THE HUMAN HEALTH IMPACTS OF FUTURE CHANGES IN AIR QUALITY AND TEMPERATURE IN THE UNITED STATES

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ABSTRACT

Douglas Allen Becker: The human health impacts of future changes in air quality and temperature in the United States
(Under the direction of J. Jason West)

Human emissions influence ozone concentrations, $PM_{2.5}$ concentrations, and temperature levels, which are known to increase morbidity and mortality. Here we use the BenMap program to estimate the health impacts of modeled changes in air quality and temperature in the continental United States in 2025 relative to 2005. In a simulation containing changes in both anthropogenic emissions and meteorology, we estimate that ozone-related respiratory mortality decreases by 2,400 (90% CI 1,100-3,700) annually and all-cause mortality associated with $PM_{2.5}$ decreases by 26,000 (90% CI 19,000-32,000). In this same simulation, heat-related cardiovascular mortality increases by 31,000 (90% CI 18,000-44,000). Additionally, we find substantial decreases across all morbidity endpoints and significant geographical variation throughout all endpoints. Finally, the economic costs of these health impacts are estimated at $48 billion per year. Our results suggest that emissions control schemes may provide substantial human health benefits, and mitigation and adaptation measures against heat-related impacts are needed.

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LIST OF ABBREVIATIONS

BenMap	Environmental Benefits Mapping and Analysis Program
CDC	Center for Disease Control and Prevention
CMAQ	Community Multi-scale Air Quality Model
EPA	Environmental Protection Agency
IPCC	Intergovernmental Panel on Climate Change
NEI	National Emissions Inventory
$PM_{2.5}$	Fine particulate matter (with a diameter less than 2.5 micrometers)

CHAPTER 1: INTRODUCTION

Human activities including electricity generation, motorized transportation, construction, and manufacturing all rely on the combustion of fossil fuels. This combustion emits air pollutant precursors (Brauer et al. 2012). These air pollutant precursors undergo atmospheric reactions, leading to the creation of secondary air pollutants. The air pollutants of interest in this study are ozone and fine particulate matter, both of which influence air quality and contribute to climate change.

The fossil fuel combustion involved in many human activities also leads to the emission of greenhouse gases. Greenhouse gases (such as carbon dioxide, methane, and nitrous oxide) absorb radiation, increasing the temperature of the atmosphere and contributing to climate change.

Additionally, climate variability impacts air quality and temperature. Unlike climate change, climate variability represents change over short periods of time and does not indicate long-term climate trends. Significant year-to-year climate variations may exist while long-term averages may remain static. When considering data from short time periods, like the year-long samples used in this study, results may not be driven by climate change alone; climate variability is a potentially confounding cause.

Alterations in emissions levels, a changing climate system, and temporal climate variability all contribute to changes in temperature and air quality. Changes in temperature and air pollutant concentrations in turn drive changes in human morbidity and mortality.

Air Pollution

Ozone and $PM_{2.5}$ have well-documented human health effects and are influenced significantly by anthropogenic emissions and climate change (Tagaris et al., 2009). Ozone, a powerful oxidant comprised of three oxygen atoms, is formed by a complex photochemical oxidation in the troposphere of carbon monoxide, methane, and volatile organic compounds (VOCs) via the hydroxyl radical (OH). This reaction requires the presence of reactive nitrogen oxide species (NO_x) and solar energy (Jacob and Winner, 2009). Anthropogenic emissions contribute significantly to ozone formation.

Particulate matter is comprised of many compounds including sulfate, nitrate, and organic carbon, which are produced by the atmospheric oxidation of SO_2, NO_x, and VOCs, respectively. Sulfur dioxide, NO_x, VOCs, and constituents of particulate matter are emitted by human activity. Forest fires, dust storms, and other natural events eject dust, salt, and other components into the atmosphere (Forster et al., 2001).

Climate Change

The Intergovernmental Panel on Climate Change (IPCC) estimates that the global average temperature has increased by 0.85 [0.65 to 1.06] degrees Celsius between the years 1880 and 2012 and projects that global average temperatures will increase at an accelerating rate, enhancing temperatures by another 0.47 to 1.00 °C by 2035 (IPCC, 2013). In the United States alone in 2011, greenhouse gas emissions totaled 6,702 million metric tons of CO_2 equivalent (EPA, 2012).

Air Pollution, Emissions, and Climate Change

As secondary pollutants produced by complex atmospheric reactions, ozone and particulate matter concentrations depend heavily on atmospheric conditions. Climate change affects air pollutant concentrations by altering meteorology, chemical reaction rates, temperature, precipitation, biogenic and natural emissions, deposition, and atmospheric circulation and ventilation (Weaver et al., 2009). Conversely, ozone and particulate matter are climate forcing agents (IPCC, 2007).

Climate change influences ozone concentrations by inducing higher temperatures, altering humidity and water vapor concentrations, and changing meteorological conditions (Weaver et al., 2009). Particulate matter is also sensitive to atmospheric water content; in areas with increasing precipitation rates, particulate matter will be scavenged out of the atmosphere more readily (Fiore et al., 2012). Climate change may alter natural aerosol emissions as well, in many cases augmenting the release of aerosols and particulate matter precursors (Lam et al., 2011). The correlation between $PM_{2.5}$ and meteorology is not as strong as for ozone, and no significant correlation has been found between $PM_{2.5}$ and temperature (Wise and Comrie, 2005).

Many studies have modeled future air quality and the influence of changes in emissions and climate on air quality. Global ozone concentrations are expected to decrease over the course of the century as a result of decreasing emissions levels, perhaps by as much as 8 ppb (IPCC, 2013). Global particulate matter concentrations are expected to decrease by an average of 1 $\mu g/m^3$ as a result of declining emissions during the same time period (IPCC, 2013). However, areas with currently high pollutant levels will experience higher pollutant concentrations as a result of regional feedback mechanisms involving higher temperatures and altered atmospheric chemistry (IPCC, 2007). In addition to climate change, inter-annual climate variability affects air pollutant concentrations (Bernard, 2001).

Air Pollution and Human Health

Ozone exposure causes or contributes to asthma exacerbation, respiratory disease, cardiovascular disease, hospital admissions, emergency room visits, acute and chronic respiratory symptoms, school absences, and premature mortality (Jerrett et al., 2009, Pope et al., 2011).

Particulate matter exposure causes or contributes to respiratory symptoms and disease, asthma exacerbation, chronic and acute bronchitis, cardiovascular disease, hospital admissions, and premature mortality (Lepuele et al., 2012, Krewski et al., 2009).

Temperature and Human Health

Average surface temperatures are expected to increase due to global warming. Summers are projected to be longer and warmer than in previous years. The frequency and intensity of extreme heat events (heat waves) are also projected to increase under a changing climate system (Zanobetti and Schwarz, 2008). Elevated temperatures and heat waves occur frequently in cities due to the urban heat island effect, as impervious surfaces and heat-absorbing materials prevent the escape of heat back into the atmosphere, and this effect is amplified by global warming (Jackson et al., 2010).

Rising temperatures endanger human health. A high correlation between heat and excess all-cause mortality has been observed (Harlan and Ruddell, 2011). There are 400-700 estimated deaths associated with high temperature annually in the United States (Luber et al., 2008). Other health effects of heat exposure include heat stroke, heat exhaustion, acute renal failure, cardiovascular disease, electrolyte imbalance, nephritic syndrome, and diabetes exacerbation. Extreme heat events can cause thousands of deaths in a short period of time, such as the 2003 heat wave in France with its nearly 15,000 estimated deaths (Poumadere et al., 2005).

Related Studies

Research by the EPA using BenMap estimated the air pollution-related health impacts of 2005 modeled air pollution as compared to a non-anthropogenic background in the United States (Fann et al., 2011). Their annual health impact estimates associated with $PM_{2.5}$ include 130,000 premature deaths, 180,000 nonfatal heart attacks, 30,000 respiratory hospital admissions, 110,000 emergency room visits, and 18 million lost days of work. In regards to ozone health impacts, they estimate 4,700 premature deaths, 31,000 respiratory hospital admissions, 19,000 emergency room visits, and 11 million school absences per year.

A study investigating the influence of climate change in the US from 2001 to 2050 on the health impacts caused by ozone and $PM_{2.5}$ utilizing BenMap estimated 4,000 annual $PM_{2.5}$-related premature deaths and 300 annual premature deaths associated with ozone (Tagaris et al., 2009). A follow up to this research found significant regional variation in climate change-induced air pollution impacts as well as high sensitivity of pollutant concentrations to precursor emission levels (Tagaris et al. 2010). Post et al. incorporated seven modeling systems (based on the A1, A2, and B1 IPCC emissions scenarios), five population projections, and three health impact functions in BenMap in order to elucidate the variation in ozone mortality estimates, and found a range of -600 to 2,500 annual deaths in the US associated with climate change-induced changes in ozone concentrations from 2000 to 2050 (Post et al., 2012).

Research using modeled temperature data performed in BenMap estimated heat-related premature mortality between the years 2000 and 2050 in the United States. Their results include annual estimates of 3,700-3,800 all-cause deaths, 3,500 cardiovascular deaths, and 21,000-27,000 non-accidental deaths by 2050, relative to 2000 (Voorhees et al., 2011).

Objective

The objective of this study is to estimate the future morbidity and mortality attributable to ozone, $PM_{2.5}$, and high temperature exposure in the continental United States. We use the single years 2005 and 2025 as an illustration of the influence of changing emissions and climate change, although inter-annual climate variability may play a larger role than climate change during our time period.

Air quality and temperature are inextricably linked and both impact human health. The combined impact of air pollution and heat may be larger than the sum of the impacts of each, indicating a synergy between the two factors. Urban dwellers are particularly vulnerable to the combined impact of air pollution and heat, as the heat island effect, existing health problems, and high population density exacerbate the problem.

The human health impacts and corresponding economic effects of air quality and temperature are rarely quantified in the same modeling simulation. Given the close relationship between these two factors and the danger they impose on public health, air quality and temperature justify simultaneous investigation. In this study, we estimate and compare the magnitude of health impacts of air pollutants and heat in the same modeling simulation. We estimate the health effects of air pollution and temperature independently for lack of a clear epidemiological function that might account for interactions between these variables on health.

Using different air quality scenarios, we also aim to distinguish the effects of changes in emissions and climate change in regard to the health impacts of air pollution. Additionally, we seek to illustrate the geographical distribution and regional heterogeneity of these health impact estimates throughout the continental United States. The final aspect of this study entails assigning financial value to the morbidity and mortality caused by ozone, $PM_{2.5}$, and temperature.

Our practical objective of producing these morbidity and mortality estimates, health impact maps, and economic valuations is to inform air quality managers, public health professionals, government officials, and other interested parties about the extent of the impacts of emissions and climate change on human health.

CHAPTER 2: METHODS

In this study, we estimate and map the morbidity and mortality associated with changes in three air quality scenarios and temperature between the years 2005 and 2025 in the continental United States using an environmental health impact assessment modeling program, BenMap. By using modeled air quality and temperature data sets from 2005 and 2025, we are able to incorporate precursor emissions data (from the National Emissions Inventory) and meteorology projections for the same years, giving a comprehensive picture of the interaction between emissions and climate change in determining the health impacts of air quality and temperature.

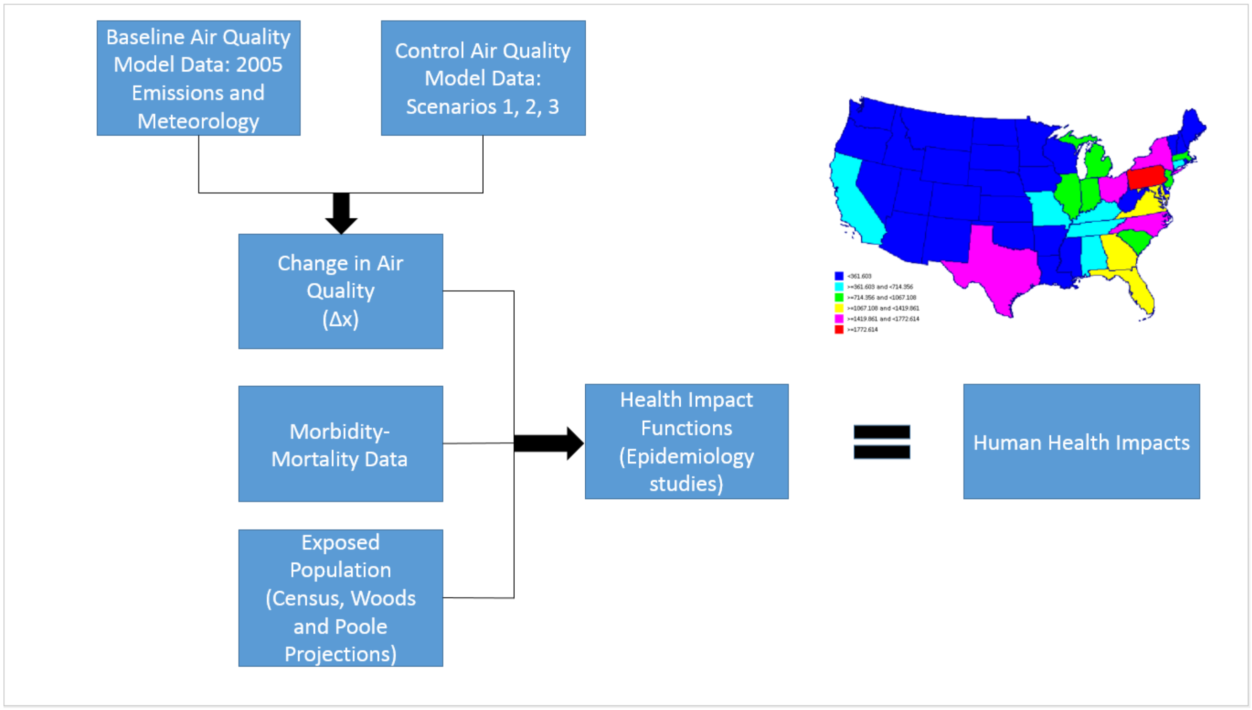
BenMap

The analyses for this project are conducted in the Community Edition Version 1.0.8 of the Environmental Benefits Mapping and Analysis Program (BenMap) developed by the United States Environmental Protection Agency (EPA, 2013). The EPA has developed this program to evaluate air quality management policies by quantifying and mapping the health impacts associated with changes in air quality. BenMap calculates the morbidity and mortality resulting from changes in air quality, as well as the associated financial costs.

To do this, BenMap uses a health impact function with the following variables: air pollution change, concentration-response function, incidence, and exposed population. BenMap also contains a geographical information processing system, which calculates health impacts at various grid cell resolutions. The health impact assessment process of BenMap is shown in

Figure 1. With these estimates, BenMap can then perform an economic valuation by multiplying the change in incidence by the value of a statistical life and other economic indicators.

Figure 1. The health impact assessment process used by BenMap.



Health Impact Functions

Health impact functions employed in air quality and temperature analyses are derived from epidemiology studies and provide the standard mathematical basis for conducting health impact assessments. The typical health impact function follows the basic formula:

$$\Delta y= y_0(e^{\beta * \Delta x} - 1)Pop$$

where Δy is the change in morbidity or mortality, y_0 is the baseline morbidity or mortality rate, β is the coefficient derived from the relative risk of the exposure, Δx is the change in pollutant concentration, and Pop is the exposed population.

The BenMap program contains a robust database of health impact functions. These functions are derived from prominent air pollution epidemiology studies.

We use the health impact studies found in the 2008 ozone Regulatory Impact Analysis (RIA), including premature mortality (with the exception of respiratory mortality), emergency room visits, hospital admissions, restricted activity days, and lost days of school (EPA, 2008). These studies were carefully chosen via a rigorous selection process by the EPA. Since the most recent ozone RIA (published in 2008), a new, influential study on ozone-related mortality has been conducted by Jerrett et al. using the American Cancer Society cohort (Jerrett et al., 2009). This seminal study has become the standard in ozone epidemiology, and has been used in many important air pollution mortality studies (Anenberg et al., 2010, Lim et al., 2013, Silva et al., 2013). We use this study to estimate ozone respiratory mortality, which serves as an indicator of total ozone mortality in this study. Similarly, for our analysis of $PM_{2.5}$, we rely on the health impact studies used in the 2012 $PM_{2.5}$ RIA, including premature mortality, bronchitis, asthma, emergency room visits, hospital admissions, and lost days of school (EPA, 2012). A key study used in the PM RIA is that of Krewski, and that study was chosen as the basis of the mortality estimates in this research as well (Krewski et al., 2009).

Health impact functions that correspond to the pollutant and temperature metrics found in Table 1 were chosen. Temperature health impact functions (Base and Ostra, 2008) were chosen from a proof-of-concept study which used BenMap to produce heat-related health impact estimates (Voorhees et al., 2011). One health impact function, beta coefficient, and age range was selected for each health endpoint. The specifications of the health impact functions used in this study, including age groups, beta coefficients, and references can be found in Appendix A (ozone), Appendix B ($PM_{2.5}$), and Appendix C (temperature).

Table 1. The metric specifications of ozone, $PM_{2.5}$, and temperature.

Pollutant Metrics		
Pollutant	Seasonal Metric	Daily Metric
Ozone	Six month summer average (April-September)	8-Hour daily maximum
$PM_{2.5}$	Annual average	24-Hour daily average
Temperature	Warm season average (May-September)	24-Hour daily average apparent (heat index)

Air Pollutant Concentrations

Air quality modeled data, supplied by the University of North Carolina's Institute for the Environment, were simulated using the Community Multi-scale Air Quality Model (CMAQ), developed by the EPA's Atmospheric Science Modeling Division. These CMAQ simulations were conducted as part of a downscaling exercise using results from a global general circulation model (the Community Earth System Model). Meteorology was downscaled to the continental US using the Weather Research and Forecasting (WRF) model and these meteorological simulations were used to drive CMAQ. The emissions assumptions for these modeling exercises were derived from the RCP (Representative Concentration Pathway) 4.5 scenarios established by the Intergovernmental Panel on Climate Change (Thomson et. al., 2011). The air quality grid resolution of these modeled data for ozone and particulate matter is 36km.

