnancy and early childhood resulted in a 1 percent increase in annual earnings once the children became adults.

## Calculations

In this section, we project future pollution impacts from climate change on several indicators of child wellbeing. To do so, we combine pollution projections under various climate scenarios with selected estimates of pollution's effects on wellbeing to calculate potential impacts throughout the United States, assuming that current air quality policy remains unchanged. We recognize that this exercise is fraught with tenuous assumptions; in the absence of an approach that avoids such limitations, we proceed with caution.

Among the several studies we described earlier that project future $PM_{2.5}$ and ozone, we base our projections on Tagaris and colleagues, for three reasons. First, they use the same set of models to predict both pollutants. Second, they predict what would happen under both a business-as-usual scenario and a mitigation scenario, thereby letting us compare a particular mitigation strategy with no mitigation. Third, they make regional projections, so we can assess the distribution of impacts across the country. Table 2 shows ozone and $PM_{2.5}$ projections under each scenario by region. For all of our calculations, we make three comparisons: mitigation in 2050 versus baseline values in 2001, no mitigation in 2050 versus baseline values in 2001, and mitigation in 2050 versus no mitigation in 2050. The last scenario is the most useful one for thinking about the effects of climate change policy versus the effects of inaction, because inaction is a scenario with no mitigation.

Based on the $PM_{2.5}$ and ozone projections, we calculate three separate outcomes: $PM_{2.5}$ and infant mortality, $PM_{2.5}$ and adult earnings, and ozone and childhood hospitalizations.

### Infant Mortality

For infant mortality, we obtain data on the number of births in each region based on vital statistics as of 2012, and we assume that the number of births will remain constant in the future. We then multiply the number of births by (1) the estimated relationship between $PM_{2.5}$ and infant mortality and (2) the difference in $PM_{2.5}$ across the various scenarios. This gives us the change in infant

**Table 2.** Ozone and $PM_{2.5}$ Projections by Region under Alternative Mitigation Scenarios

| | West | | Plains | | Midwest | |
|---|---|---|---|---|---|---|
| | Ozone (ppb) | $PM_{2.5}$ (µg/m³) | Ozone (ppb) | $PM_{2.5}$ (µg/m³) | Ozone (ppb) | $PM_{2.5}$ (µg/m³) |
| 2001 | 49.75 | 4.05 | 48.25 | 6.925 | 45.25 | 11.725 |
| 2050 | 46.25 | 3.65 | 44.25 | 5.425 | 40.5 | 9.025 |
| 2050 BAU | 49.75 | 4.15 | 49 | 6.875 | 45.25 | 12.2 |

| | West | | Plains | | Midwest | |
|---|---|---|---|---|---|---|
| | Ozone (ppb) | $PM_{2.5}$ (µg/m³) | Ozone (ppb) | $PM_{2.5}$ (µg/m³) | Ozone (ppb) | $PM_{2.5}$ (µg/m³) |
| 2001 | 46.25 | 9 | 54 | 12.3 | 48.75 | 8 |
| 2050 | 41.75 | 6.425 | 46.25 | 8.425 | 44.25 | 6.125 |
| 2050 BAU | 46 | 9.625 | 55.5 | 11.975 | 49.25 | 8.1 |

*Note:* Projections include a baseline mitigation scenario as well as a business-as-usual scenario (no mitigation). Ozone is the annual average of daily eight-hour maximum ozone. $PM_{2.5}$ is the annual average of the daily $PM_{2.5}$.

*Abbreviations:* BAU = business as usual; ppb = parts per billion; µg/m³ = micrograms per cubic meter

*Source:* Efthimios Tagaris et al., "Impacts of Global Climate Change and Emissions on Regional Ozone and Fine Particulate Matter Concentrations over the United States," *Journal of Geophysical Research: Atmospheres* 112 (2007): D14312.

mortality in each region under each scenario. We then calculate the percentage change in infant mortality by dividing the change in deaths from pollution by the estimated number of infant deaths from all causes, which is calculated by assuming that the current rate of 6.1 deaths per 1,000 births will remain the same in the future.

After consulting a variety of studies, our best estimate of the relationship between $PM_{2.5}$ and infant mortality is 34 deaths per 100,000 births.[35]

As panel A of table 3 shows, under a 2050 scenario of no mitigation, we see some variation in impacts across the country from the projected change in $PM_{2.5}$, including small decreases in the number of infant deaths in the Plains and the Southwest and small increases in the West, the Midwest, and the Northeast. The changes are quite small, however, amounting to a total of 133 extra deaths. The percentage changes are likewise generally small, at less than 4 percent by region. The small size of those impacts is not surprising because, unlike ozone, $PM_{2.5}$ isn't expected to be directly affected by climate change, but only by mitigation policies. Figure 1 shows the percentage changes graphically.

