3 AIR QUALITY IMPACTS

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3 AIR QUALITY IMPACTS

Key Findings

Exacerbated Ozone Health Impacts

Key Finding 1: Climate change will make it harder for any given regulatory approach to reduce ground-level ozone pollution in the future as meteorological conditions become increasingly conducive to forming ozone over most of the United States *[Likely, High Confidence]*. Unless offset by additional emissions reductions of ozone precursors, these climate-driven increases in ozone will cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms *[Likely, High Confidence]*.

Increased Health Impacts from Wildfires

Key Finding 2: Wildfires emit fine particles and ozone precursors that in turn increase the risk of premature death and adverse chronic and acute cardiovascular and respiratory health outcomes *[Likely, High Confidence]*. Climate change is projected to increase the number and severity of naturally occurring wildfires in parts of the United States, increasing emissions of particulate matter and ozone precursors and resulting in additional adverse health outcomes *[Likely, High Confidence]*.

Worsened Allergy and Asthma Conditions

Key Finding 3: Changes in climate, specifically rising temperatures, altered precipitation patterns, and increasing concentrations of atmospheric carbon dioxide, are expected to contribute to increases in the levels of some airborne allergens and associated increases in asthma episodes and other allergic illnesses *[High Confidence]*.

3.1 Introduction

Changes in the climate affect the air we breathe, both indoors and outdoors. Taken together, changes in the climate affect air quality through three pathways—via outdoor air pollution, aeroallergens, and indoor air pollution. The changing climate has modified weather patterns, which in turn have influenced the levels and location of outdoor air pollutants such as ground-level ozone (O_3) and fine particulate matter.[1, 2, 3, 4] Increasing carbon dioxide (CO_2) levels also promote the growth of plants that release airborne allergens (aeroallergens). Finally, these changes to outdoor air quality and aeroallergens also affect indoor air quality as both pollutants and aeroallergens infiltrate homes, schools, and other buildings.

Climate change influences outdoor air pollutant concentrations in many ways (Figure 1). The climate influences temperatures, cloudiness, humidity, the frequency and intensity of precipitation, and wind patterns,[5] each of which can influence air quality. At the same time, climate-driven changes in meteorology can also lead to changes in naturally occurring emissions that influence air quality (for example, wildfires, wind-blown dust, and emissions from vegetation). Over longer time scales, human responses to climate change may also affect the amount of energy that humans use, as well as how land is used and where people live. These changes would in turn modify emissions (depending on the fuel source) and thus further influence air quality.[6, 7] Some air pollutants such as ozone, sulfates, and black carbon also cause changes in