The baseline scenario in these model runs was chosen to be 2002, the coldest year of the five year period of 2001-2005. The warmest year of the 2021 to 2025 period, 2024, was chosen for future projections. By selecting the coldest year as the baseline and the warmest year as the control, the largest temperature and meteorological difference between the baseline and control is selected. We use the simulation years of 2002 and 2024 to represent the years 2005 and 2025. Although we aim to discern the influence of changes in emissions and climate, inter-annual climate variability also plays a role in the changes between 2005 and 2025, although this role is difficult to quantify.

The current and future simulation years in this study were set at 2005 and 2025, respectively, due to limited availability of emissions data (Woody et al., 2011). The year 2005 was selected as the current year as it coincides with a recent National Emissions Inventory (NEI) by the Environmental Protection Agency (EPA, 2007). The future year was set at 2025, as emissions for this year could be interpolated from the EPA's projections of 2020 and 2030 national emissions levels based on the 2005 NEI.

These interpolations include both current and planned national emissions control programs, and show a decrease in emissions and pollutant concentrations between 2005 and 2025. Using simulations from the year 2025 also allows for changes in both emissions and meteorology to be accounted for, whereas future years beyond 2025 or 2030 contain a high degree of uncertainty with regard to emissions projections. A complete description of these modeling choices can be found in Woody et al. (Woody et al., 2011)

Emission levels and meteorology from the year 2005 served as the baseline, which was then compared against three different air quality scenarios. The specifications of the baseline and three scenarios are seen in Table 2. Scenario 1 was compared against the baseline in order to conduct the health impact assessment of air pollution changes from the interactive effect of anthropogenic emissions and climate change. We also compare the baseline to Scenario 2 and

Scenario 3 to discern the air pollution-related health impacts associated individually with climate change and emissions, respectively.

Table 2. The specifications for the baseline and three air quality scenarios.

Air Quality Scenarios		
Scenario	Emissions	Meteorology
Baseline	2005	2005
One	2025	2025
Two	2005	2025
Three	2025	2005

Due to the photochemical nature of the reaction that produces ozone, an eight-hour window is selected as the metric to reflect high ozone concentrations during the day. Another determining factor of ozone concentrations is seasonality. Ozone concentrations are highest during the summer, due to the higher amounts of solar radiation. The modeled ozone values in this study consist of the average of these daily 8 hour maximum values for every day in the warm season of April 1 through September 30. The epidemiology studies from which our health impact functions are derived use this 8-hour summer season metric.

The chemical formation of particulate matter is not as sensitive to solar energy as is ozone. Particulate matter concentrations are generally more uniform throughout the day and across seasons than is ozone. For this reason, $PM_{2.5}$ concentration values in this study are the simple annual averages of the baseline and control years. As with ozone, the metric we use corresponds with the metric used in our epidemiology-derived health impact functions.

The domain average deltas for ozone in the time period of 2005 to 2025 are as follows: Scenario 1: -1.273 ppb; Scenario 2: +0.560 ppb; Scenario 3: -1.782 ppb. National average deltas of $PM_{2.5}$ concentrations in the 2005 to 2025 period are: Scenario 1: -0.592 $\mu g/m^3$; Scenario 2: -0.019 $\mu g/m^3$; Scenario 3: -0/572 $\mu g/m^3$. Between 2005 and 2025, pollutant concentrations of ozone follow a general pattern of increases in urban areas in the Northeast, Midwest, and southern California and decreases across much of the central part of the US. Maps showing the change in air pollutant concentrations for both ozone and particulate matter in all three scenarios can be found in Appendix D.

Temperature Data

We use air temperature data modeled with the Weather Research and Forecasting Model (WRF). The WRF model is a powerful numerical weather prediction system relied on for weather forecasting on scales ranging from meters to thousands of kilometers. The modeled temperature data we use are from the same simulation used to drive CMAQ simulations of air quality.

To be consistent with previous temperature-related mortality estimates using BenMap, the twenty-four hourly apparent temperature values for each day were averaged to produce a daily mean for each day in the high temperature season of May 1 through September 30 (Voorhees et al., 2011). (Apparent temperature is defined as the air temperature as perceived by the body as a combined effect of temperature and relative humidity.) Then, summer averages were calculated for both 2005 and 2025. The national average apparent temperature change during this time period is +1.29 degrees Kelvin. The map illustrating the change in apparent temperature between 2002 and 2024 can be seen in Appendix D.

Population Data Sets

BenMap contains population data from the 2010 United States Census and future population projections calculated by an economic forecasting model developed by Woods and Poole Economics, Inc. (Woods and Poole, 2013). We set population to the year 2025, which is projected to be 354 million by the Woods and Poole model. This amounts to a 19% increase in population during the study period of 2005 to 2025, as the US population in 2005 was 298 million.

Baseline Morbidity and Mortality Rates

The BenMap program contains cause-specific morbidity and mortality data at the county level. These data are provided by the Center for Disease Control's Wide-ranging Online Data for Epidemiologic Research (CDC-WONDER) online database (CDC, 2006). For this study, baseline mortality incidence rates projected for the year 2025 by the CDC for the WONDER database were selected. Morbidity incidence rate projections do not exist in the BenMap database. In place of projections, we use baseline morbidity incidence rates from the years 2007 and 2008, which are also included in the BenMap program and derived from the CDC WONDER database. Via a spatial distribution formula, BenMap aggregates these county-level baseline incidence rates to each grid cell.

Aggregation and Valuation

We aggregate the incidence and valuation at the national level. Economic valuation was performed using valuation formulas built into BenMap by the Environmental Protection Agency. This calculation uses the valuation functions and standard values used by the EPA in health impact and regulatory assessments. EPA standard values include the value of a statistical life, inflation, income growth projections, as well as consumer goods, medical cost, and wage indices.

CHAPTER 3: RESULTS

Here we estimate the change in morbidity and mortality between 2005 and 2025 in the US for eleven ozone-related endpoints, twenty endpoints associated with $PM_{2.5}$, and two heat-related endpoints. The large amount and variety of health endpoints analyzed in this study were chosen to evaluate the extensive impacts of changes in air pollution and high temperature.

Throughout this paper, individual morbidity and mortality estimates were chosen to represent health endpoint groups. Different mortality types are independent estimates and are not considered additive. For this reason, one mortality endpoint must be selected as the best estimate of total mortality. This applies to mortality estimates as well as the economic valuation of mortality.

We select respiratory mortality to represent ozone-related mortality, as ozone was identified by Jerrett et al. to have a significant effect on respiratory mortality compared to other types of mortality (Jerrett et al., 2009). All-cause mortality was selected to approximate total mortality attributable $PM_{2.5}$, as $PM_{2.5}$ has been shown to have systemic effect on the body and thus exerts a substantial effect on all-cause mortality (Krewski et. al., 2009). Finally, cardiovascular mortality was chosen to represent total heat-related mortality, as heat has been documented to have a disproportionate impact on the cardiovascular system (Luber et al., 2008).

Section 1: Air Pollution Health Impact Assessment

Ozone Estimates

By comparing Scenario 1, which contains both 2025 emissions and climate change, to the baseline, we estimate 2,400 fewer cases of respiratory mortality, 4,100 fewer emergency room visits, 1,500 fewer respiratory hospital admissions, 3.1 million fewer restricted activity days, and 2.3 fewer million lost days of school at the national level per year. Complete ozone-related mortality and morbidity results in the Scenario 1 comparison can be seen in Tables 3 and 6.

Scenario 2 illustrates how climate change influences ozone morbidity and mortality. In this scenario, we estimate increases in the following endpoints: respiratory mortality of 1,700 cases, 3,000 emergency room visits, 1,100 respiratory hospital admissions, 2.1 million restricted activity days, and 1.7 million lost days of school. Tables 4 and 7 display the full range of estimates from the ozone Scenario 2 comparison. A key characteristic of Scenario 2 is that all ozone health endpoints increase, suggesting that climate change has a strong positive influence on ozone concentrations and thus on ozone-related mortality and morbidity.

By comparing Scenario 3 (which simulates 2025 emissions while holding current meteorology constant) to the baseline, we calculate a decrease in respiratory mortality of 3,700, 2,400 fewer respiratory hospital admissions, 4.8 million fewer restricted activity days, and 3.7 million fewer lost days of school. Full estimates of ozone-related mortality and morbidity are found in Tables 5 and 8, respectively. Without the interactive influence of climate change, changes in ozone mortality and morbidity are significantly lower.

Table 3. The change in ozone mortality in 2025 relative to 2005 in the comparison of Scenario 1 to the baseline.

Scenario 1 Ozone Mortality					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
All Cause	0	99	-2,500	-1,800	-3,100
Cardiopulmonary	0	99	-800	-380	-1,200
Non-Accidental	0	99	-540	-240	-840
Respiratory	30	99	-2,400	-1,100	-3,700

Table 4. The change in ozone mortality in the Scenario 2 comparison.

Scenario 2 Ozone Mortality					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
All Cause	0	99	+1,700	+1,300	+2,200
Cardiopulmonary	0	99	+560	+260	+850
Non-Accidental	0	99	+380	+170	+590
Respiratory	30	99	+1,700	+730	+2,600

Table 5. Changes in ozone mortality in the Scenario 3 comparison.

Scenario 3 Ozone Mortality					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
All Cause	0	99	-3,900	-2,900	-4,900
Cardiopulmonary	0	99	-1,300	-600	-1,900
Non-Accidental	0	99	-860	-380	-1,300
Respiratory	30	99	-3,700	-1,700	-5,800

Table 6. The change in ozone morbidity in Scenario 1 relative to the baseline.

Scenario 1 Ozone Morbidity					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
Emergency Room Visits Asthma	0	99	-4,100	-1,800	-6,300
Hospital Admissions All Respiratory	0	1	-1,500	-800	-2,200
Hospital Admissions Chronic Lung Disease	65	99	-1,100	+40	-2,200
Hospital Admissions Chronic Lung Disease (less Asthma)	65	99	-1,500	-580	-2,500
Hospital Admissions Pneumonia	65	99	-1,900	-430	-3,300
Minor Restricted Activity Days	18	64	-3,100,000	-1,600,000	-4,600,000
School Loss Days All Cause	5	17	-2,300,000	-100,000	-4,400,000

Table 7. Changes in ozone morbidity in Scenario 2 compared to the baseline.

Scenario 2 Ozone Morbidity					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
Emergency Room Visits Asthma	0	99	+3,000	+1,300	+4,600
Hospital Admissions All Respiratory	0	1	+1,100	+560	+1,600
Hospital Admissions Chronic Lung Disease	65	99	+900	-40	+1,800
Hospital Admissions Chronic Lung Disease (less Asthma)	65	99	+1,300	+480	+2,100
Hospital Admissions Pneumonia	65	99	+1,400	+330	+2,600
Minor Restricted Activity Days	18	64	+2,100,000	+1,100,000	+3,200,000
School Loss Days All Cause	5	17	+1,700,000	+100,000	+3,300,000

Table 8. The change in ozone morbidity in the Scenario 3 comparison.

Scenario 3 Ozone Morbidity					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
Emergency Room Visits Asthma	0	99	-6,600	-3,000	-10,200
Hospital Admissions All Respiratory	0	1	-2,400	-1,260	-3,500
Hospital Admissions Chronic Lung Disease	65	99	-1,800	+70	-3,600
Hospital Admissions Chronic Lung Disease (less Asthma)	65	99	-2,600	-980	-4,200
Hospital Admissions Pneumonia	65	99	-3,100	-700	-5,400
Minor Restricted Activity Days	18	64	-4,900,000	-2,500,000	-7,200,000
School Loss Days All Cause	5	17	-3,700,000	-200,000	-7,100,000

Geographical Distribution of Ozone Health Impacts

The changes in ozone concentrations exhibit significant geographical variation, as can be seen in Appendix D. This pattern is reflected in the health impact maps. Ozone concentrations rise significantly in some areas and fall in many others, with this pattern varying significantly by scenario.

In the scenario including both emissions and climate change projections, regions exhibiting ozone concentration decreases include the East Coast, Midwest, and the Southwest and California, whereas ozone levels are projected to increase across much of the central part of the nation. For these reasons, we estimate ozone-related health impacts to decrease at the national level between 2005 and 2025.

In the Scenario 1 ozone analysis, decreases in ozone-related mortality are most prevalent in highly populated regions near the US coasts, as shown in Figure 2. Southern California and Arizona experience the largest reductions of morbidity and mortality. Eastern metropolitan areas, including Boston, New York, Atlanta, and Raleigh also stand out as areas with large downturns in ozone concentrations in Scenario 1. Maps of other health endpoints in Scenario 1 can be found in Appendix E.

Figure 2 illustrates the ozone Scenario 2 analysis. In Scenario 2, ozone-related mortality rises throughout much of the country, with the largest increases in cities in the Eastern half of the nation. The analysis of ozone in Scenario 3 shows a pattern similar to that of Scenario 1, with urban centers and coastal regions experiencing large reductions in mortality (Figure 3). Additional health endpoint examples can be seen in Appendix E.

Figure 2. The decrease in respiratory mortality attributable to ozone in Scenario 1, shown at the county level. Positive values indicate falling mortality rates; negative values are associated with increasing mortality.

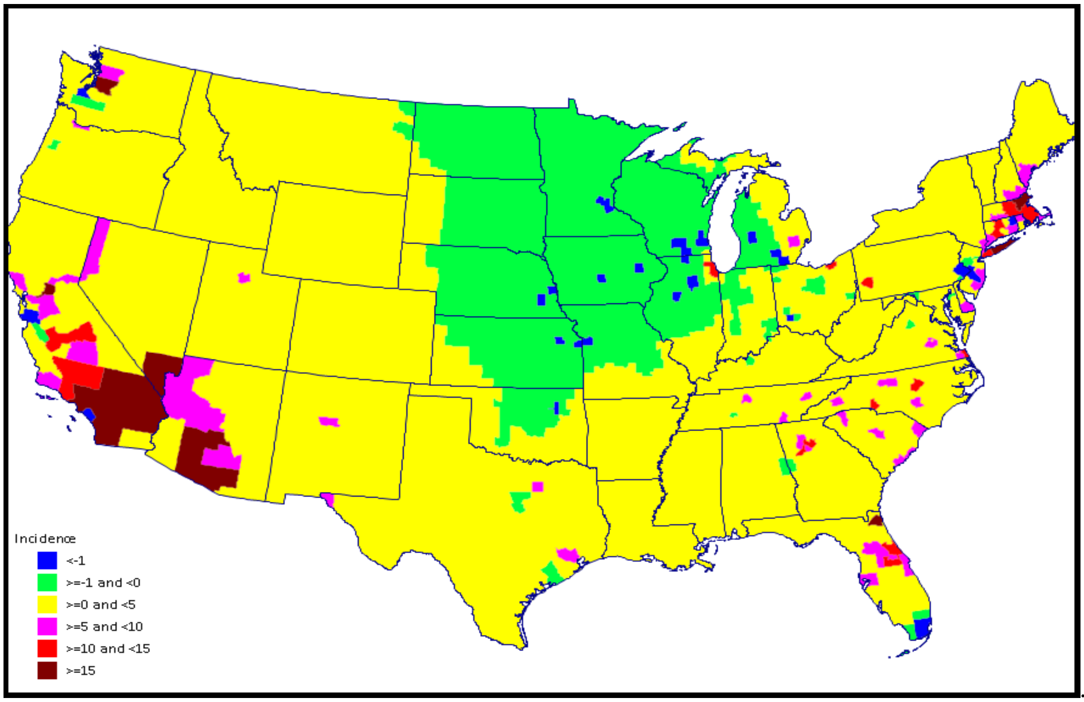


Figure 3. The change in ozone-related respiratory mortality in Scenario 2. The negative values throughout much of the country, which indicate rising mortality between 2005 and 2025, reflects the rising ozone concentrations under a climate change-only simulation.