Under the mitigation scenario, panel A of table 3 shows infant mortality falling across all regions, with the largest drops in the Midwest, Northeast, and Southeast. Overall, the estimates show a decrease of 2,501 infant deaths, which represents a decrease in overall US infant mortality of 10.5 percent and a decrease as high as 21.6 percent in

## **Table 3.** Projected Pollution Impacts on Child Wellbeing

**Panel A**. Impacts on infant mortality from contemporaneous exposure to $PM_{2.5}$

| | Births | Infant deaths | No mitigation vs. 2001 | Mitigation vs. 2001 | Mitigation vs. no mitigation | No mitigation vs. 2001 | Mitigation vs. 2001 | Mitigation vs. no mitigation |
|---|---|---|---|---|---|---|---|---|
| West | 832,065 | 5,076 | 28 | –113 | –141 | 0.56% | –2.23% | –2.79% |
| Plains | 635,916 | 3,879 | –11 | –324 | –314 | –0.28% | –8.36% | –8.08% |
| Midwest | 820,761 | 5,007 | 133 | –753 | –886 | 2.65% | –15.05% | –17.70% |
| Northeast | 835,041 | 5,094 | 177 | –731 | –909 | 3.48% | –14.35% | –17.84 |
| Southeast | 798,891 | 4,873 | –88 | –1,053 | –964 | –1.81% | –21.60% | –19.79% |
| All | 3,922,674 | 23,928 | 133 | –2,501 | –2,634 | 0.56% | –10.45% | –11.01% |

*Note:* This panel presents estimates for the number and percentage of infant deaths avoided by region under various climate scenarios. Births are from 2012.

**Panel B.** Impacts on adult earnings from early childhood exposure to $PM_{2.5}$

| | Per capita income | No mitigation vs. 2001 | Mitigation vs. 2001 | Mitigation vs. no mitigation | No mitigation vs. 2001 | Mitigation vs.2001 | Mitigation vs. no mitigation |
|---|---|---|---|---|---|---|---|
| West | $44,589 | –$30 | $121 | $151 | –0.1% | 0.3% | 0.3% |
| Plains | $43,680 | $15 | $443 | $429 | 0.0% | 1.0% | 1.0% |
| Midwest | $41,548 | –$134 | $759 | $893 | –0.3% | 1.8% | 2.1% |
| Northeast | $52,417 | –$222 | $913 | $1,135 | –0.4% | 1.7% | 2.2% |
| Southeast | $38,550 | $85 | $1,011 | $926 | 0.2% | 2.6% | 2.4% |
| All | $44,455 | –$30 | $564 | $594 | –0.1% | 1.3% | 1.3% |

*Note:* This panel presents estimates for the dollar and percentage change in adult earnings by region under various climate scenarios. Per-capita income is from 2012.

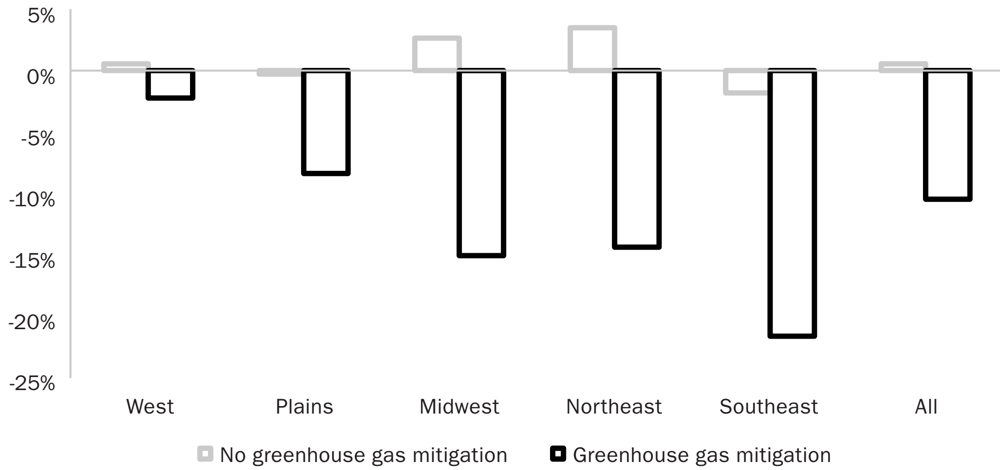
**Panel C.** Impacts on respiratory hospitalizations from contemporaneous ozone exposure

| | No mitigation vs. 2001 | | Mitigation vs. 2001 | | Mitigation vs. no mitigation | |
|---|---|---|---|---|---|---|
| | BS | LM | BS | LM | BS | LM |
| West | 0.0% | 0.0% | -3.6% | –6.9% | –3.6% | –6.95% |
| Plains | 0.8% | 1.5% | –4.1% | –7.9% | –4.9% | –9.4% |
| Midwest | 0.0% | 0.0% | –4.9% | –9.4% | –4.9% | –9.4% |
| Northeast | –0.3% | –0.5% | –4.6% | –8.9% | –4.4% | –8.4% |
| Southeast | 1.5% | 3.0% | –8.0% | –15.3% | –9.5% | –18.2% |
| All | 0.5% | 1.0% | –4.6% | –8.9% | –5.1% | –9.9% |

*Note:* This panel presents estimates for the percentage change in respiratory admissions by region under various climate scenarios.