Climate Change and Health—Outdoor Air Quality

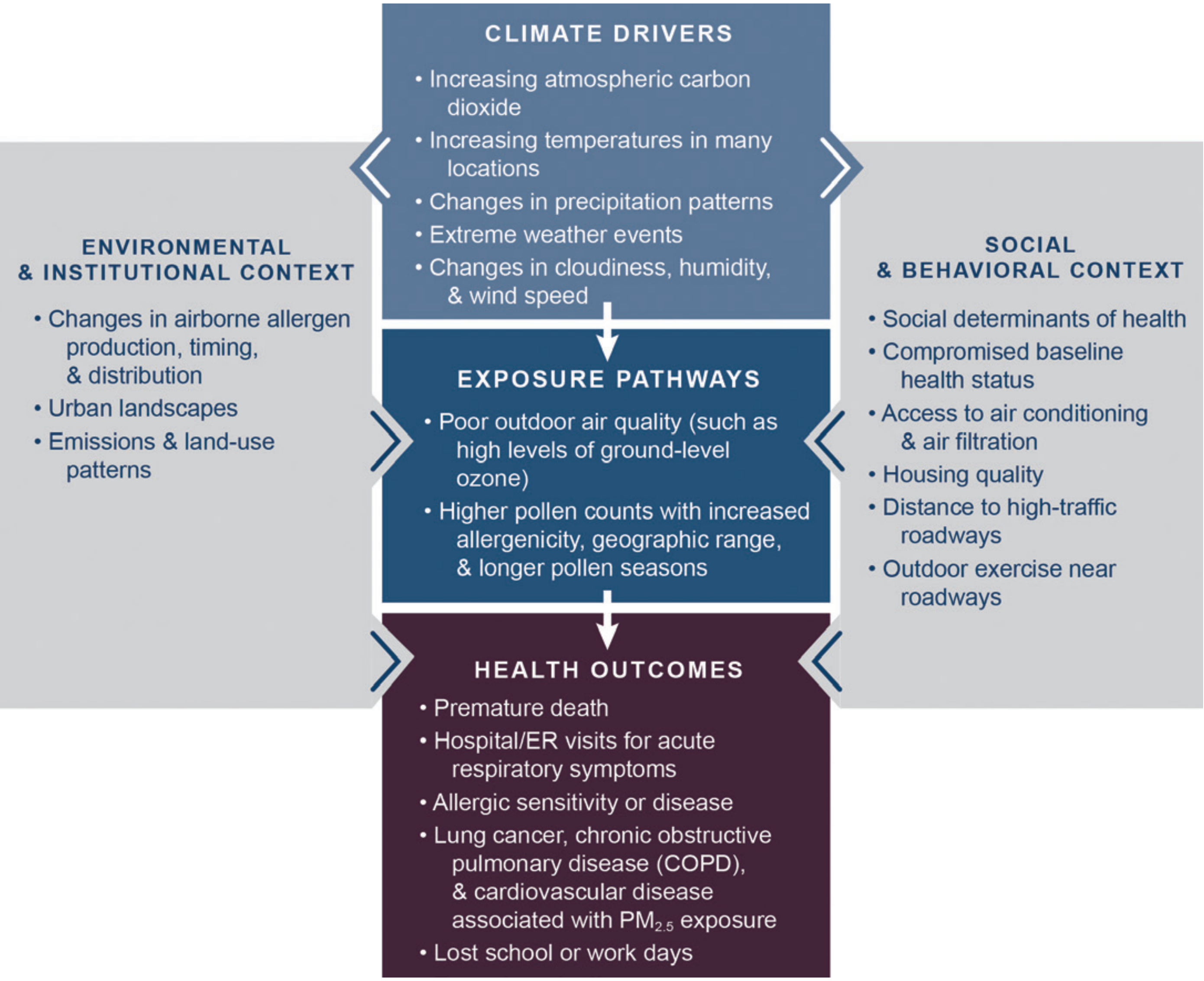


Figure 1: This conceptual diagram for an outdoor air quality example illustrates the key pathways by which humans are exposed to health threats from climate drivers, and potential resulting health outcomes (center boxes). These exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box, and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. All of these influencing factors can affect an individual's or a community's vulnerability through changes in exposure, sensitivity, and adaptive capacity and may also be affected by climate change. See Chapter 1: Introduction for more information.

climate.[8] However, this chapter does not consider the climate effects of air pollutants, remaining focused on the health effects resulting from climate-related changes in air pollution exposure.

Poor air quality, whether outdoors or indoors, can negatively affect the human respiratory and cardiovascular systems. Outdoor ground-level ozone and particle pollution can have a range of adverse effects on human health. Current levels of ground-level ozone have been estimated to be responsible for tens of thousands of hospital and emergency room visits, millions of cases of acute respiratory symptoms and school absences, and thousands of premature deaths each year in the United States.[9, 10] Fine particle pollution has also been linked to even greater health consequences through harmful cardiovascular and respiratory effects.[11]

Human-caused climate change has the potential to increase ozone levels, may have already increased ozone pollution in some regions of the United States, and has the potential to affect future concentrations of ozone and fine particles.

A changing climate can also influence the level of aeroallergens such as pollen, which in turn adversely affect human health. Rising levels of CO_2 and resulting climate changes alter the production, allergenicity (a measure of how much particular allergens, such as ragweed, affect people), distribution, and seasonal timing of aeroallergens. These changes increase the severity and prevalence of allergic diseases in humans. Higher pollen concentrations and longer pollen seasons can increase allergic sensitization and asthma episodes and thereby limit productivity at work and school.

Finally, climate change may alter the indoor concentrations of pollutants generated outdoors (such as ground-level ozone), particulate matter, and aeroallergens (such as pollen). Changes in the climate may also increase pollutants generated indoors, such as mold and volatile organic compounds. Most of the air people breathe over their lifetimes will be indoors, since people spend the vast majority of their time in indoor environments. Thus, alterations in indoor air pollutant concentrations from climate change have important health implications.

Higher pollen concentrations and longer pollen seasons can increase allergic sensitization and asthma episodes.

3.2 Climate Impacts on Outdoor Air Pollutants and Health

Changes in the climate affect air pollution levels.[8, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22] Human-caused climate change has the potential to increase ozone levels,[1, 4] may have already increased ozone pollution in some regions of the United States,[3] and has the potential to affect future concentrations of ozone and fine particles (particulate matter smaller than 2.5 microns in diameter, referred to as $PM_{2.5}$).[2, 7] Climate change and air quality are both affected by, and influence, several factors; these include the levels and types of pollutants emitted, how land is used, the chemistry governing how these pollutants form in the atmosphere, and weather conditions.

Ground-Level Ozone

Ozone levels and subsequent ozone-related health impacts depend on 1) the amount of pollutants emitted that form ozone, and 2) the meteorological conditions that help determine the amount of ozone produced from those emissions. Both of these factors are expected to change in the future. The emissions of pollutants from anthropogenic (of human origin) sources that form ozone (that is, ozone “precursors”) are expected to decrease over the next few decades in the United States.[23] However, irrespective of these changes in emissions, climate change will result in meteorological conditions more favorable to forming ozone. Consequently, attaining national air quality standards for ground-level ozone will also be more difficult, as climate changes offset some of the improvements that would otherwise be expected from emissions reductions. This effect is referred to as the “climate penalty.”[7, 24]

Meteorological conditions influencing ozone levels include air temperatures, humidity, cloud cover, precipitation, wind trajectories, and the amount of vertical mixing in the atmosphere.[1, 2, 25, 26] Higher temperatures can increase the chemical rates at which ozone is formed and increase ozone precursor emissions from anthropogenic sources and biogenic (vegetative) sources. Lower relative humidity reduces cloud cover and rainfall, promoting the formation of ozone and extending ozone lifetime in the atmosphere. A changing climate will also modify wind patterns across the United States, which will influence local ozone levels. Over much of the country, the worst ozone episodes tend to occur when the local air mass does not change over a period of several days, allowing ozone and ozone precursor emissions

What is Ozone?