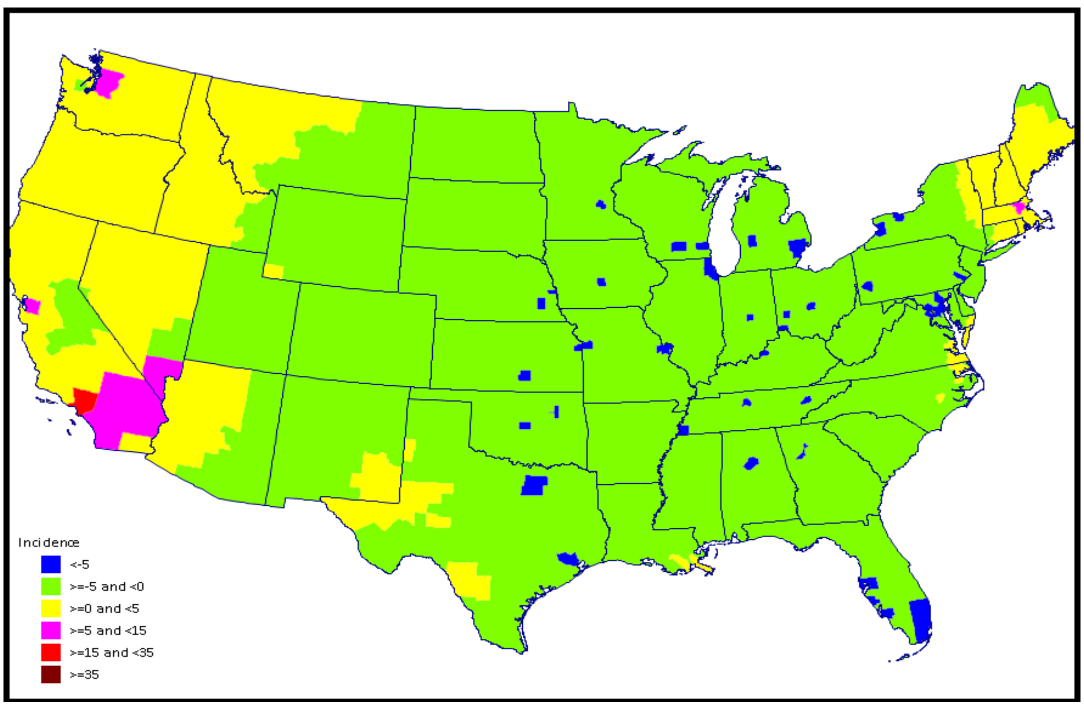
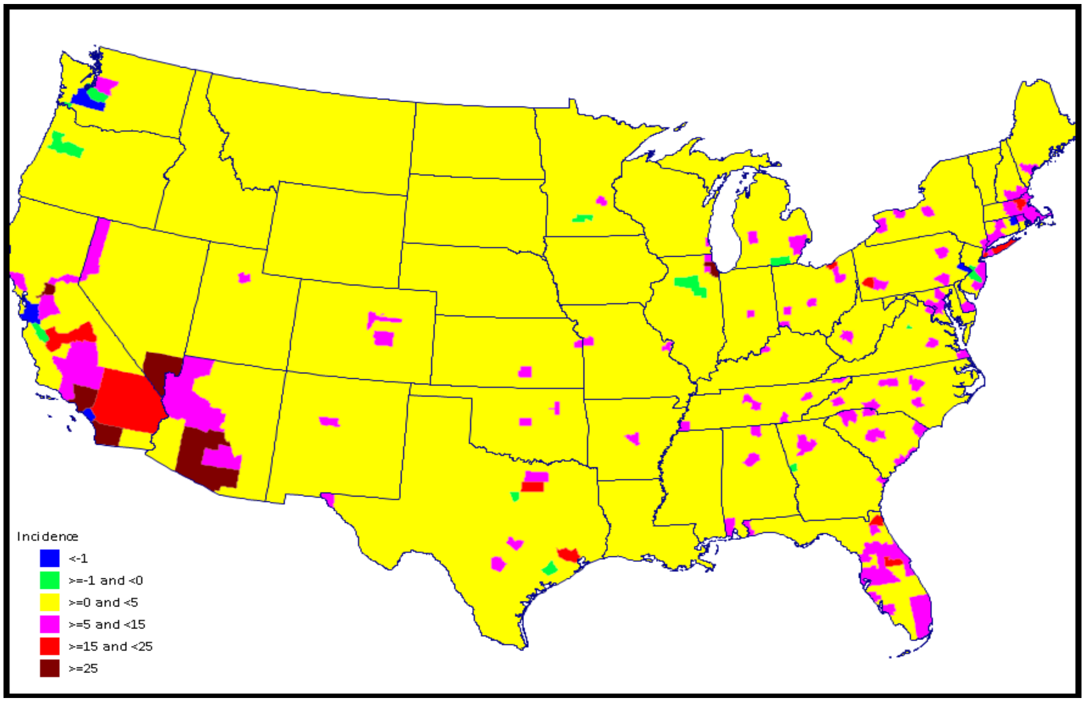


Figure 3. Trends in respiratory mortality due to ozone exposure in Scenario 3.



Particulate Matter Estimates

In the comparison of Scenario 1 with the baseline, we estimate 26,000 fewer cases of all-cause mortality, 8 million fewer instances of exacerbated asthma cough, 10,000 fewer cardiovascular hospital admissions, 670,000 fewer occurrences of upper respiratory symptoms, 35,000 fewer cases of acute bronchitis, 18 million fewer restricted activity days, and 3.1 million fewer lost days of work per year. Estimates for all health endpoints can be seen in Tables 9 and 12.

From the $PM_{2.5}$ Scenario 2 comparison, our results show the following reductions: all-cause mortality at 350, 140,000 cases of exacerbated asthma, 170 cardiovascular hospital admissions, 380 cases of chronic bronchitis, and 70,000 lost days of work. All endpoint estimates related to this scenario comparison can be found in tables 10 and 13. The results of this comparison represent the individual influence of climate change on $PM_{2.5}$-related morbidity and mortality. Estimates from Scenario 2 are significantly lower than those of Scenario 1, suggesting that the health impacts associated with $PM_{2.5}$ are much less sensitive to climate change than to emissions levels.

The Scenario 3 comparison yields very similar health impact reductions to those of Scenario 1. In Scenario 3, we estimate 25,000 fewer cases of all-cause mortality, 8.0 million fewer exacerbated asthma cases, 10,000 fewer cardiovascular hospital admissions, 17,000 fewer chronic bronchitis cases, and 3.0 fewer million lost days of work. Tables 11 and 14 display all mortality and morbidity endpoint estimates. It is noteworthy that these estimates so closely approximate those of the Scenario 1 analysis, as this demonstrates that $PM_{2.5}$-related health impacts are heavily moderated by precursor emissions.

Table 9. Changes in $PM_{2.5}$-related mortality in Scenario 1 compared to the baseline.

Scenario 1 $PM_{2.5}$ Mortality					
Health Endpoint	Start Age	End Age	Point Estimate	5^{th} Percentile	95^{th} Percentile
All Cause	30	99	-26,000	-19,000	-32,000
Ischemic Heart Disease	30	99	-17,000	-15,000	-20,000
Lung Cancer	30	99	-4,100	-2,200	-6,000

Table 10. The change in mortality associated with $PM_{2.5}$ in Scenario 2 relative to the baseline.

Scenario 2 $PM_{2.5}$ Mortality					
Health Endpoint	Start Age	End Age	Point Estimate	5^{th} Percentile	95^{th} Percentile
All Cause	30	99	-350	-260	-450
Ischemic Heart Disease	30	99	-340	-290	-390
Lung Cancer	30	99	-30	-20	-40

Table 11. The change in mortality of the Scenario 3 attributable to $PM_{2.5}$.

Scenario 3 $PM_{2.5}$ Mortality					
Health Endpoint	Start Age	End Age	Point Estimate	5^{th} Percentile	95^{th} Percentile
All Cause	30	99	-25,000	-18,000	-32,000
Ischemic Heart Disease	30	99	-17,000	-15,000	-20,000
Lung Cancer	30	99	-4,100	-2,200	-6,000

Table 12. The morbidity associated with particulate matter exposure in Scenario 1 relative to the baseline.

Scenario 1 $PM_{2.5}$ Morbidity					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
Acute Bronchitis	8	12	-36,000	+1,300	-70,000
Acute Myocardial Infarction Nonfatal	0	99	-2,800	-1,600	-4,000
Asthma Exacerbation Cough	18	64	-8,100,000	-1,200,000	-15,000,000
Asthma Exacerbation Shortness of Breath	6	18	-610,000	-87,000	-1,100,000
Asthma Exacerbation Wheeze	6	18	-970,000	-310,000	-1,600,000
Chronic Bronchitis	6	18	-17,000	-3,100	-30,000
Emergency Room Visits Asthma	27	99	-17,000	-6,500	-27,000
Hospital Admissions All Cardiovascular (less Myocardial Infarctions)	0	99	-10,000	-7,700	-13,000
Hospital Admissions All Respiratory	65	99	-8,100	-5,200	-11,000
Hospital Admissions Congestive Heart Failure	65	99	-5,500	-1,700	-9,200
Hospital Admissions Dysrhythmia	0	17	-1,500	+2,600	-5,600
Hospital Admissions Ischemic Heart Disease (less Myocardial Infarctions)	65	99	-2,000	+650	-4,600
Hospital Admissions Pneumonia	18	64	-5,600	-1,800	-9,400
Lower Respiratory Symptoms	65	99	-460,000	-220,000	-690,000
Minor Restricted Activity Days	7	14	-18,000,000	-15,000,000	-21,000,000
Upper Respiratory Symptoms	9	11	-670,000	-210,000	-1,100,000
Work Loss Days	18	64	-3,100,000	-2,660,000	-3,400,000

Table 13. Particulate matter morbidity incidence in Scenario 2 relative to the baseline.

Scenario 2 $PM_{2.5}$ Morbidity					
Health Endpoint	Start Age	End Age	Point Estimate	5th Percentile	95th Percentile
Acute Bronchitis	8	12	-600	+20	-1,100
Acute Myocardial Infarction Nonfatal	0	99	-50	-30	-60
Asthma Exacerbation Cough	18	64	-140,000	-23,000	-260,000
Asthma Exacerbation Shortness of Breath	6	18	-11,000	-1,600	-21,000
Asthma Exacerbation Wheeze	6	18	-18,000	-5,700	-30,000
Chronic Bronchitis	6	18	-380	-70	-660
Emergency Room Visits Asthma	27	99	-590	-220	-940
Hospital Admissions All Cardiovascular	0	99	-170	-130	-210

(less Myocardial Infarctions)					
Hospital Admissions All Respiratory	65	99	-100	-60	-130
Hospital Admissions Congestive Heart Failure	65	99	-100	-30	-170
Hospital Admissions Dysrhythmia	0	17	-30	+50	-100
Hospital Admissions Ischemic Heart Disease (less Myocardial Infarctions)	65	99	-20	+10	-50
Hospital Admissions Pneumonia	18	64	-50	-20	-80
Lower Respiratory Symptoms	65	99	-7,800	-3,900	-11,000
Minor Restricted Activity Days	7	14	-410,000	-350,000	-470,000
Upper Respiratory Symptoms	9	11	-12,000	-3,700	-20,000
Work Loss Days	18	64	-70,000	-61,000	-79,000

Table 14. Particulate matter morbidity in the Scenario 3-baseline comparison.

Scenario 3 $PM_{2.5}$ Morbidity					
Health Endpoint	Start Age	End Age	Point Estimate	5^{th} Percentile	95^{th} Percentile
Acute Bronchitis	8	12	-35,000	+1,300	-70,000
Acute Myocardial Infarction Nonfatal	0	99	-2,800	-1,600	-3,900
Asthma Exacerbation Cough	18	64	-8,000,000	-1,200,000	-15,000,000
Asthma Exacerbation Shortness of Breath	6	18	-600,000	-86,000	-1,100,000
Asthma Exacerbation Wheeze	6	18	-960,000	-300,000	-1,600,000
Chronic Bronchitis	6	18	-17,000	-3,100	-30,000
Emergency Room Visits Asthma	27	99	-17,000	-6,400	-27,000
Hospital Admissions All Cardiovascular (less Myocardial Infarctions)	0	99	-10,000	-7,600	-13,000
Hospital Admissions All Respiratory	65	99	-8,000	-5,200	-11,000
Hospital Admissions Congestive Heart Failure	65	99	-5,400	-1,700	-9,100
Hospital Admissions Dysrhythmia	0	17	-1,500	+2,600	-5,500
Hospital Admissions Ischemic Heart Disease (less Myocardial Infarctions)	65	99	-2,000	+700	-4,600
Hospital Admissions Pneumonia	18	64	-5,500	-1,700	-9,300

Lower Respiratory Symptoms	65	99	-450,000	-220,000	-680,000
Minor Restricted Activity Days	7	14	-18,000,000	-15,000,000	-20,000,000
Upper Respiratory Symptoms	9	11	-660,000	-210,000	-1,100,000
Work Loss Days	18	64	-3,000,000	-2,600,000	-3,400,000

Geographical Distribution of $PM_{2.5}$ Health Impacts

In Scenario 1, the decreases in $PM_{2.5}$-related health impacts are concentrated around highly populated urban areas such as Chicago; Atlanta; Los Angeles; Washington, D.C.; Baltimore; and New York City. An example of this is seen in Figure 4. Densely populated areas are estimated to have larger improvements in air quality and thus higher reductions of mortality and morbidity rates than surrounding rural areas. Maps of other examples of $PM_{2.5}$-related health endpoints can be found in Appendix F.

As seen in Tables 10 and 13, the levels of $PM_{2.5}$ impacts in Scenario 2 differ from those in Scenarios 1 and 3. In many areas of the country, such as the Southeast and Southwest, morbidity and mortality actually increases slightly in Scenario 2 (Figure 5.) Without emissions changes, changes in climate cause higher rates of $PM_{2.5}$-related illness and death in some regions of the country. At the national level, however, mortality and morbidity fall in Scenario 2.

The map of mortality for $PM_{2.5}$ in Scenario 3 is very similar in appearance to that of Scenario 1, as seen in Figure 6. With meteorological conditions held constant, changes in emission levels between 2005 and 2025 lead to substantially lower morbidity and mortality levels in eastern and southern states, as well as the Southwest. As in Scenario 1, the largest reductions in morbidity and mortality occur in cities, including Atlanta, Houston, Raleigh, Baltimore, New York, Pittsburgh, Chicago, and Los Angeles.

Figure 4. Changes in $PM_{2.5}$-related all-cause mortality at the county level in Scenario 1. The largest decreases in mortality are found in urban areas, especially in the Northeast.

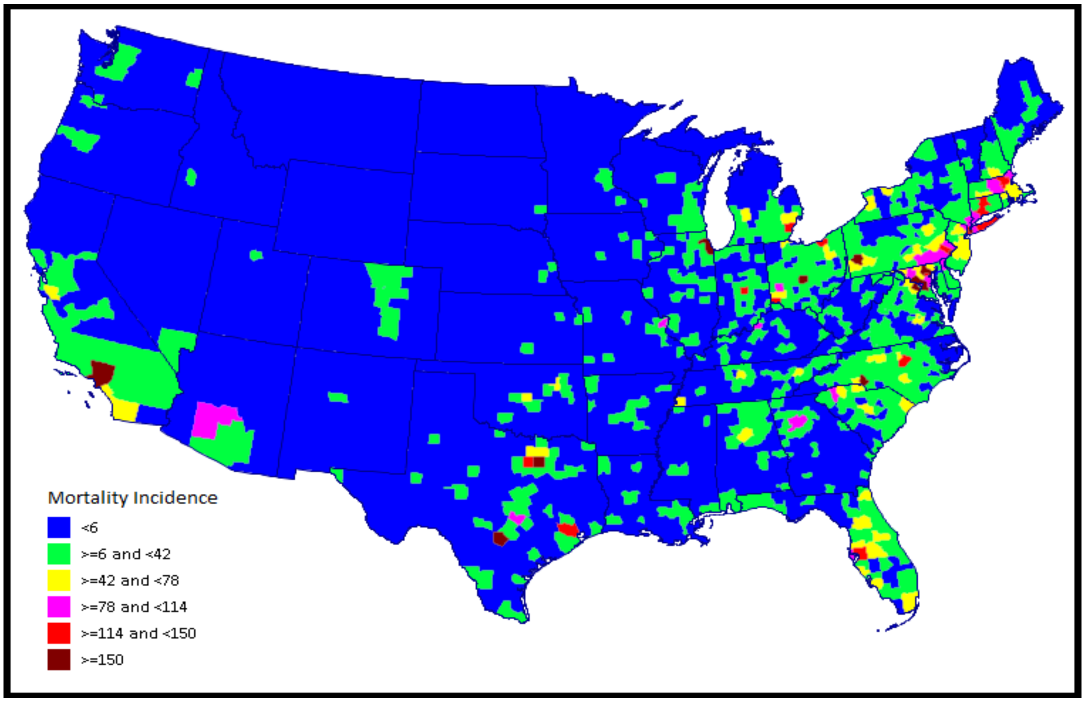


Figure 5. The trends of $PM_{2.5}$-related all-cause mortality from Scenario 2 at the county level. .

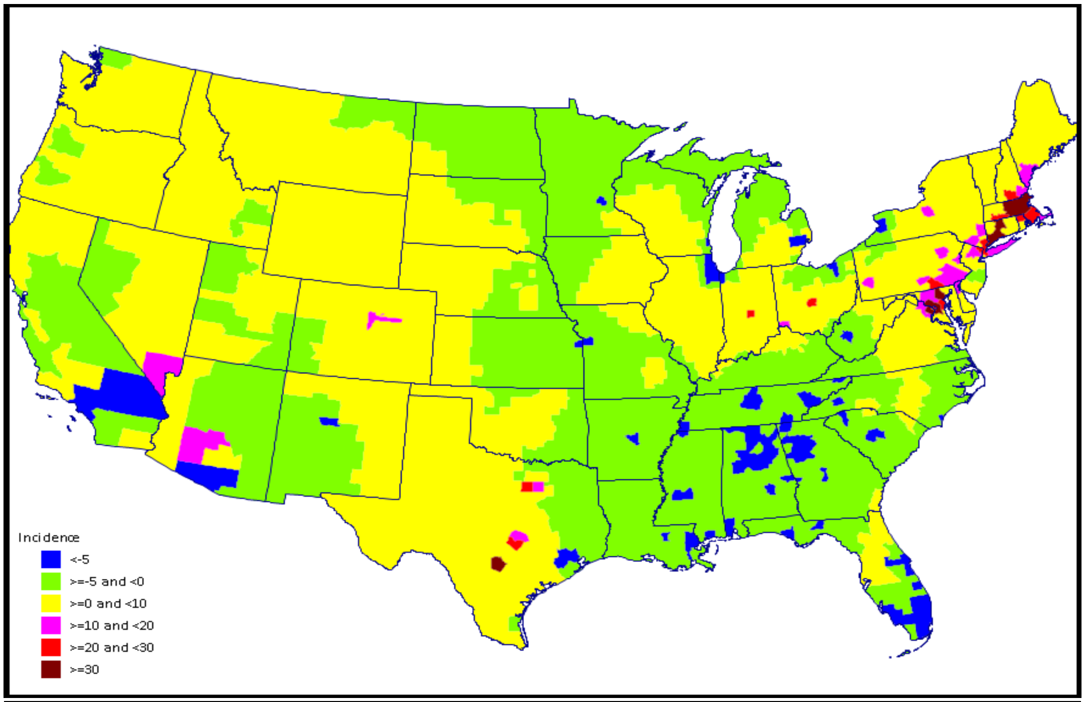
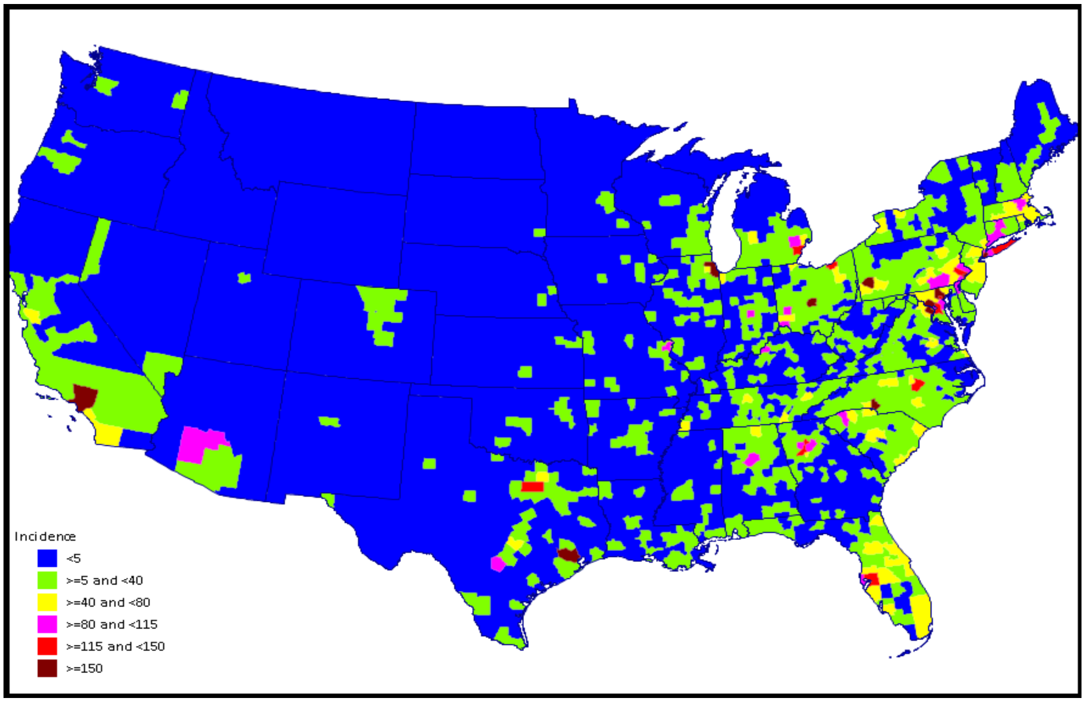


Figure 6. The changes in all-cause mortality attributable to $PM_{2.5}$ exposure in Scenario 3.