*Sources:* BS = Timothy K. M. Beatty and Jay P. Shimshack, "Air Pollution and Children's Respiratory Health: A Cohort Analysis," *Journal of Environmental Economics and Management* 7 (2014): 39–57; LM = Adriana Lleras-Muney, "The Needs of the Army: Using Compulsory Relocation in the Military to Estimate the Effect of Air Pollutants on Children's Health," *Journal of Human Resources* 45 (2010): 549–90.

**Figure 1.** Percentage change in 2050 US infant mortality from $PM_{2.5}$ under two scenarios, by region




*Note:* This figure displays the percentage change in infant mortality rates, by region, from the projected change in $PM_{2.5}$ under scenarios of greenhouse gas mitigation and no greenhouse gas mitigation.

the Southeast. Given the small difference in $PM_{2.5}$ levels between no mitigation in 2050 and baseline values in 2001, we also find large infant mortality estimates for the mitigation versus no mitigation scenarios.

## Adult Earnings

In panel B, we turn to projections of how early childhood exposure to $PM_{2.5}$ affects adult earnings. We use a procedure similar to the one we used for infant mortality: we obtain per capita income by region from the Bureau of Economic Analysis Regional Economic Accounts and multiply it by the estimated relationship between $PM_{2.5}$ and adult earnings and by the projected changes in $PM_{2.5}$. Following the study we discussed earlier about how pollution exposure after the 1970 Clean Air Act Amendments affected adult earnings, we estimate a 1.1 percent change in earnings from a 10-unit change in total suspended particles, and we scale this to obtain a 0.68 percent change from a 1-unit change in $PM_{2.5}$.[36] Under the no mitigation scenario, we again find small projected impacts compared with the baseline year, with an estimated overall decrease in earnings of $30 per year per person. Once again, the estimates are considerably larger under a mitigation scenario compared both with the baseline and with no mitigation: $564 and $594, respectively, in additional earnings per person per year. The effects continue to be largest in the Midwest, Northeast, and Southeast, with estimates of more than $1,000 in additional earnings per person in the Southeast. The estimate for the entire United States suggests a 1.3 percent increase in earnings and up to 2.6 percent in the Southeast.

## Hospitalizations

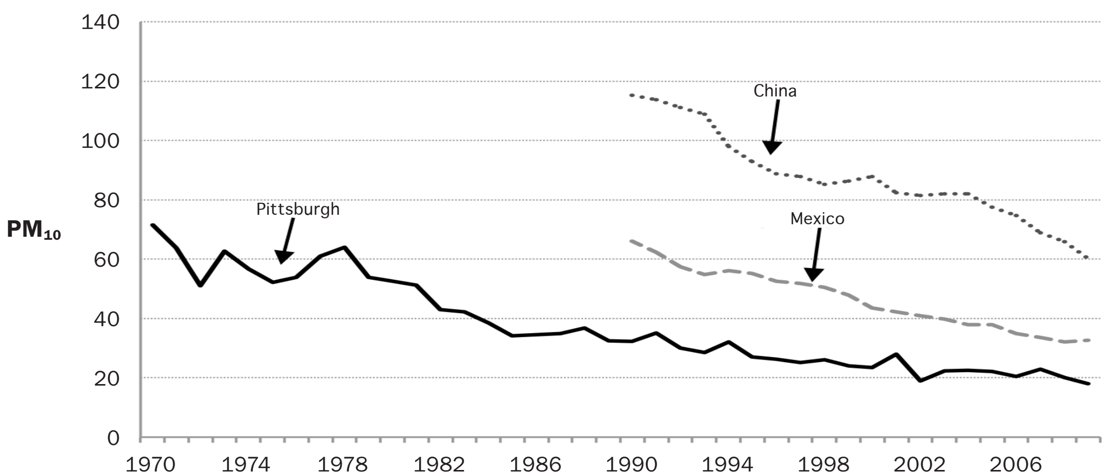
Here we look at how changes in ozone are projected to affect childhood hospitalizations for respiratory-related symptoms. Because we don't have a background rate of children's respiratory hospitalizations by region, we present only the percentage change in this outcome. To do so, we multiply the change in ozone by the percentage change from the best available estimates, giving estimates that range from a 1.03 to a 1.97 percent change in hospitalizations from a change in ozone concentration of 1 part per billion.[37]