Ozone (O_3) is a compound that occurs naturally in Earth's atmosphere but is also formed by human activities. In the stratosphere (10–50 kilometers above the Earth's surface), O_3 prevents harmful solar ultraviolet radiation from reaching the Earth's surface. Near the surface, however, O_3 irritates the respiratory system. Ground-level O_3, a key component of smog, is formed by chemical interactions between sunlight and pollutants including nitrogen oxides (NO_x) and volatile organic compounds (VOCs). The emissions leading to O_3 formation can result from both human sources (for example, motor vehicles and electric power generation) and natural sources (for example, vegetation and wildfires). Occasionally, O_3 that is created naturally in the stratosphere can be mixed downward and contribute to O_3 levels near the surface. Once formed, O_3 can be transported by the wind before eventually being removed from the atmosphere via chemical reactions or by depositing on the surface.

At any given location, O_3 levels are influenced by complex interactions between emissions and meteorological conditions. Generally, higher temperatures, sunnier skies, and lighter winds lead to higher O_3 concentrations by increasing the rate of chemical reactions and by decreasing the extent to which pollutants are mixed with "clean" (less polluted) background air.

For a given level of emissions of O_3 precursors, climate change is generally expected to increase O_3 pollution in the future throughout much of the United States, in part due to higher temperatures and more frequent stagnant air conditions.[7] Unless offset by additional emissions reductions of ozone precursors, these climate-driven increases in O_3 will cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms.[14]

to accumulate over time.[27, 28] Climate change is already increasing the frequency of these types of stagnation events over parts of the United States,[3] and further increases are projected.[29] Ozone concentrations near the ground are strongly influenced by upward and downward movement of air ("vertical mixing"). For example, high concentrations of ozone near the ground often occur in urban areas when there is downward movement of air associated with high pressure ("subsidence"), reducing the extent to which locally emitted pollutants are diluted in the atmosphere.[30] In addition, high concentrations of ozone can occur in some rural areas resulting from downward transport of ozone from the stratosphere or upper troposphere to the ground.[31]

Aside from the direct meteorological influences, there are also indirect impacts on U.S. ozone levels from other climate-influenced factors. For instance, higher water vapor concentrations due to increased temperatures will increase the natural rate of ozone depletion, particularly in remote areas,[32] thus decreasing the baseline level of ozone. Additionally, potential climate-driven increases in nitrogen oxides (NO_x) created by lightning or increased exchange of naturally produced ozone in the stratosphere to the troposphere could also affect ozone in those areas of the country most influenced by background ozone concentrations.[33] Increased occurrences of wildfires due to climate change can also lead to increased ozone concentrations near the ground.[34]

There is natural year-to-year variability in temperature and other meteorological factors that influence ozone levels.[7] While global average temperature over 30-year climatic timescales is expected to increase, natural interannual variability will continue to play a significant role in year-to-year changes in temperature.[35] Over the next several decades, the influence of climate change on meteorological parameters affecting average levels of ozone is expected to be smaller than the natural interannual variability.[36]

To address these issues, most assessments of climate impacts on meteorology and associated ozone formation concurrently simulate global and regional chemical transport over multiple years using "coupled" models. This approach can isolate the influence of meteorology in forming ozone from the effect of changes in emissions. The consensus of these model-based assessments is that accelerated rates of photochemical reaction, increased occurrence of stagnation events, and other direct meteorological influences are likely to lead to higher levels of ozone over large portions of the United States.[8, 14, 16, 17] At the same time, ozone levels in certain regions are projected to decrease as a result of climate change, likely due to localized increases in cloud cover, precipitation, and/or increased dilution resulting from deeper mixed layers. These climate-driven changes in projected ozone vary by season and location, with climate and air quality models showing the most consistency in ozone increases due to climate change in the northeastern United States.[8, 37]

Generally, ozone levels will likely increase across the United States if ozone precursors are unchanged (see "Research Highlight: Ozone-Related Health Effects" on page 74).[4, 7, 8] This climate penalty for ozone will offset some of the expected health benefits that would otherwise result from the expected ongoing reductions of ozone precursor emissions, and could prompt the need for adaptive measures (for example, additional ozone precursor emissions reductions) to meet national air quality goals.

Research Highlight: Ozone-Related Health Effects

Los Angeles, California, May 22, 2012. Unless offset by additional emissions reductions of ozone precursors, climate-driven increases in ozone will cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms.

Importance: Ozone is formed in the atmosphere by photochemical reactions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the presence of sunlight. Although U.S. air quality policies are projected to reduce VOC and NO_x emissions,[56] climate change will increase the frequency of regional weather patterns conducive to increasing ground-level ozone, partially offsetting the expected improvements in air quality.