Influence of Emissions and Climate Change on Health Impacts

Here, the interaction of emissions and climate change, as well as the individual influence of each factor, is discerned by comparing the results of the three scenarios. Due to the nonlinearities between emissions and climate change, the scenario containing both climate change and emissions (Scenario 1) cannot be achieved simply by combining the climate change of Scenario 2 with the emissions of Scenario 3, although summing Scenarios 2 and 3 provide a close approximation of Scenario 1. Scenario 1 represents the combined and interactive effect of emissions and climate change on the health impacts of air pollution.

In the context of ozone health impacts, the three scenarios exhibit significant variability. Figure 7 illustrates the discrepancy between the health impacts in the three ozone scenarios.

Under the “climate change only” scenario (Scenario 2), an increase in ozone-related mortality is estimated, suggesting that climate change exacerbates ozone concentrations. Without the effect of climate change, changing emissions levels would lead to substantially lower mortality rates. The large variation in the three-scenario comparison demonstrates the high sensitivity of ozone concentrations to a changing climate system and supports the importance of limiting emissions of ozone precursors and greenhouse gases in concert.

The estimates of $PM_{2.5}$ health impacts demonstrate the large influence of emissions as compared to climate change (Figure 8). For example, in Scenario 2 relative to the baseline, all-cause mortality attributable to $PM_{2.5}$ exposure is -350, as compared to -26,000 in the Scenario 1 comparison. All-cause mortality levels in Scenario 3 (-25,000), however, are almost identical to those of Scenario 1 (-26,000). This pattern emerges across all health endpoint estimates associated with $PM_{2.5}$ exposure. These results suggest that the concentrations and health impacts of $PM_{2.5}$ are determined mostly by changes in emissions, and display low sensitivity to climate change.

Figure 7. The ozone respiratory mortality for the three different scenarios relative to the baseline.

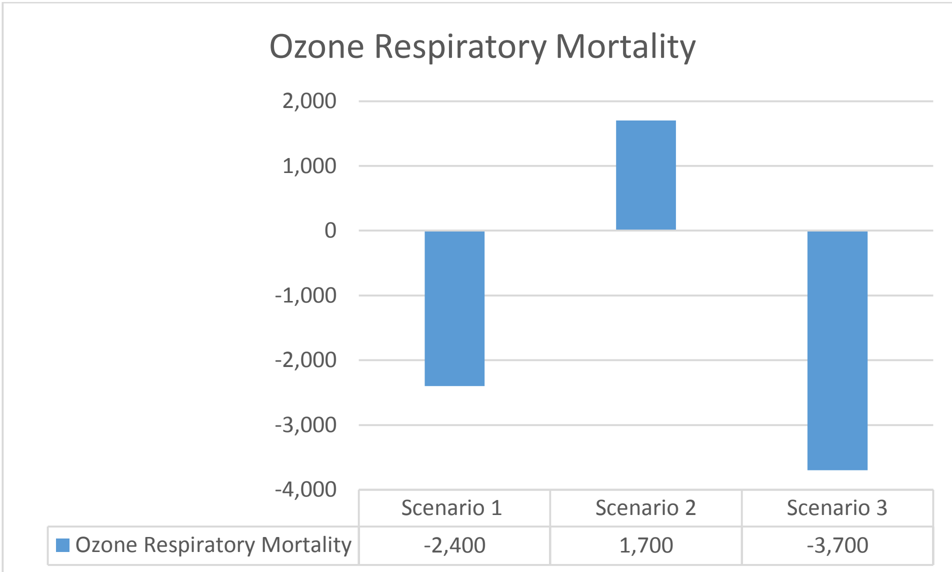
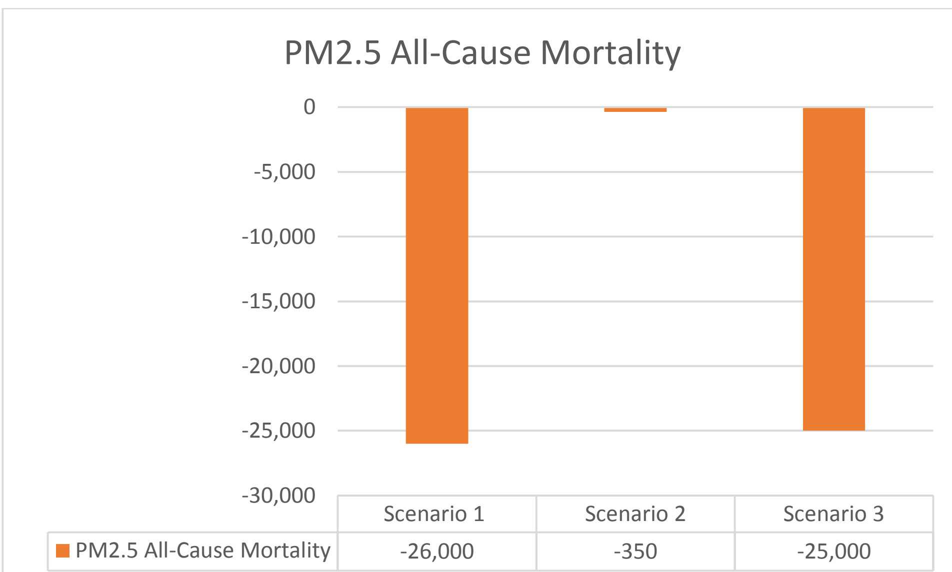


Figure 8. The all-cause mortality attributable to $PM_{2.5}$ is shown in this figure. The marked difference between Scenario 2 and the other two scenarios illustrates the substantial influence of emissions on $PM_{2.5}$ concentrations.



Section 2: Air Pollution Economic Valuation

We use BenMap to calculate the economic impact associated with each health endpoint in Scenarios 1, 2, and 3. For ozone health endpoints in Scenario 1, we estimate savings of $6 billion from respiratory mortality annually, $30 million in hospital admissions, $77 million from lost days of school, and $74 million lost in restricted activity days. All ozone-related economic valuation estimates are seen in Table 15.

In the $PM_{2.5}$ valuation for Scenario 1, we find cost reductions in the following endpoints: $140 billion attributable to all-cause mortality, $1.5 billion associated with asthma, $800 million in hospital admissions, $130 million in respiratory symptoms, and $1.3 billion from restricted activity days and lost days of work. Table 16 lists all the economic values associated with $PM_{2.5}$ across all three Scenarios.

Table 15. The annual economic value of the health impacts due to ozone exposure in the three scenarios.

Ozone Valuation						
Mortality						
	Scenario 1		Scenario 2		Scenario 3	
Endpoint	Incidence	Value ($ billions)	Incidence	Value ($ billions)	Incidence	Value ($ billions)
All Cause	-2,500	-6.5	+1,700	+4.6	-3,900	-10
Cardiopulmonary	-800	-2.1	+560	+1.5	-1,300	-3.3
Non-accidental	-540	-1.4	+380	+1.0	-860	-2.3
Respiratory	-2,400	-6.2	+1,700	+4.4	-3,700	-9.8
Morbidity						
	Scenario 1		Scenario 2		Scenario 3	
Endpoint	Incidence	Value ($ millions)	Incidence	Value ($ millions)	Incidence	Value ($ millions)
Emergency Room Visits, Asthma	-4,100	-0.37	+3,000	+0.27	-6,600	-0.59
Hospital Admissions, All Respiratory	-1,500	-8.8	+1,100	+6.2	-2,400	-14
Hospital Admissions, Chronic Lung Disease	-1,100	-4.9	+900	+3.9	-1,800	-8.1

Hospital Admissions, Chronic Lung Disease (less Asthma)	-1,500	-6.9	+1,300	+5.7	-2,600	-12
Hospital Admissions, Pneumonia	-1,900	-10	+1,400	+7.8	-3,100	-17
Minor Restricted Activity Days	-3,100,000	-74	+2,100,000	+51	-4,900,000	-120
School Loss Days	-2,300,000	-78	+1,700,000	+57	-3,700,000	-124

Table 16. The annual economic value of the health impacts associated with $PM_{2.5}$ in the three scenarios.

$PM_{2.5}$ Valuation						
Mortality						
	Scenario 1		Scenario 2		Scenario 3	
Endpoint	Incidence	Value ($ billions)	Incidence	Value ($ billions)	Incidence	Value ($ billions)
All Cause	-26,000	-140	-350	-1.9	-25,000	-139
Ischemic Heart Disease	-17,000	-96	-340	-1.9	-17,000	-95
Lung Cancer	-4,100	-23	-30	-0.18	-4,100	-22
Morbidity						
	Scenario 1		Scenario 2		Scenario 3	
Endpoint	Incidence	Value ($ millions)	Incidence	Value ($ millions)	Incidence	Value ($ millions)
Acute Bronchitis	-36,000	-2.1	-600	-35	-35,000	-2.1
Acute Myocardial Infarction, Nonfatal	-2,800	-140	-50	-2.2	-2,800	-140
Asthma Exacerbation, Cough	-8,100,000	-1,300	-140,000	-23	-8,000,000	-1,300
Asthma Exacerbation, Shortness of Breath	-610,000	-96	-11,000	-1.7	-600,000	-94
Asthma Exacerbation, Wheeze	-970,000	-152	-18,000	-2.7	-960,000	-150
Chronic Bronchitis	-17,000	-2,600	-380	-58	-17,000	-2,600
Emergency Room Visits, Asthma	-17,000	-5.3	-590	-180	-17,000	-5.2
Hospital Admissions, All Cardiovascular	-10,000	-260	-170	-4.3	-10,000	-260
Hospital Admissions, All Respiratory	-8,100	-170	-100	-2.1	-8,000	-170
Hospital Admissions,	-5,500	-110	-100	-2.0	-5,400	-110

Congestive Heart Failure						
Hospital Admissions, Dysrhythmia	-1,500	-30	-30	-0.57	-1,500	-39
Hospital Admissions, Ischemic Heart Disease	-2,000	-66	-20	-0.75	-2,000	-65
Hospital Admissions, Pneumonia	-5,600	-100	-50	-0.87	-5,500	-100
Lower Respiratory Symptoms	-460,000	-7.1	-7,800	-0.12	-450,000	-7.0
Minor Restricted Activity Days	-18,000,000	-910	-410,000	-21	-18,000,000	-900
Upper Respiratory Symptoms	-670,000	-130	-12,000	-2.2	-660,000	-120
Work Loss Days	-3,100,000	-380	-70,000	-8.7	-3,000,000	-s380

Section 3: Temperature Health Impact Assessment

We estimate 31,000 instances of cardiovascular mortality and 25,000 non-accidental mortality cases in 2025 relative to 2005 using BenMap. These estimates are similar to those of $PM_{2.5}$ mortality in Scenario 1 (26,000), and are substantially higher than those of ozone respiratory mortality (2,400). Although our aim is to evaluate the influence of climate change on heat-related mortality, year-to-year climate variability may be responsible for a large portion of our estimated increase in mortality, due to our choice of especially cold (2002) and warm (2024) years.

Table 17. The nationwide temperature mortality between 2005 and 2025. Non-accidental mortality includes all mortality types excluding those caused by traumatic incidents.

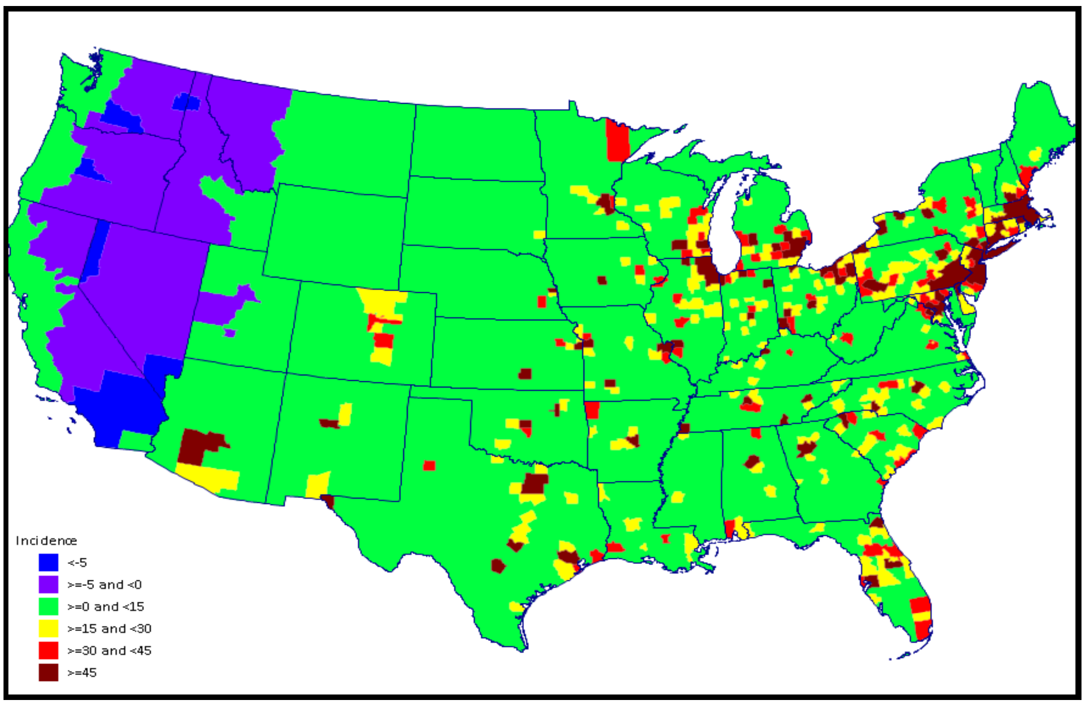
Temperature Mortality					
Endpoint	Start Age	End Age	Estimate	5th Percentile	95th Percentile
Cardiovascular	0	99	+31,000	+18,000	+44,000
Non-Accidental	0	99	+25,000	+6,000	+43,000

Geographical Distribution of Temperature Mortality

As seen in Figure 9, the mortality due to temperature change is projected to be highest in densely populated urban centers such as Chicago, IL; Detroit, MI; Dallas-Fort Worth, TX; Pittsburg, PA; Washington, D.C; Boston, MA; and New York City, NY. Several key factors may account for this phenomenon, including more vulnerable individuals living in cities and the large general population of urban centers.

Another pattern that emerges in Figure 9 is that temperature mortality is confined mostly to the Eastern United States. The Pacific Northwest, California, and much of the western United States have low temperature-related mortality, especially when compared to those of the Midwest or Northeast and New England. A map of non-accidental temperature mortality can be found in Appendix G.

Figure 9. Cardiovascular mortality due to temperature change at the county level. The majority of the increase in mortality is concentrated in highly populated urban areas, especially in the Midwest and Northeast.



Section 4: Temperature Economic Valuation

By using the economic valuation equations and standard mortality cost variables loaded in the BenMap program, we estimate the financial costs of temperature-related mortality in the United States. We estimate a $200 billion cost associated with the 31,000 excess cases of cardiovascular mortality annually and $160 billion due to the 25,000 cases of non-accidental mortality (Table 18.)

Our results demonstrate that the economic toll of temperature-related mortality is staggering, totaling hundreds of billions of dollars. High temperatures place strain on the economies of urban areas especially, as the heat island effect, vulnerable populations, and lack of air conditioning exacerbate hot summer temperatures. These findings suggest that the benefits of adaptation measures against rising temperatures may outweigh the costs.

Table 18. Annual Economic valuation of the temperature-caused mortality in the United States.