The results, as panel C shows, indicate small to modest changes in respiratory hospitalizations without mitigation, ranging from a decrease of 0.5 percent in the Northeast to an increase of 3 percent in the Southeast. Overall, we see a net increase of 0.5 to 1.0 percent depending on the estimate used. Those modest effects suggest that the ozone increases expected under climate change are not likely to significantly increase respiratory hospitalizations among young children. Under a mitigation scenario, however, we again see large decreases in respiratory admissions, ranging from 3.6 percent in the West to 8 percent in the Southeast (with an overall estimate of 4.6 percent) under one set of assumptions; the decreases would be nearly twice as large under a second set of assumptions. Comparing the mitigation scenario with no mitigation leads to even larger projected impacts.

## Developing Countries

Our discussion thus far has focused almost exclusively on the most-developed countries. Hanna and Oliva discuss developing countries in detail; here we point out two key factors relevant to pollution. First, countries going through rapid development often witness considerably higher levels of pollution. A big question is whether those higher levels of pollution lead to greater health insults. Figure 2 shows air pollution levels over time for China, Mexico, and one city in the United States, Pittsburgh, focusing on $PM_{10}$. Although the pollution levels in China and Mexico are always higher than levels in the United States at the same point in time, the levels experienced in those countries today are not unlike historical levels in the United States. Contemporary pollution levels in

**Figure 2.** Trends in Air Pollution for Pittsburgh, China, and Mexico




*Note:* All data are annual averages of daily measures of particulate matter less than 10 microns in diameter ($PM_{10}$), measured in micrograms per cubic meter.

*Sources:* Data for Mexico and China are averages across all major cities, obtained from the World Bank's database of World Development Indicators. Pittsburgh data from 1990 to 2009 are from the US Environmental Protection Agency's Air Quality System Data Mart. Data from before 1990 are courtesy of Cliff Davidson via Thomas Rawski; these data are total suspended particles multiplied by 0.55, which is the ratio of $PM_{10}$ to TSP, where missing values for total suspended particles are imputed by using dustfall.

China and Mexico are similar to those found in Pittsburgh in the mid-1970s and mid-1990s, respectively. As such, studies based on historical pollution levels in the United States are likely to tell us something about current health and human capital impacts in developing countries.

Second, equatorial regions are expected to see larger heat effects from climate change, and they're also home to a much greater share of poorer nations, suggesting that increases in ozone from global warming are likely to be worse in poorer, equatorial nations. Mitigation is also likely to be more costly for those countries both because expenditures for mitigation would mean forgoing growth and because those countries have less capacity to regulate emissions, so they are less likely to experience mitigation's cobenefits. In fact, the Kyoto Protocol, the only ratified international treaty on climate change, exempted developing nations.

Those two factors suggest that even if the estimated pollution–health relationship is similar across nations, developing nations are likely to be hit by higher doses of pollution and thus suffer greater harm to child wellbeing.

## Conclusions

Climate change, if it continues unabated, is expected to increase pollution concentrations in the future. Mitigation policies that reduce carbon emissions would not only offset that expected pollution increase but also further reduce pollution below current levels. Given children's sensitivity to pollution on a range of measures of wellbeing, this suggests that climate change and any policies to mitigate it may have significant effects on child wellbeing through changes in air quality. We have described some of the background behind expected changes in air quality, reviewed quasi-experimental evidence that links the expected changes in $PM_{2.5}$ and ozone with several measures of child wellbeing, and performed some rough calculations to project how those changes in air quality might affect children.

Our calculations suggest that mitigating emissions that lead to climate change would likely produce significant improvements in child wellbeing. Infant mortality and respiratory diseases would decrease, and human capital and productivity would increase. Such improvements arise whether we compare mitigating emissions with the current situation or with a future scenario where no mitigation takes place. On the other hand, a scenario of no mitigation is unlikely to yield much change in wellbeing compared with the current situation. Though adaptation to temperature may moderate heat's direct effect on child wellbeing, adaptation is less likely to play a role when it comes to pollution. We have fewer technologies and biological responses that reduce the threat from pollution exposure.

Of course, our projections encompass many unknowns, and we must be cautious in taking them at face value. Projections of future climate are filled with uncertainty, as are projections of climate's relationship to emissions. How mitigation policies would affect pollution levels involves uncertainties as well. Moreover, technology may alter the ways we treat children throughout the life course. Given the need to act in the face of such uncertainty, we hope our estimates serve as a useful starting point.

## ENDNOTES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