Objective: Project the number and geographic distribution of additional ozone-related illnesses and premature deaths in the contiguous United States due to climate change between 2000 and 2030 under projected U.S. air quality policies.

Method: Climate scenarios from two global climate models (GCMs) using two different emissions pathways (RCP8.5 and RCP6.0) were dynamically downscaled following Otte et al. (2012)[57] and used with emissions projections for 2030 and a regional chemical transport model to simulate air quality in the contiguous United States. The resulting changes in ozone in each scenario were then used to compute regional ozone-related health effects attributable to climate change. Ozone-related health impacts were estimated using the environmental Benefits Mapping and Analysis Program–Community Edition (BenMAP–CE). Population exposure was estimated using projected population data from the Integrated Climate and Land Use Scenarios (ICLUS). Further details can be found in Fann et al. (2015).[14]

Results: The two downscaled GCM projections result in 1°C to 4°C (1.8°F to 7.2°F) increases in average daily maximum temperatures and 1 to 5 parts per billion increases in daily 8-hour maximum ozone in 2030 throughout the contiguous United States. As seen in previous modeling analyses of climate impacts on ozone, the air quality response to climate change can vary substantially by region and across scenarios.[22, 58] Unless reductions in ozone precursor emissions offset the influence of climate change, this climate penalty of increased ozone concentrations due to climate change would result in tens to thousands of additional ozone-related illnesses and premature deaths per year.

Research Highlight: Ozone-Related Health Effects, continued

Conclusions: Future climate change will result in higher ozone levels in polluted regions of the contiguous United States. This study isolates the effect of climate change on ozone by using the same emissions of ozone precursors for both 2000-era and 2030-era climate. In addition, this study uses the latest generation of GCM scenarios and represents the most comprehensive analysis of climate-related, ozone-attributable health effects in 2030, and includes not only deaths but also emergency department admissions for asthma, hospital visits for respiratory causes, acute respiratory symptoms, and missed days of school. These results are subject to important uncertainties and limitations. The ozone-climate modeling reflects two scenarios (based on two separate GCMs) considered. Several emissions categories that are important in the formation of ozone and that could be affected by climate, such as motor vehicles, electrical generating units, and wildfires, were left unchanged between the current and future periods. The analysis applied concentration–response relationships from epidemiology studies of historical air pollution episodes; this both implies that the relationship between air pollution and risk will remain constant into the future and that populations will not attempt to reduce their exposure to ozone.

Projected Change in Temperature, Ozone, and Ozone-Related Premature Deaths in 2030

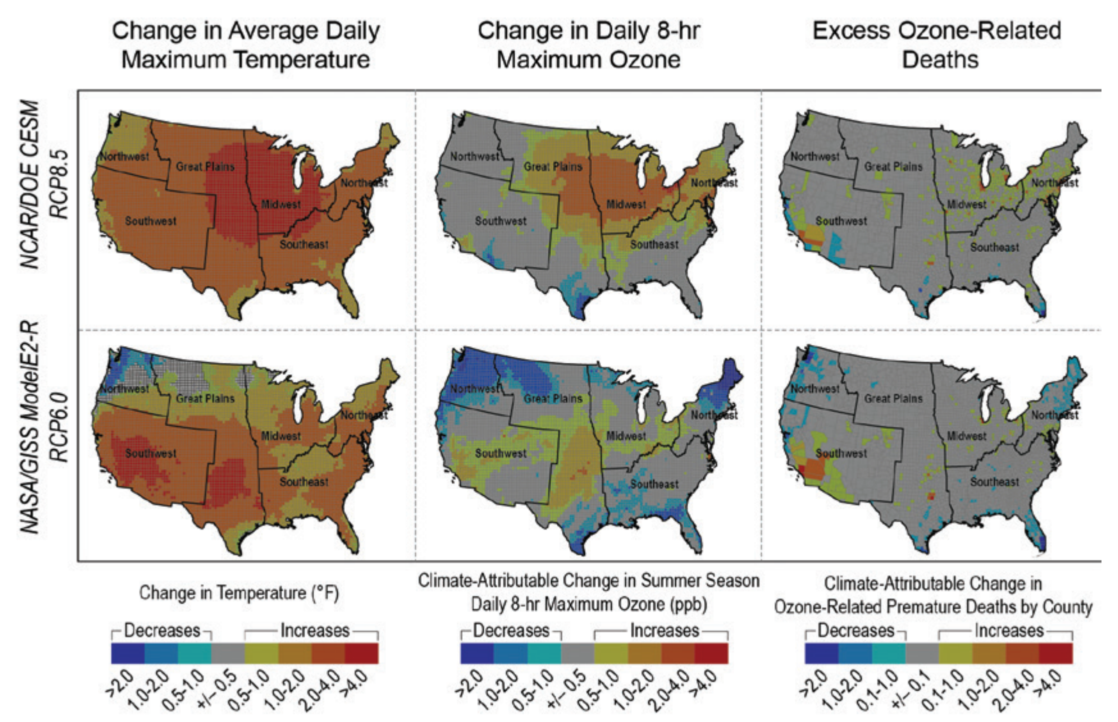


Figure 2. Projected changes in average daily maximum temperature (degrees Fahrenheit), summer average maximum daily 8-hour ozone (parts per billion), and excess ozone-related deaths (incidences per year by county) in the year 2030 relative to the year 2000, following two global climate models and two greenhouse gas concentration pathways, known as Representative Concentration Pathways, or RCPs (see van Vuuren et al. 2011[49]). Each year (2000 and 2030) is represented by 11 years of modeled data for May through September, the traditional ozone season in the United States.