Temperature Economic Valuation		
Endpoint	Incidence	Valuation (billions of $)
Cardiovascular	+31,000	+200
Non-Accidental	+25,000	+160

Section 5: Total Economic Valuation

The future economic costs of ozone, fine particulate matter, and high temperature exposure number in the hundreds of billions of dollars. We estimate that these costs could amount to over $47 billion (Table 19) in the total change scenario. These increases in costs are due mainly to temperature mortality. Along with the underlying mortality and morbidity estimates, these economic values suggest that future changes in air pollution and high temperature may cause substantial damage to society.

All health endpoint groups (mortality, hospital admissions, emergency room visits, etc.) were accounted for in the total economic valuation. Various health endpoints were chosen as representatives of each endpoint, to avoid redundancy or double-counting. For example, the endpoints “All respiratory hospital admissions” and “All cardiovascular hospital admissions” were chosen to represent the totals of the different respiratory and cardiovascular hospital admissions, respectively.

The total ozone economic value was summed in similar fashion to the 2008 ozone RIA and includes the following endpoints: respiratory mortality, all respiratory hospital admissions, emergency room visits, restricted activity days, and lost days of school (EPA, 2008). The total economic valuation of $PM_{2.5}$ is based on the 2012 $PM_{2.5}$ RIA and includes the following endpoints: all-cause mortality, acute and chronic bronchitis, acute myocardial infarction, asthma exacerbation, emergency room visits, all respiratory and all cardiovascular hospital admissions, upper and lower respiratory symptoms, restricted activity days, and lost days of work (EPA, 2012). Cardiovascular mortality was chosen to represent the economic total for temperature.

Table 19. The economic value totals of the three air quality scenarios and one temperature scenario.

Total Economic Valuation			
Pollutant	Scenario 1	Scenario 2	Scenario 3
Ozone	-6.4	+4.5	-10.1
$PM_{2.5}$	-145.9	-2.2	-144.9
Temperature	200	200	NA
Total	**47.7**	**202.3**	**-155**

CHAPTER 4: DISCUSSION

Future Temperature and Air Quality

Our results suggest a trend of increasing temperatures in the continental United States between 2005 and 2025. These rising temperatures have the potential to cause thousands of deaths and cost billions of dollars.

Ozone and particulate matter levels are projected to decrease across North America over the course of the 21st century in the RCP4.5 scenario (West et al., 2013, Fiore et al., 2012). Our analysis of an ozone concentration scenario simulating both emissions and meteorology suggests that ozone concentrations will increase slightly throughout a large portion of the country, including the central part of the nation (Midwest, Great Plains), while falling significantly along the East Coast and in the Southwest. Simultaneously, $PM_{2.5}$ concentrations in this scenario demonstrate decreases in the Eastern and Central US, while increasing throughout the western part of the country. Fine particulate matter is also significantly less sensitive to changes in meteorology than is ozone, whereas both pollutants are heavily influenced by precursor emissions levels.

The health impacts of air pollution follow this geographical pattern, with the largest reductions in morbidity and mortality occurring in cities and coastal regions and increases in rural areas and the central part of the country. Climate change and climate variability both influence these trends in air quality and temperature, although it is unclear how influential each factor might be.

Magnitude of Change and Comparison with Previous Studies

The main objective of this study is to estimate the changes in mortality of air pollution and heat in the same modeling simulation. Our results show decreasing air pollution-related mortality; 26,000 fewer cases of mortality due to $PM_{2.5}$ and 2,400 fewer cases associated with ozone. We estimate heat-related mortality to increase by 31,000, leading to a net mortality increase of 2,600 associated with changes in these atmospheric phenomena in the combined emissions/climate scenario.

Previous studies have investigated air quality and temperature health impacts using BenMap, and have shown a range of results. Table 20 displays the findings of four related studies. Different assumptions and inputs were used in different studies, but comparisons between these studies and ours reveals a similar order of magnitude in changing mortality and morbidity rates.

Studies by Post et al., Tagaris et al., and Voorhees et a., investigated the health impacts of changes in either air quality or temperature between 2000 and 2050 and found a wide range of results (Table 20). The air quality-related mortality estimates from Tagaris et al., and Post et al., exhibit significant deviation from our estimates. Whereas our estimates of non-accidental temperature-related mortality coincide closely with those of Voorhees et al., our cardiovascular mortality estimates differ substantially from those of that study. The significant difference in results between our study and similar studies may be accounted for by the large difference in air quality and temperature modeling scenarios; our modeled scenario comprised a twenty year period whereas the related studies use a fifty year scenario comparison.

Table 20. Previous health impact studies of air pollution or temperature using BenMap.

Study	Pollutant(s)	Subject	Annual Results
Fann et al., 2011	Ozone, $PM_{2.5}$	2005 anthropogenic vs natural air quality	130,000 $PM_{2.5}$ deaths, 4,700 ozone deaths
Tagaris et al., 2009	Ozone, $PM_{2.5}$	Climate change and air quality, 2000-2050	4,000 $PM_{2.5}$-related mortality, ozone mortality of 300
Post et al., 2012	Ozone	Climate change 2000-2050, sensitivity analysis	Range of -600 to 2,500 deaths due to ozone
Voorhees et al., 2011	Temperature	Climate change 2000-2050	3,800 all-cause deaths, 3,500 cardiovascular deaths, and 24,000 non-accidental deaths

Uncertainties and Limitations

The air pollutant concentrations are calculated by computer models, which are subject to inherent assumptions by the modeler and limitations of computing power. Only two years are compared in this study, and thus year-to-year climate variability is not accounted for. Our results may be more heavily determined by climate variability rather than climate change. Additionally, the time period used in our comparison comprises only twenty years, whereas many air quality and temperature projections compare longer time periods, which may identify a larger signal of change.

We did not estimate particulate matter-related mortality for those under the age of thirty, due to the age cohort of the study from which the health impact function is derived (Krewski et al., 2009). For this reason, our results of mortality attributable to $PM_{2.5}$ may be significantly underestimated. Other health endpoints based on studies with limited age ranges may also have underestimated results.

Whereas BenMap includes baseline mortality data projections for the year 2025, baseline morbidity data in this study do not include projections for future years. Because population and baseline mortality projections for the year 2025 were used, projected changes in population and baseline incidence rates may exert significant influence on our results.

Modeled temperature data were taken from the WRF model, which BenMap was not designed to be used with. As with air pollutant concentrations, assumptions and uncertainties exist in modeling temperature levels. Health impact functions, beta coefficients and standard error values for temperature analysis had to be created in BenMap, along with the pollutant profile and metrics for temperature.

In estimating $PM_{2.5}$ changes, modeled $PM_{2.5}$ was used directly, and not processed through the Speciated Modeled Attainment Test (SMAT) (Frank, 2006) used by EPA. SMAT is a procedure that entails the combination of quarterly mean estimates of the six major components of $PM_{2.5}$ with a pollutant-specific relative reduction factor derived from model simulations, giving weighted concentrations for each component. These quarterly values are then averaged to produce annual mean concentrations of each component, which are summed to give annual concentrations of $PM_{2.5}$. The SMAT procedure allows for modeled PM data to be adjusted for observations before those data are used in other analyses. This process was not used in this study, as the modeled changes in $PM_{2.5}$ were used directly from the CMAQ model outputs. Our $PM_{2.5}$-related health impacts might have differed had the SMAT procedure been used.

CHAPTER 5: CONCLUSION

In this study, we analyze an air quality and temperature scenario in the continental United States for the year 2025 as compared to the baseline year of 2005. The Scenario 1-baseline comparison most closely reflects real-world conditions, as it includes simultaneous projections of emissions and meteorology.

Our ozone-related health impact results include the following: respiratory mortality estimated at -2,400 (90% CI -1,100 to -3,700) in Scenario 1 (2025 emissions and meteorology) relative to the baseline, +1,700 (90% +730 to +2,600) in the Scenario 2 (climate change only) comparison, and -3,900 (90% CI -2,900 to -4,900) in Scenario 3 (emissions only.) Other notable health impacts of ozone exposure include thousands of fewer hospital admissions and emergency room visits, and millions fewer lost days of school.

We estimate the change in all-cause mortality attributable to $PM_{2.5}$ at -26,000 (90% -19,000 to -32,000) in Scenario 1, -350 (90% CI -260 to -450) in the Scenario 2, and -25,000 (90% CI -18,000 to -32,000) in Scenario 3 as compared to the baseline. In Scenario 1, $PM_{2.5}$ is estimated to cause many thousands fewer hospital admissions, emergency room visits, and cases of bronchitis, as well as millions fewer restricted activity days and lost days of work. In the temperature health impact assessment, we estimate cardiovascular mortality to be +31,000 (90% CI +18,000 to +44,000). It is noteworthy that heat-related mortality increases significantly while mortality and morbidity due to air pollution decrease substantially in the combined climate/emissions simulation.

Our economic valuation of health impacts due to ozone, $PM_{2.5}$, and temperature include billions of dollars annually in mortality-related costs, with the escalation in costs attributable heat-related mortality. We also show reductions of hundreds of millions of dollars associated with air pollution-related morbidity, with the exception of Scenario 2. The total economic cost of air pollution and temperature health impacts may be as high as 47 billion dollars when both emissions and meteorology are considered.

These results demonstrate the importance of emissions mitigation and climate change adaptation measures, especially in sensitive areas. Mitigation of ozone and particulate matter precursors substantially reduce morbidity and mortality levels, and the mitigation of greenhouse gas emissions contribute to improved human health by limiting dangerous increases in temperature and air pollutant concentrations, specifically ozone. Adaptation measures are also supported by our findings, including enhanced public health monitoring and services, reductions in the urban heat island effect, and expanded access to air conditioning and cooling centers.

A wide range of human health impacts may be limited through air pollution mitigation and climate change adaptation. The potential benefits to human and economic health in the United States achieved by controlling emissions and limiting global warming will be substantial and long-lasting.

Future Work

In the future, this project can be built upon by addressing the issue of climate variability. Climate variability can be controlled for in two ways. First, selecting a longer scenario time period, such as 2000 to 2050, allows for a larger influence of changing climate, a phenomenon that arises over long periods of time, and of changing emissions. Second, comparing multi-year averages instead of single years accounts for the variability between years.

Further work is needed to investigate the interaction of air pollutants and temperature on human health. Additional health endpoints, such as ozone-related COPD and respiratory infections, should also be investigated to gain a more comprehensive view of the health impacts of air pollution. Temperature-related morbidity can also benefit from further study by using the methodology used for temperature-related mortality in this research.

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APPENDIX A: OZONE HEALTH IMPACT FUNCTIONS SPECIFICATIONS

Endpoint	Start Age	End Age	Beta	Reference
Emergency Room Visits, Asthma	0	99	-0.001	Wilson, A.M., C.P. Wake, T. Kelly et al. 2005. Air pollution and weather, and respiratory emergency room visits in two northern New England cities: an ecological time-series study. Environ Res. Vol. 97 (3): 312-21.
HA, All Respiratory	0	1	0.008177	Burnett, R.T., et al. Association between ozone and hospitalization for acute respiratory diseases in children less than 2 years of age. Am J Epidemiol, 2001. 153(5): p. 444-52.
HA, Chronic Lung Disease	65	99	0.00196	Moolgavkar, S.H., E.G. Luebeck, and E.L. Anderson. Air pollution and hospital admissions for respiratory causes in Minneapolis St. Paul and Birmingham. Epidemiology, 1997. 8(4): p. 364-370.
HA, Chronic Lung Disease (less Asthma)	65	99	0.003424	Schwartz, J. Air Pollution and Hospital Admissions For the Elderly in Detroit, Michigan. American Journal of Respiratory and Critical Care Medicine, 1994 150(3): p. 648-655.
HA, Pneumonia	65	99	0.002784	Schwartz, J. PM(10) Ozone, and Hospital Admissions For the Elderly in Minneapolis St Paul, Minnesota. Archives of Environmental Health, 1994. 49(5): p. 366-374.
Minor Restricted Activity Days	18	64	0.002596	Ostro, B.D. and S. Rothschild. Air Pollution and Acute Respiratory Morbidity – an Observational Study of Multiple Pollutants. Environ Res, 1989. 50(2): p. 238-247.
Mortality, All Cause	0	99	0.001121	Levy, J.I., S.M. Chemerynski, and J.A. Sarnat. Ozone exposure and mortality: an empiric bayes metaregression analysis. Epidemiology, 2005. 16(4): p. 458-68.
Mortality, Cardiopulmonary	0	99	0.000813	Huang, Y., F. Dominici and M. L. Bell. 2005. Bayesian hierarchical distributed lag models for summer ozone exposure and cardio-respiratory mortality. Environmetrics. Vol. 16: 547–562.
Mortality, Non-Accidental	0	99	0.000261	Bell, M.L., et al. Ozone and short-term mortality in 95 US urban communities, 1987-2000. JAMA, 2004. 292(19): p. 2372-8.
Mortality, Respiratory	30	99	0.004471	Jerrett, Michael, Burnett, Richard T, Pope, Arden C, et al. 2009. Long-Term Ozone Exposure and Mortality. New England Journal of Medicine.
School Loss Days, All Cause	5	17	0.007824	Gilliland, F.D., K. Berhane, E.B. Rappaport, D.C. Thomas, E. Avol, W.J. Gauderman, S.J. London, H.G. Margolis, R. McConnell, K.T. Islam and J.M. Peters. 2001. The effects of ambient air pollution on school absenteeism due to respiratory illnesses. Epidemiology, 12(1), 43-54.

APPENDIX B: $PM_{2.5}$ HEALTH IMPACT FUNCTIONS SPECIFICATIONS

Endpoint	Start Age	End Age	Beta	Reference
Acute Bronchitis	8	12	0.027212	Dockery, D.W., J. Cunningham, A.I. Damokosh, L.M. Neas, J.D. Spengler, P. Koutrakis, J.H. Ware, M. Raizenne and F.E. Speizer. 1996. Health Effects of Acid Aerosols On North American Children - Respiratory Symptoms. Environmental Health Perspectives. Vol.
Acute Myocardial Infarction, Nonfatal	0	99	0.00225	Zanobetti, A., M. Franklin and J. Schwartz. 2009. Fine particulate air pollution and its components in association with cause-specific emergency admissions. Environmental Health Vol. 8: 58-60.
Asthma Exacerbation, Cough	18	64	0.00741	Ostro, B.D. and S. Rothschild. Air Pollution and Acute Respiratory Morbidity - an Observational Study of Multiple Pollutants. Environ Res, 1989. 50(2): p. 238-247.
Asthma Exacerbation, Shortness of Breath	6	18	0.019062	Mar, T. F., T. V. Larson, R. A. Stier, C. Claiborn and J. Q. Koenig. 2004. An analysis of the association between respiratory symptoms in subjects with asthma and daily air pollution in Spokane, Washington. Inhal Toxicol. Vol. 16 (13): 809-15.
Asthma Exacerbation, Wheeze	6	18	0.002565	Ostro, B., M. Lipsett, J. Mann, H. Braxton-Owens and M. White. 2001. Air pollution and exacerbation of asthma in African-American children in Los Angeles. Epidemiology. Vol. 12 (2): 200-8.
Chronic Bronchitis	6	18	0.001942	Ostro, B., M. Lipsett, J. Mann, H. Braxton-Owens and M. White. 2001. Air pollution and exacerbation of asthma in African-American children in Los Angeles. Epidemiology. Vol. 12 (2): 200-8.
Emergency Room Visits, Asthma	27	99	0.0137	Abbey, D.E., B.E. Ostro, F. Petersen and R.J. Burchette. 1995. Chronic Respiratory Symptoms Associated with Estimated Long-Term Ambient Concentrations of Fine Particulates Less Than 2.5 Microns in Aerodynamic Diameter ($PM_{2.5}$) and Other Air Pollutants. J E
Hospital Admissions, All Cardiovascular (less Myocardial Infarctions)	0	99	0.005603	Mar, T. F., J. Q. Koenig and J. Primomo. 2010. Associations between asthma emergency visits and particulate matter sources, including diesel emissions from stationary generators in Tacoma, Washington. Inhal Toxicol. Vol. 22 (6): 445-8.
Hospital Admissions, All Respiratory	65	99	0.00189	Zanobetti, A., M. Franklin and J. Schwartz. 2009. Fine particulate air pollution and its components in association with cause-specific emergency admissions. Environmental Health Vol. 8: 58-60.
Hospital Admissions, Congestive Heart Failure	65	99	0.00207	Zanobetti, A., M. Franklin and J. Schwartz. 2009. Fine particulate air pollution and its components in association with cause-specific emergency admissions. Environmental Health Vol. 8: 58-60.
Hospital Admissions, Dysrhythmia	0	17	0.002	Babin, S. M., H. S. Burkom, et al. 2007. Pediatric patient asthma-related emergency department visits and admissions in Washington, DC, from 2001–2004, and associations with air quality, socio-economic status and age group. Environ Health 6: 9.