The top panels are based on the National Center for Atmospheric Research/Department of Energy (NCAR/DOE) Community Earth System Model (CESM) following RCP8.5 (a higher greenhouse gas concentration pathway), and the bottom panels are based on the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) ModelE2-R following RCP6.0 (a moderate greenhouse gas concentration pathway).

The leftmost panels are based on dynamically downscaled regional climate using the NCAR Weather Research and Forecasting (WRF) model, the center panels are based on air quality simulations from the U.S. Environmental Protection Agency (EPA) Community Multiscale Air Quality (CMAQ) model, and the rightmost panels are based on the U.S. EPA Environmental Benefits and Mapping Program (BenMAP).

Fann et al. 2015 reports a range of mortality outcomes based on different methods of computing the mortality effects of ozone changes—the changes in the number of deaths shown in the rightmost panels were computed using the method described in Bell et al. 2004.[14, 38] (Figure source: adapted from Fann et al. 2015)[14]

Research Highlight: Ozone-Related Health Effects, continued

Projected Change in Ozone-Related Premature Deaths

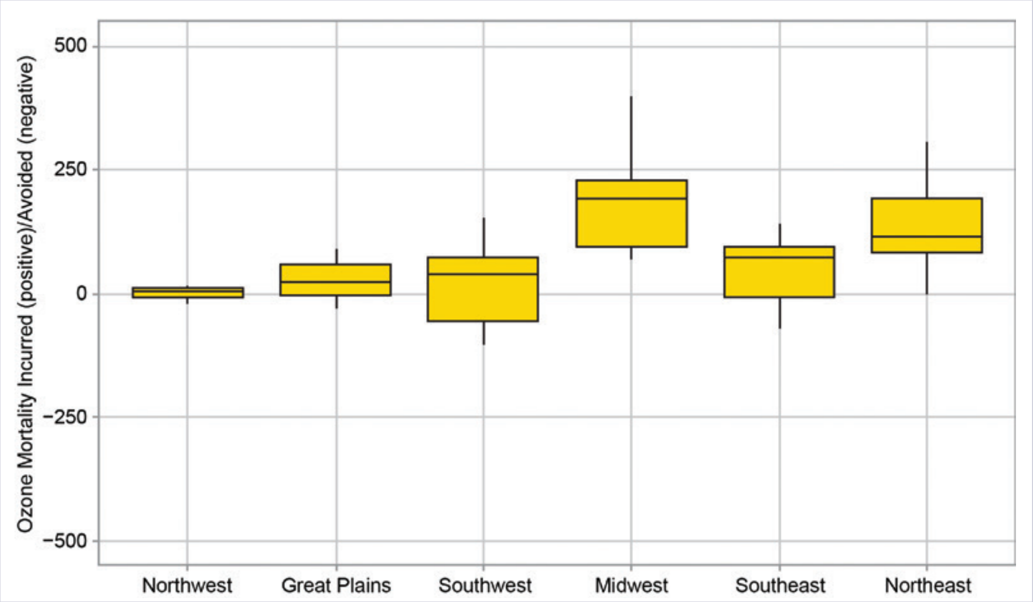


Figure 3. Projected change in ozone-related premature deaths from 2000 to 2030 by U.S. region and based on CESM/RCP8.5. Each year (2000 and 2030) is represented by 11 years of modeled data. Ozone-related premature deaths were calculated using the risk coefficient from Bell et al. (2004).[38] Boxes indicate 25th, 50th, and 75th percentile change over 11-year sample periods, and vertical lines extend to 1.5 times the interquartile range. U.S. regions follow geopolitical boundaries shown in Figure 2. (Figure source: Fann et al. 2015)[14]

Air pollution epidemiology studies describe the relationship between a population's historical exposure to air pollutants and the risk of adverse health outcomes. Populations exposed to ozone air pollution are at greater risk of dying prematurely, being admitted to the hospital for respiratory hospital admissions, being admitted to the emergency department, and suffering from aggravated asthma, among other impacts.[38, 39, 40]

Air pollution health impact assessments combine risk estimates from these epidemiology studies with modeled changes in future or historical air quality changes to estimate the number of air-pollution-related premature deaths and illness.[41] Future ozone-related human health impacts attributable to climate change are projected to lead to hundreds to thousands of premature deaths, hospital admissions, and cases of acute respiratory illnesses per year in the United States in 2030.[14, 42, 43, 44, 45, 46]

Health outcomes that can be attributed to climate change impacts on air pollution are sensitive to a number of factors noted above—including the climate models used to describe meteorological changes (including precipitation and cloud cover), the models simulating air quality levels (including wildfire incidence), the size and distribution of the population exposed, and the health status of that population (which influences their susceptibility to air pollution; see Ch. 1: Introduction).[42, 47, 48, 49] Moreover, there is emerging evidence that air pollution can interact with climate-related stressors such as temperature to affect the human physiological response to air pollution.[39, 42, 50, 51, 52, 53, 54, 55] For example, the risk of dying from exposure to a given level of ozone may increase on warmer days.[51]

Particulate Matter

Particulate matter (PM) is a complex mixture of solid- or liquid-phase substances in the atmosphere that arise from both natural and human sources. Principal constituents of PM include sulfate, nitrate, ammonium, organic carbon, elemental carbon, sea salt, and dust. These particles (also known as aerosols) can either be directly emitted or can be formed in the atmosphere from gas-phase precursors. PM smaller than 2.5 microns in diameter ($PM_{2.5}$) is associated with serious chronic and acute health effects, including lung cancer, chronic obstructive pulmonary disease (COPD), cardiovascular disease, and asthma development and exacerbation.[11] The elderly are particularly sensitive to short-term particle exposure, with a higher risk of hospitalization and death.[59, 60]

As is the case for ozone, atmospheric $PM_{2.5}$ concentrations depend on emissions and on meteorology. Emissions of sulfur dioxide (SO_2), NO_x, and black carbon are projected to decline substantially in the United States over the next few decades due to regulatory controls,[56, 61, 62, 63] which will lead to reductions in sulfate and nitrate aerosols.

Climate change is expected to alter several meteorological factors that affect $PM_{2.5}$, including precipitation patterns and humidity, although there is greater consensus regarding the effects of meteorological changes on ozone than on $PM_{2.5}$.[2] Several factors, such as increased humidity, increased stagnation events, and increased biogenic emissions are likely to increase $PM_{2.5}$ levels, while increases in precipitation, enhanced atmospheric mixing, and other factors could decrease $PM_{2.5}$ levels.[2, 8, 37, 64] Because of the strong influence of changes in precipitation and atmospheric mixing on $PM_{2.5}$ levels, and because there is more variability in projected changes to those variables, there is no consensus yet on whether meteorological changes will lead to a net increase or decrease in $PM_{2.5}$ levels in the United States.[2, 8, 17, 21, 22, 64, 65]

As a result, while it is clear that $PM_{2.5}$ accounts for most of the health burden of outdoor air pollution in the United States,[10] the health effects of climate-induced changes in $PM_{2.5}$ are poorly quantified. Some studies have found that changes in $PM_{2.5}$ will be the dominant driver of air quality-related health effects due to climate change,[44] while others have suggested a potentially more significant health burden from changes in ozone.[50]

PM resulting from natural sources (such as plants, wildfires, and dust) is sensitive to daily weather patterns, and those fluctuations can affect the intensity of extreme PM episodes (see also Ch. 4: Extreme Events, Section 4.6).[8] Wildfires are a major source of PM, especially in the western United States during summer.[66, 67, 68] Because winds carry $PM_{2.5}$ and ozone precursor gases, air pollution from wildfires can affect people even far downwind from the fire location.[35, 69] $PM_{2.5}$ from wildfires affects human health by increasing the risk of premature death and hospital and emergency department visits.[70, 71, 72]

Climate change has already led to an increased frequency of large wildfires, as well as longer durations of individual wildfires and longer wildfire seasons in the western United States.[73] Future climate change is projected to increase wildfire risks[74, 75] and associated emissions, with harmful impacts on health.[76] The area burned by wildfires in North America is expected to increase dramatically over the 21st century due to climate change.[77, 78] By 2050, changes in wildfires in the western United States are projected to result in 40% increases of organic carbon and 20% increases in elemental carbon aerosol concentrations.[79] Wildfires may dominate summertime $PM_{2.5}$ concentrations, offsetting even large reductions in anthropogenic $PM_{2.5}$ emissions.[22]

Likewise, dust can be an important constituent of PM, especially in the southwest United States. The severity and spatial extent of drought has been projected to increase as a result of climate change,[80] though the impact of increased aridity on airborne dust PM has not been quantified (see Ch. 4. Extreme Events).[2]

Nearly 6.8 million children in the United States are affected by asthma, making it a major chronic disease of childhood.