Hospital Admissions, Ischemic Heart Disease (less Myocardial Infarctions)	65	99	0.00185	Moolgavkar, S.H. Air Pollution and Daily Deaths and Hospital Admissions in Los Angeles and Cook Counties. In: Revised Analyses of Time-Series Studies of Air Pollution and Health. 2003, Health Effects Institute: Boston, MA. p. 183-198.
Hospital Admissions, Pneumonia	18	64	0.0022	Moolgavkar, S.H. Air Pollution and Hospital Admissions for Chronic Obstructive Pulmonary Disease in Three Metropolitan Areas in the United States. Inhalation Toxicology, 2000. 12(Supplement 4): p. 75-90.
Lower Respiratory Symptoms	65	99	0.003979	Ito, K. Associations of Particulate Matter Components with Daily Mortality and Morbidity in Detroit, Michigan. In: Revised Analyses of Time-Series Studies of Air Pollution and Health. 2003, Health Effects Institute: Boston, MA. p. 143-156.
Minor Restricted Activity Days	7	14	0.019012	Schwartz, J. and L.M. Neas. 2000. Fine particles are more strongly associated than coarse particles with acute respiratory health effects in schoolchildren. Epidemiology. Vol. 11 (1): 6-10.
Mortality, All Cause	30	99	0.005827	Krewski D, Jerrett M, Burnett R, et al. 2009. Extended Follow-Up and Spatial analysis of the American Cancer Society Linking Particulate Air Pollution and Mortality. Health Effects Institute, Cambridge MA
Mortality, Ischemic Heart Disease	30	99	0.021511	Krewski D, Jerrett M, Burnett R, et al. 2009. Extended Follow-Up and Spatial analysis of the American Cancer Society Linking Particulate Air Pollution and Mortality. Health Effects Institute, Cambridge MA
Mortality, Lung Cancer	30	99	0.013103	Krewski D, Jerrett M, Burnett R, et al. 2009. Extended Follow-Up and Spatial analysis of the American Cancer Society Linking Particulate Air Pollution and Mortality. Health Effects Institute, Cambridge MA
Upper Respiratory Symptoms	9	11	0.0036	Pope, C.A., et al. Respiratory Health and Pm10 Pollution - a Daily Time Series Analysis. American Review of Respiratory Disease, 1991. 144(3): p. 668-674.
Work Loss Days	18	64	0.0046	Ostro, B.D. Air Pollution and Morbidity Revisited: A Specification Test. Journal of Environmental Economics and Management, 1987. 14: p. 87-98.

APPENDIX C: TEMPERATURE HEALTH IMPACT FUNCTION SPECIFICATIONS

Temperature Health Impact Functions				
Endpoint	Start Age	End Age	Beta	Reference
Cardiovascular Mortality	0	99	0.0046248	Basu, R.; Ostro, B. A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. Am. J. Epidemiol. 2008, 168 (6), 632 – 637.
Non-Accidental Mortality	0	99	0.003921	Basu, R.; Ostro, B. A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. Am. J. Epidemiol. 2008, 168 (6), 632 – 637.

APPENDIX D: AIR QUALITY AND TEMPERATURE DELTA VALUE MAPS
Ozone

Figure 4. The ozone concentration (ppb) delta values in Scenario 1 compared to the baseline.

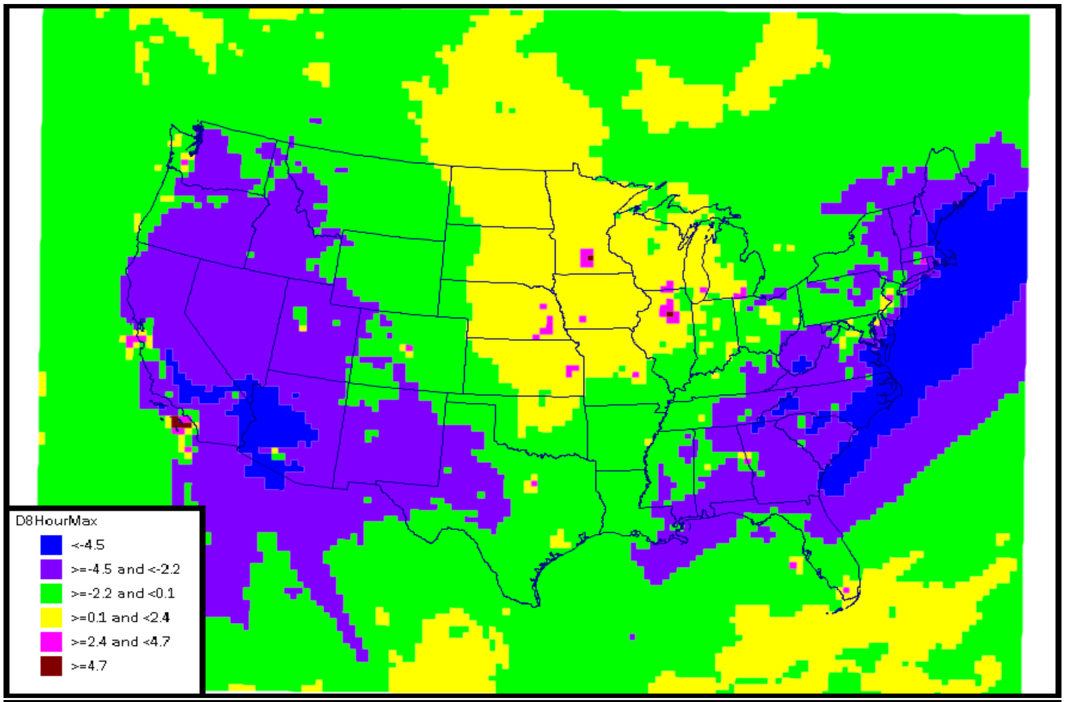


Figure 5. The ozone concentration (ppb) delta values in the comparison of Scenario 2 against the baseline.

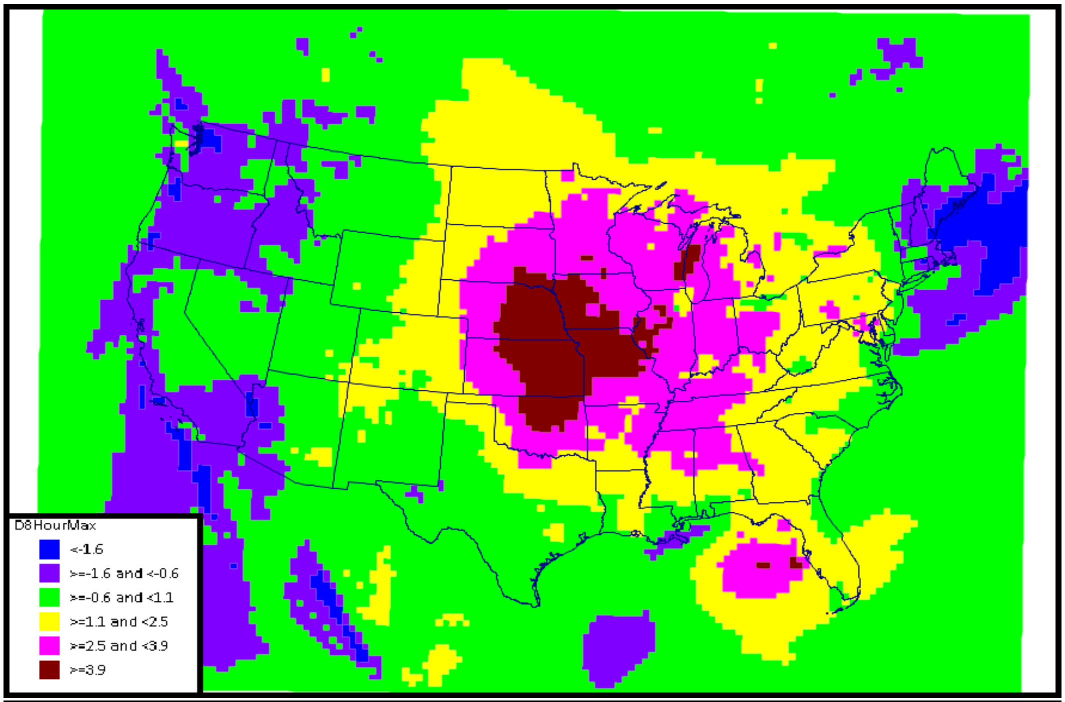
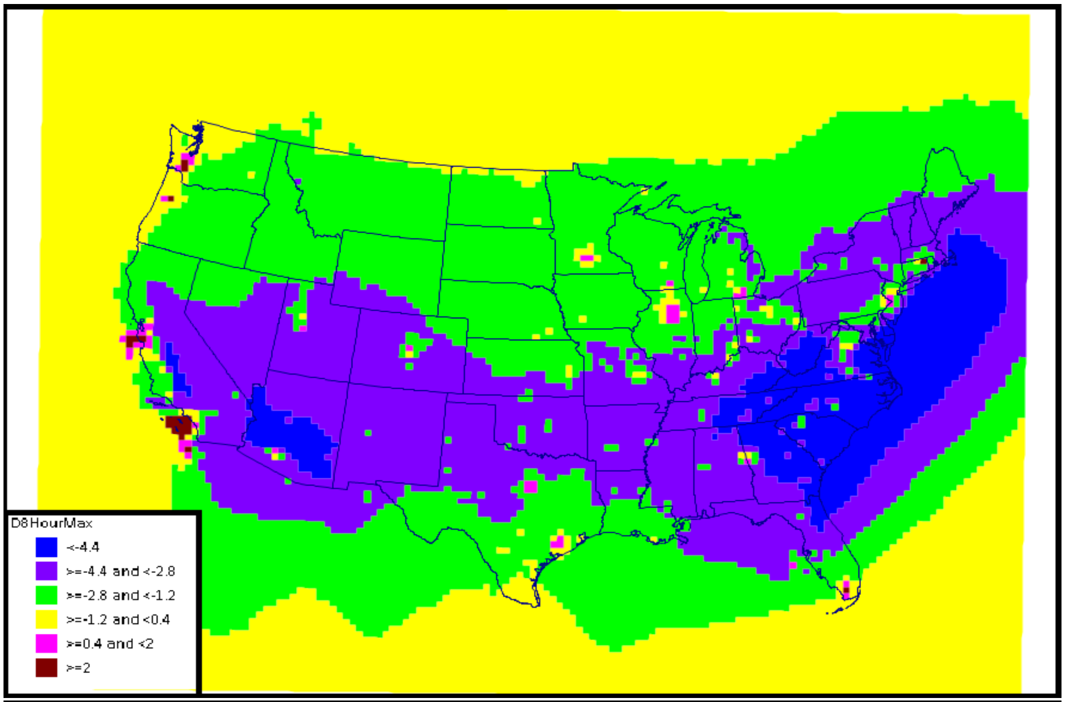


Figure 6. The ozone concentration (ppb) delta values in Scenario 3 as compared to the baseline.



Particulate Matter

Figure 7. The $PM_{2.5}$ concentration (µg/m^3) delta values in the comparison of Scenario 1 to the baseline.

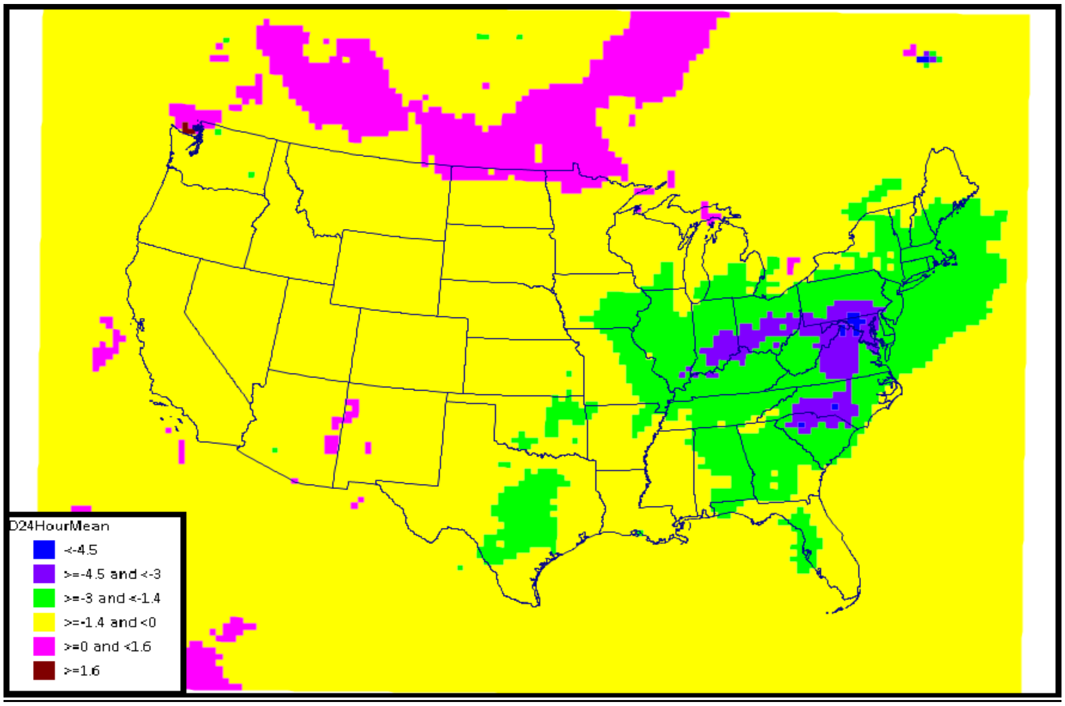


Figure 8. The $PM_{2.5}$ concentration (µg/m^3) delta values in Scenario 2 relative to the baseline.

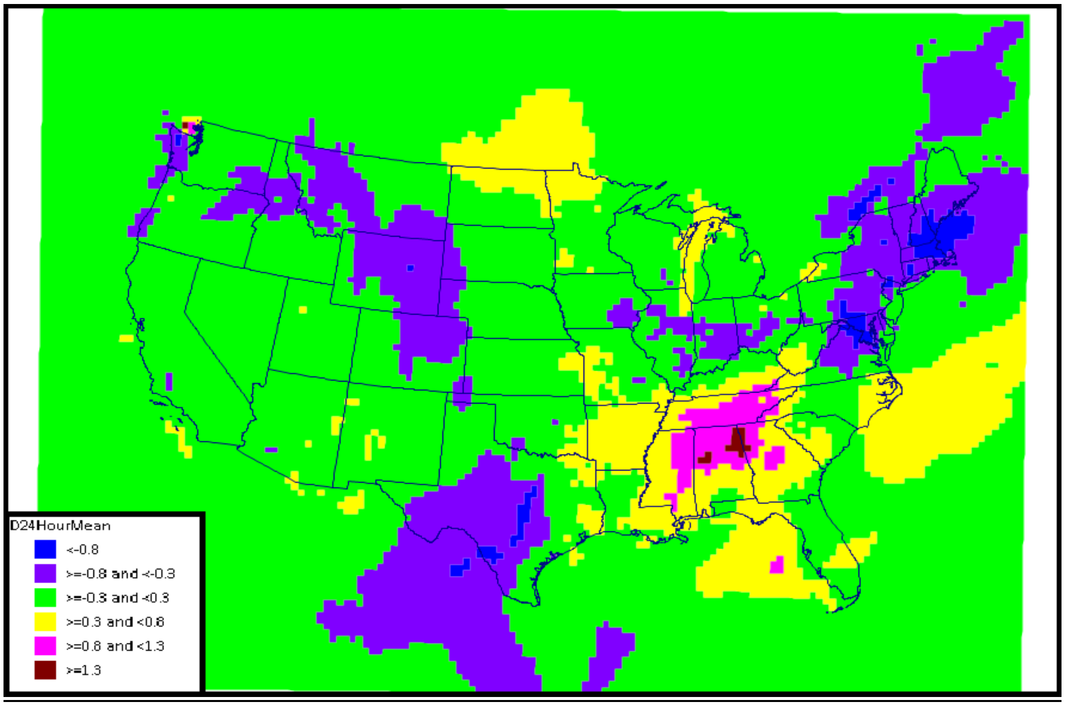
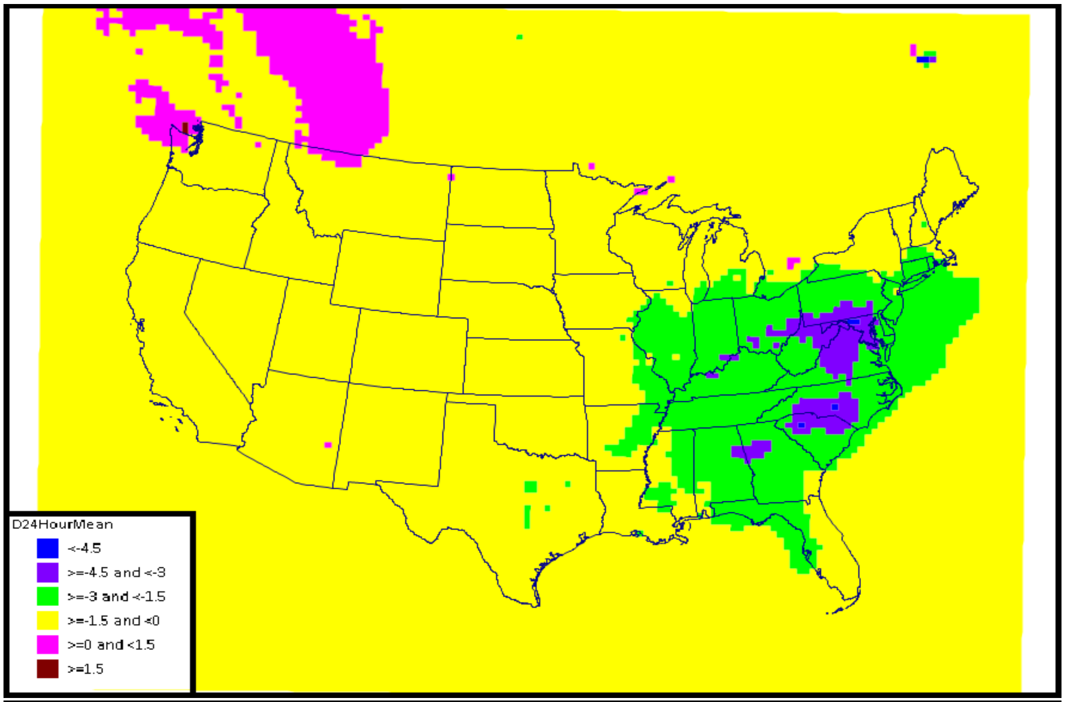
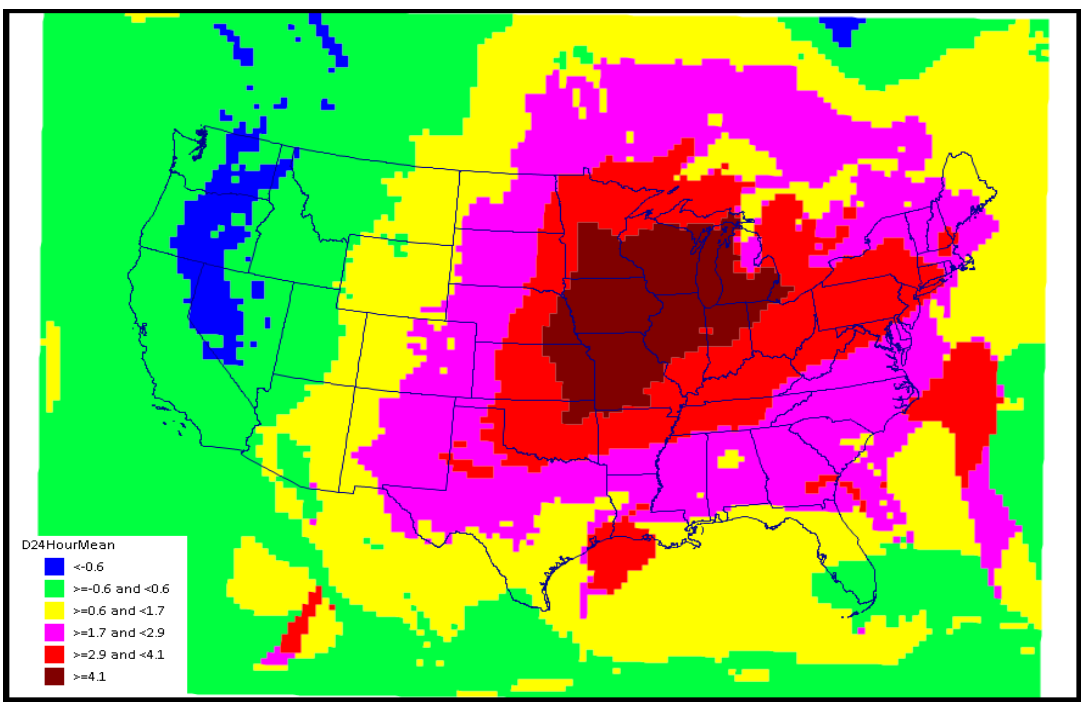


Figure 9. The PM2.5 concentration (µg/m³) delta values in Scenario 3 as compared to the baseline.