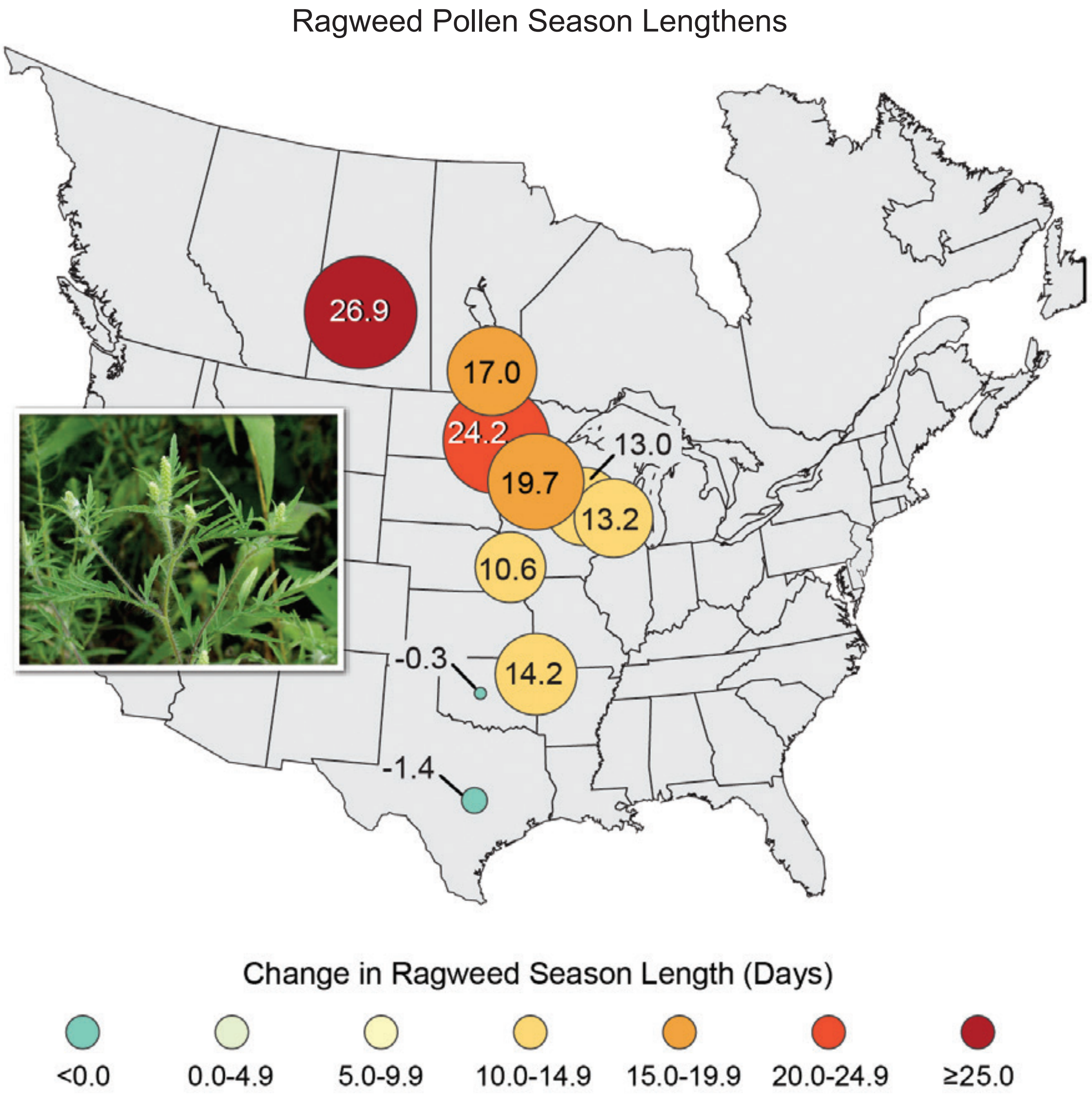
3.3 Climate Impacts on Aeroallergens and Respiratory Diseases

Climate change may alter the production, allergenicity, distribution, and timing of airborne allergens (aeroallergens). These changes contribute to the severity and prevalence of allergic disease in humans. The very young, those with compromised immune systems, and the medically uninsured bear the brunt of asthma and other allergic illnesses. While aeroallergen exposure is not the sole, or even necessarily the most significant factor associated with allergic illnesses, that relationship is part of a complex pathway that links aeroallergen exposure to the prevalence of allergic illnesses, including asthma episodes.[81, 82] On the other hand, climate change may reduce adverse allergic and asthmatic responses in some areas. For example, as some areas become drier, there is the potential for a shortening of the pollen season due to plant stress.

Aeroallergens and Rates of Allergic Diseases in the United States

Aeroallergens are substances present in the air that, once inhaled, stimulate an allergic response in sensitized individuals. Aeroallergens include tree, grass, and weed pollen; indoor and outdoor molds; and other allergenic proteins associated with animal dander, dust mites, and cockroaches.[83] Ragweed is the aeroallergen that most commonly affects persons in the United States.[84]

Allergic diseases develop in response to complex and multiple interactions among both genetic and non-genetic factors, including a developing immune system, environmental exposures (such as ambient air pollution or weather conditions), and socioeconomic and demographic factors.[85, 86, 87] Aeroallergen exposure contributes to the occurrence of asthma episodes, allergic rhinitis or hay fever, sinusitis, conjunctivitis, urticaria (hives), atopic dermatitis or eczema, and anaphylaxis (a severe, whole-body allergic reaction that can be life-threat-



Ragweed Pollen Season Lengthens

Figure 4: Ragweed pollen season length has increased in central North America between 1995 and 2011 by as much as 11 to 27 days in parts of the United States and Canada, in response to rising temperatures. Increases in the length of this allergenic pollen season are correlated with increases in the number of days before the first frost. The largest increases have been observed in northern cities. (Figure source: Melillo et al. 2014. Photo credit: Lewis Ziska, USDA).[35]

ening).[84, 88] Allergic illnesses, including hay fever, affect about one-third of the U.S. population, and more than 34 million Americans have been diagnosed with asthma.[81] These diseases have increased in the United States over the past 30 years (see Ch. 1 Introduction). The prevalence of hay fever has increased from 10% of the population in 1970 to 30% in 2000.[84] Asthma rates have increased from approximately 8 to 55 cases per 1,000 persons to approximately 55 to 90 cases per 1,000 persons over that same time period;[89] however, there is variation in reports of active cases of asthma as a function of geography and demographics.[90]