Temperature

Figure 10. The apparent temperature level delta values in degrees Kelvin, 2005-2025.



APPENDIX E: OZONE HEALTH IMPACT ASSESSMENT MAPS

Figure 11. The change in county-level rates of emergency room visits attributable to ozone exposure in Scenario 1. Positive values designate decreasing morbidity.

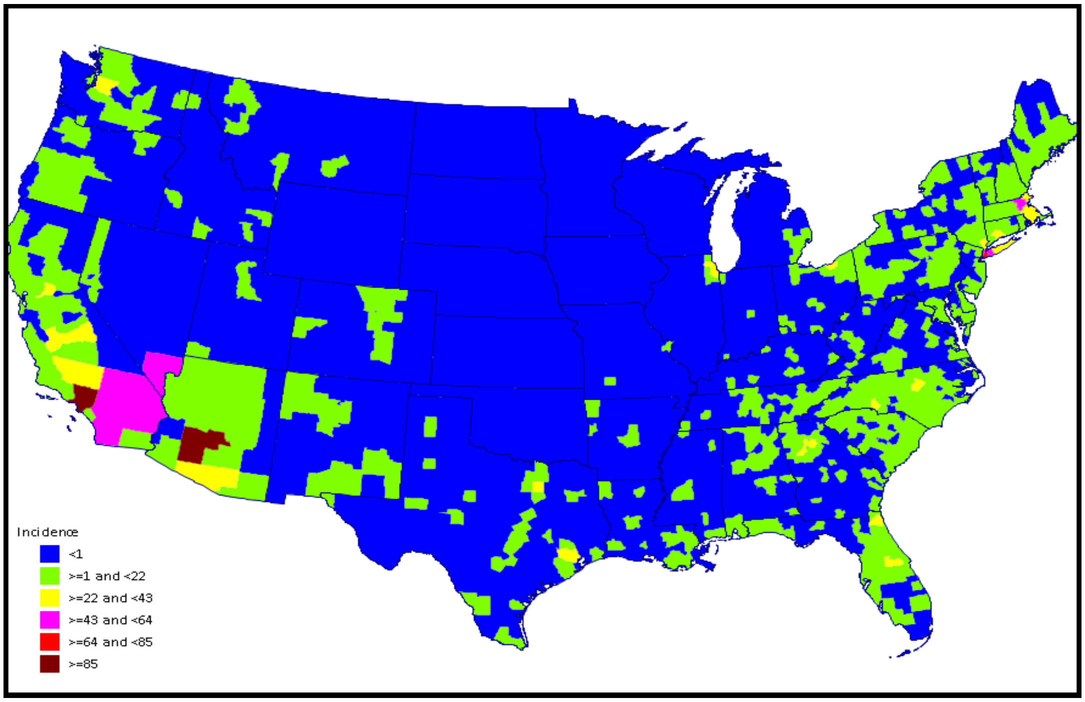


Figure 12. The change in the rate of lost days of school associated with ozone exposure in Scenario 1.

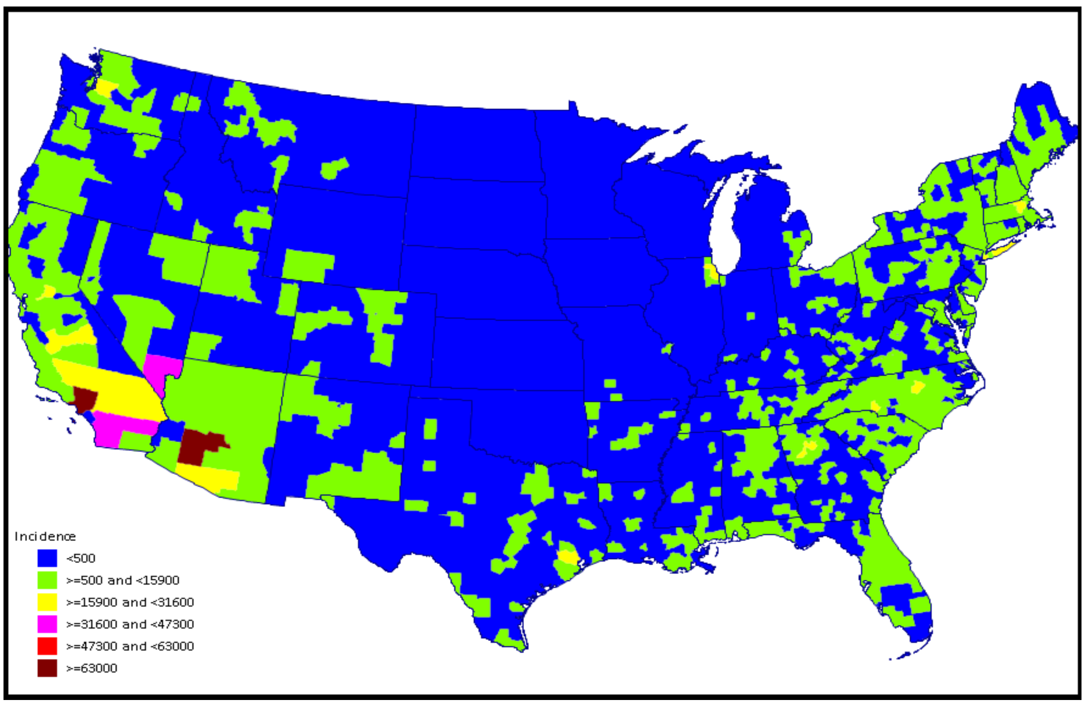


Figure 13. Emergency room visit rate changes from ozone exposure in Scenario 2.

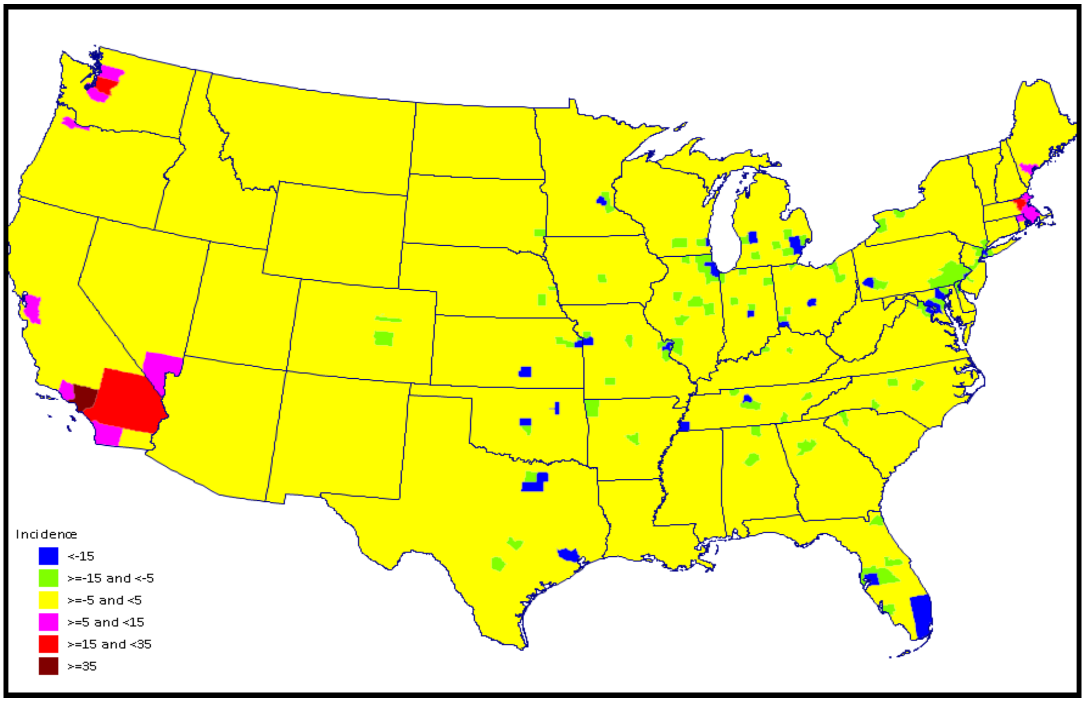


Figure 14. Changes in the rate of lost days of school due to ozone exposure in Scenario 2.

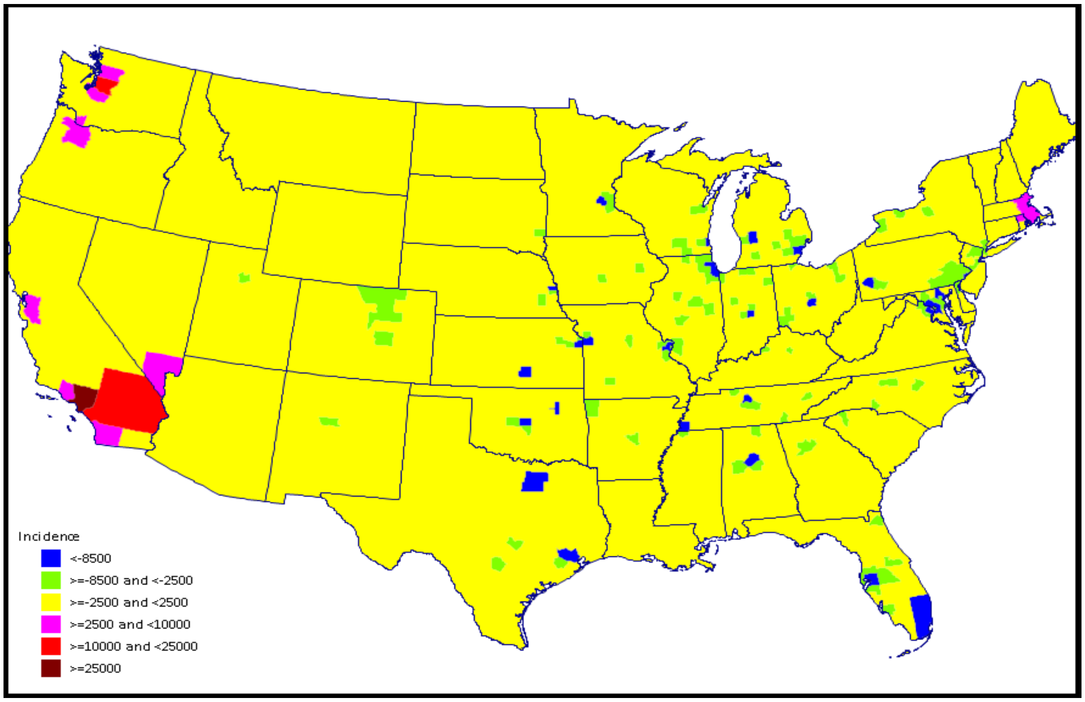


Figure 15 displays the change in ozone-caused emergency room visits in Scenario 3.

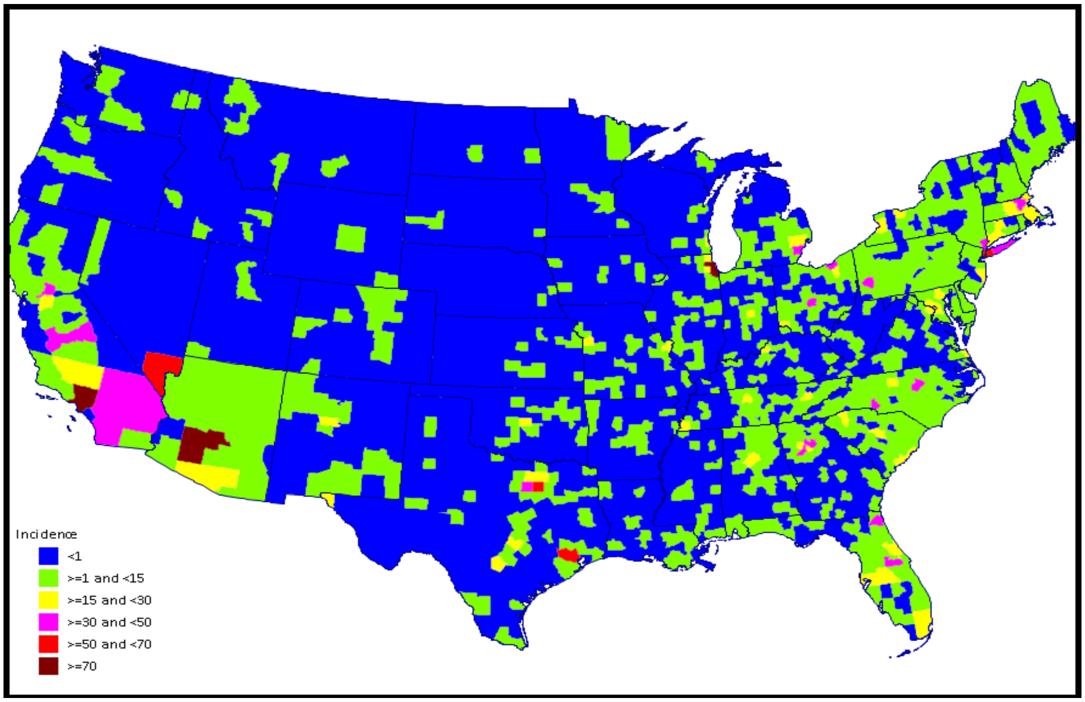
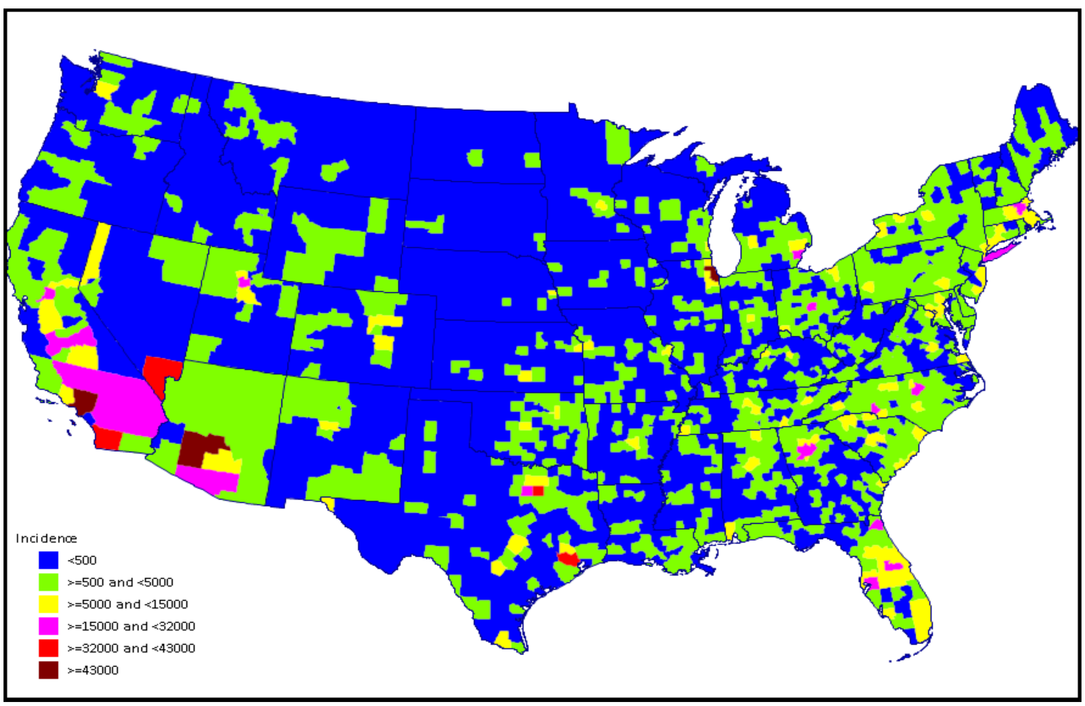


Figure 16. Changes in the rate of lost days of school associated with ozone in Scenario 3.



APPENDIX F: $PM_{2.5}$ HEALTH IMPACT ASSESSMENT MAPS

Figure 17. The change in all respiratory hospital admissions rates at the county level from $PM_{2.5}$ in Scenario 1.

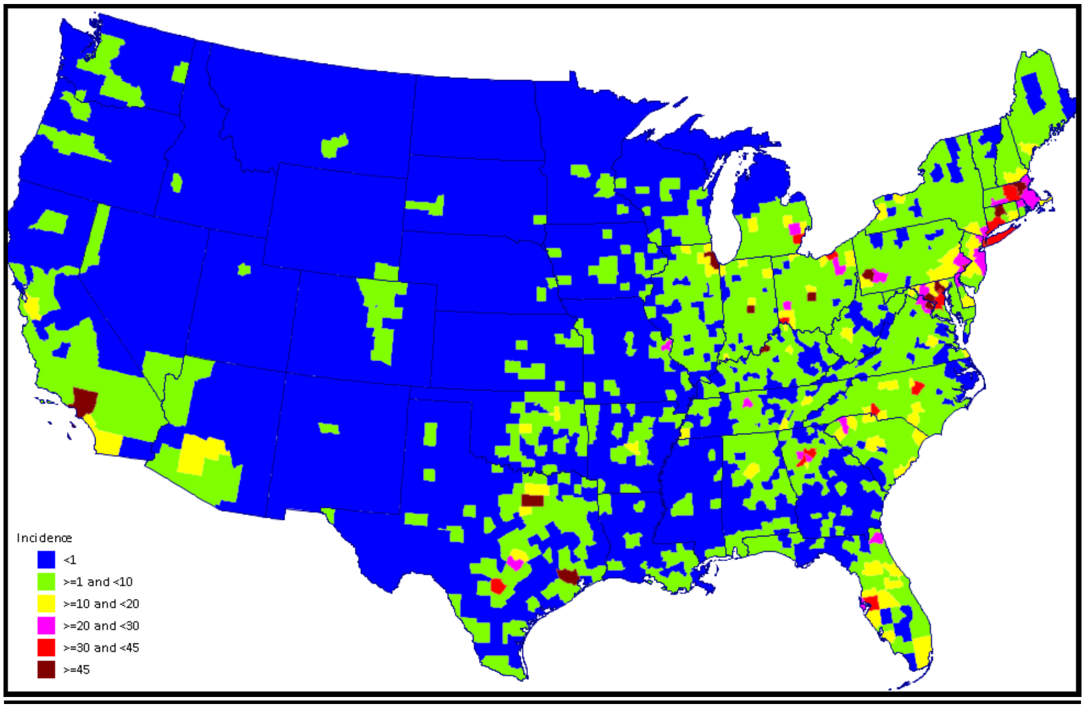


Figure 18. This map shows the change in lost days of work linked to $PM_{2.5}$ exposure in Scenario 1 at the county-level.

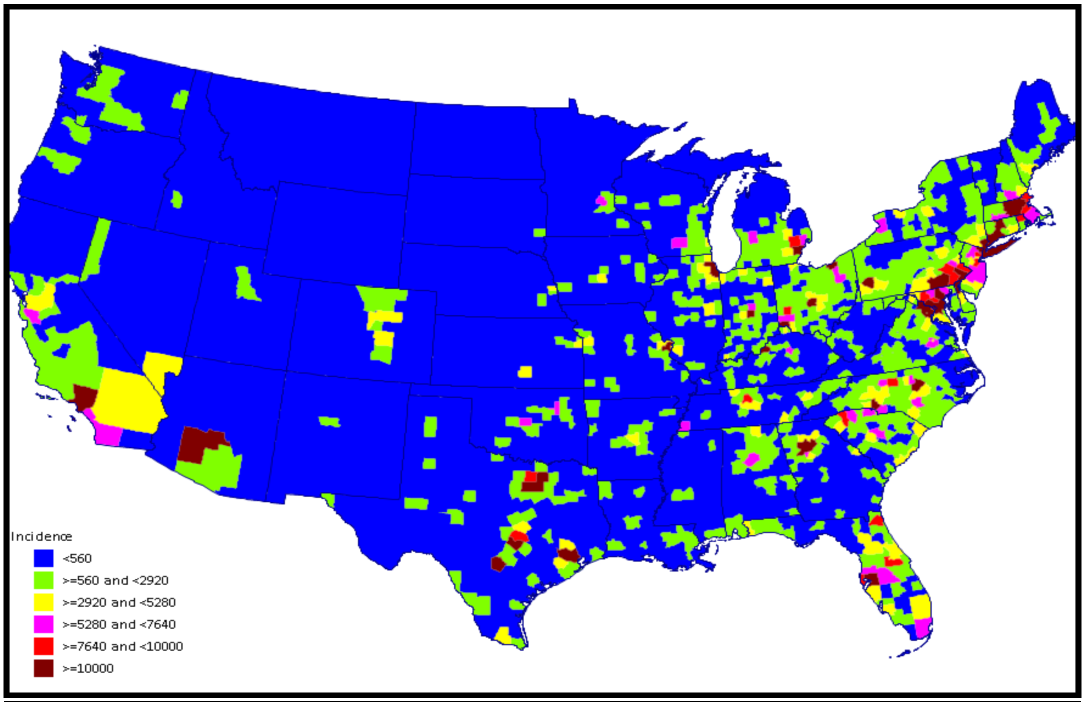


Figure 19. The change in all respiratory hospital admissions due to fine particulate matter exposure in Scenario 2.

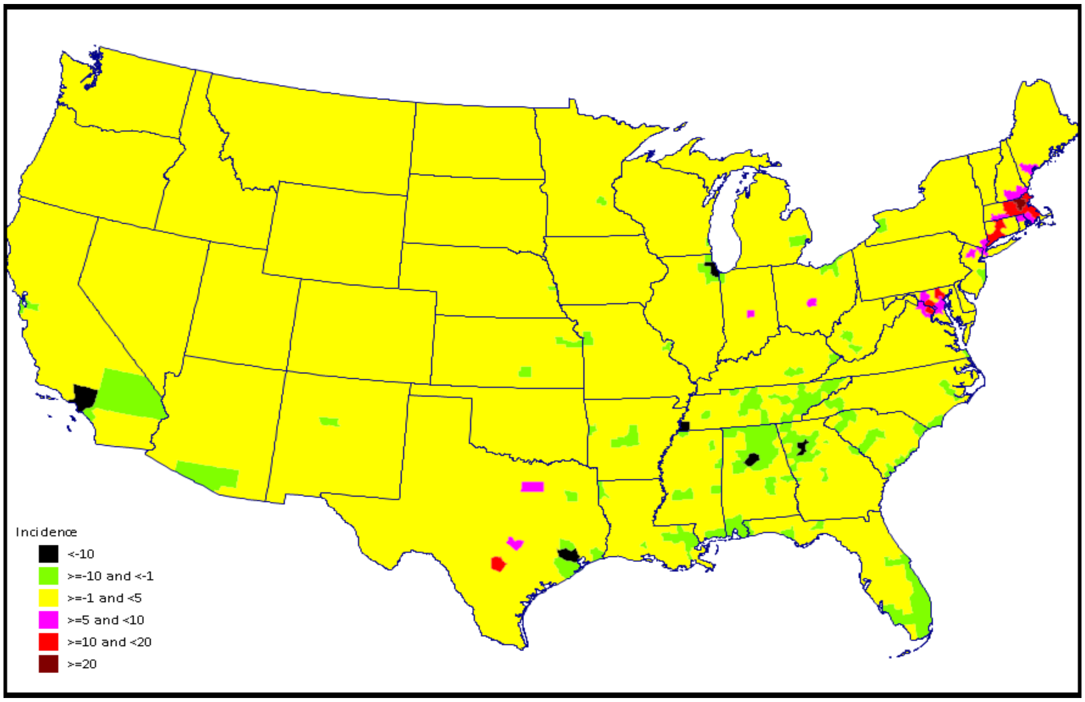


Figure 20. The change in lost days of work in Scenario 2.

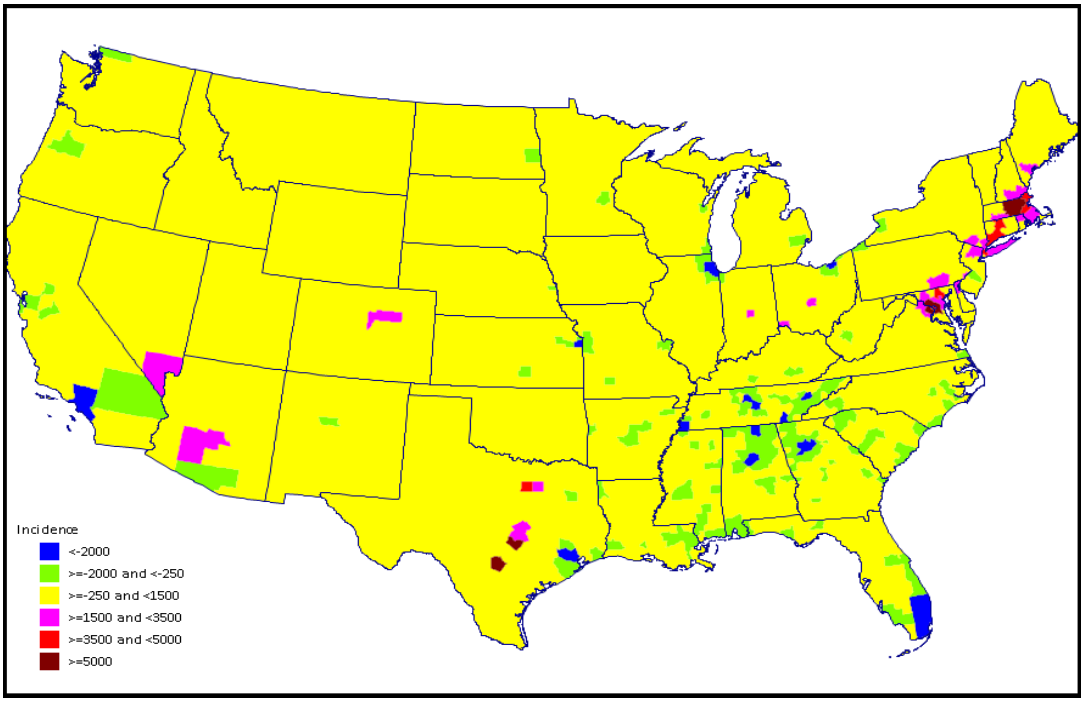


Figure 21. Change in all respiratory hospital admissions associated with fine particulate matter in Scenario 3.

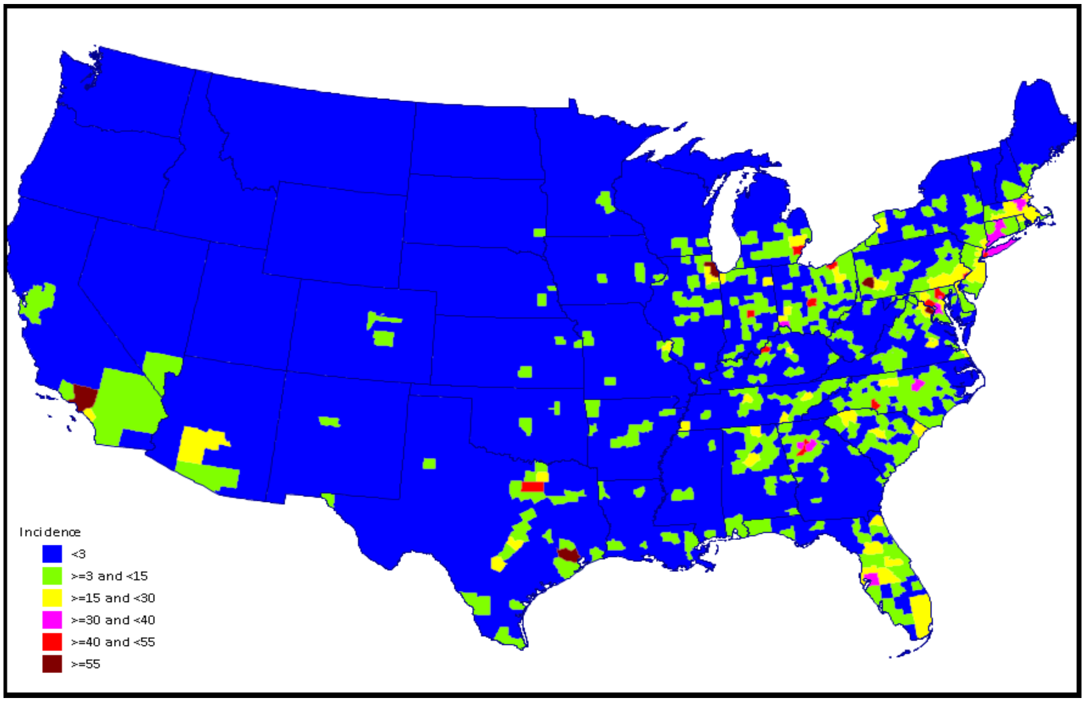
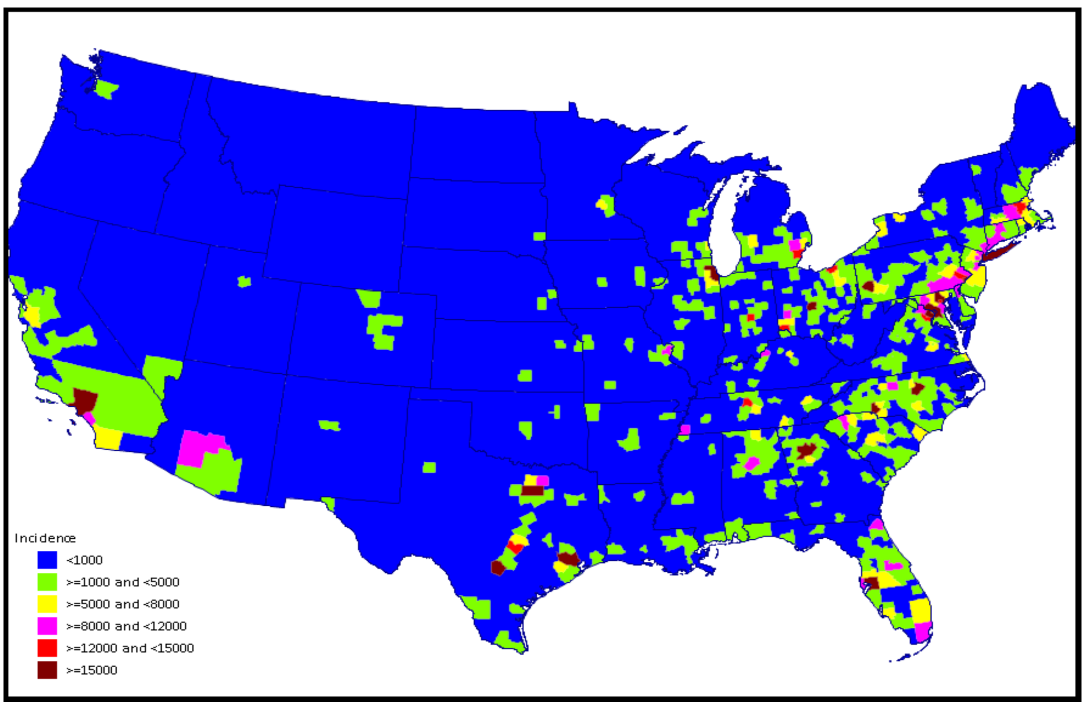
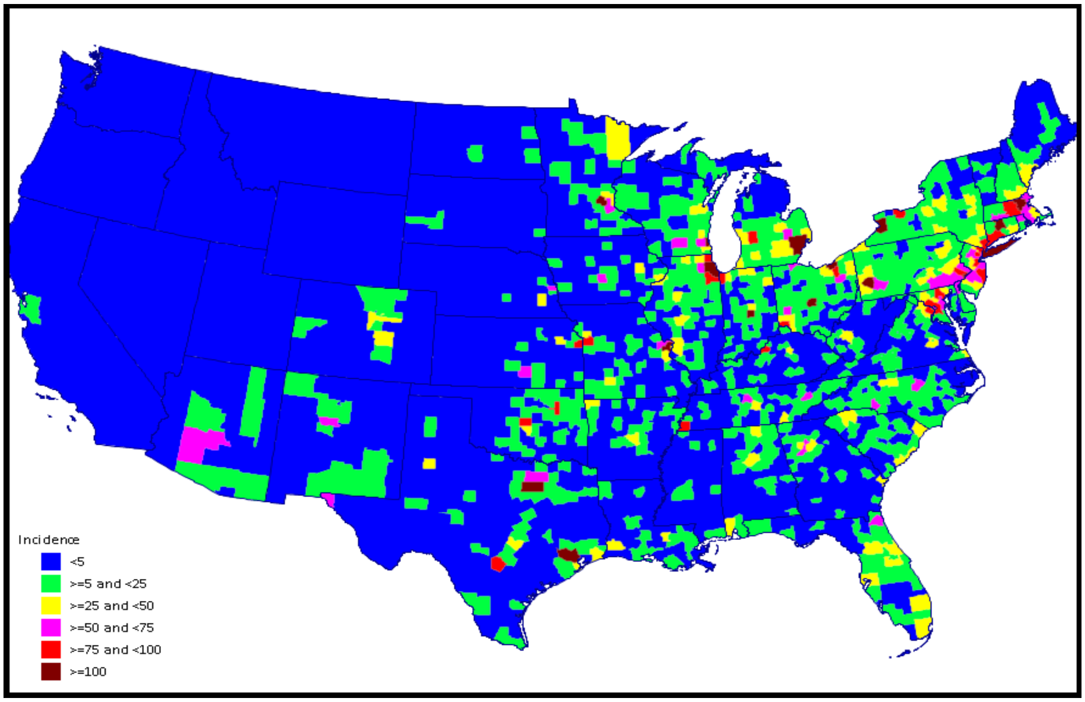


Figure 22. The change in $PM_{2.5}$-related lost days of work from Scenario 3.



APPENDIX G: TEMPERATURE HEALTH IMPACT ASSESSMENT MAPS

Figure 23. The trend of county-level heat-related non-accidental mortality in 2025 compared to 2005.



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