Climate Impacts on Aeroallergen Characteristics

Climate change contributes to changes in allergic illnesses as greater concentrations of CO_2, together with higher temperatures and changes in precipitation, extend the start or duration of the growing season, increase the quantity and allergenicity of pollen, and expand the spatial distribution of pollens.[84, 91, 92, 93, 94]

Historical trends show that climate change has led to changes in the length of the growing season for certain allergenic pollens. For instance, the duration of pollen release for common ragweed (*Ambrosia artemisiifolia*) has been increasing as a function of latitude in recent decades in the midwestern region of North America (see Figure 4). Latitudinal effects on increasing season length were associated primarily with a delay in first frost during the fall season and lengthening of the frost-free period.[95] Studies in controlled indoor environments find that increases in temperature and CO_2 result in earlier flowering, greater floral numbers, greater pollen production, and increased allergenicity in common ragweed.[96, 97] In addition, studies using urban areas as proxies for both higher CO_2 and higher temperatures demonstrate earlier flowering of pollen species, which may lead to a longer total pollen season.[98, 99, 100]

For trees, earlier flowering associated with higher winter and spring temperatures has been observed over a 50-year period for oak.[101] Research on loblolly pine (*Pinus taeda*) also demonstrates that elevated CO_2 could induce earlier and greater seasonal pollen production.[102] Annual birch (*Betula*) pollen production and peak values from 2020 to 2100 are projected to be 1.3 to 2.3 times higher, relative to average values for 2000, with the start and peak dates of pollen release advancing by two to four weeks.[103]

Climate Variability and Effects on Allergic Diseases

Climate change related alterations in local weather patterns, including changes in minimum and maximum temperatures and rainfall, affect the burden of allergic diseases.[104, 105, 106] The role of weather on the initiation or exacerbation of allergic symptoms in sensitive persons is not well understood.[86, 107] So-called “thunderstorm asthma” results as allergenic particles are dispersed through osmotic rupture, a phenomenon where cell membranes burst. Pollen grains may, after contact with rain, release part of their cellular contents, including allergen-laced fine particles. Increases in the intensity and frequency of heavy rainfall and storminess over the coming decades is likely to be associated with spikes in aeroallergen concentrations and the potential for related increases in the number and severity of allergic illnesses.[108, 109]

Potential non-linear interactions between aeroallergens and ambient air pollutants (including ozone, nitrogen dioxide, sulfur dioxide, and fine particulate matter) may increase health risks for people who are simultaneously exposed.[87, 88, 106, 108, 110, 111, 112, 113, 114] In particular, pre-exposure to air pollution (especially ozone or fine particulate matter) may magnify the effects of aeroallergens, as prior damage to airways may increase the permeability of mucous membranes to the penetration of allergens, although existing evidence suggests greater sensitivity but not necessarily a direct link with ozone exposure.[115] A recent report noted remaining uncertainties across the epidemiologic, controlled human exposure, and toxicology studies on this emerging topic.[39]

3.4 Climate Impacts on Indoor Air Quality and Health: An Emerging Issue

Climate change may worsen existing indoor air problems and create new problems by altering outdoor conditions that affect indoor conditions and by creating more favorable conditions for the growth and spread of pests, infectious agents, and disease vectors that can migrate indoors.[116] Climate change can also lead to changes in the mixing of outdoor and indoor air. Reduced mixing of outdoor and indoor air limits penetration of outdoor pollutants into the indoors, but also leads to higher concentrations of pollutants generated indoors since their dilution by outdoor air is decreased.

Indoor air contains a complex mixture of chemical and biological pollutants or contaminants. Contaminants that can be found indoors include carbon monoxide (CO), fine particles ($PM_{2.5}$), nitrogen dioxide, formaldehyde, radon, mold, and pollen. Indoor air quality varies from building to building and over the course of a day in an individual building.

Public and environmental health professionals have known for decades that poor indoor air quality is associated with adverse respiratory and other health effects.[116, 117, 118, 119, 120, 121] Since most people spend about 90% of their time indoors,[122, 123, 124, 125, 126] much of their exposures to airborne pollutants (both those influenced by climate change and those driven by other factors) happen indoors.

Outdoor Air Changes Reflected in Indoor Air

Indoor air pollutants may come from indoor sources or may be transported into the building with outdoor air.[127, 128] Indoor pollutants of outdoor origin may include ozone, dust, pollen, and fine PM ($PM_{2.5}$). Even if a building has an outdoor air intake, some air will enter the building through other openings, such as open windows or under doors, or through cracks in the buildings, bypassing any filters and bringing outdoor air pollutants inside.[129] If there are changes in airborne pollutants of outdoor origin, such as pollen and mold (see Section 3.3) and fine PM from wildfires (see "Particulate Matter" on page 76), there will be changes in indoor exposures to these contaminants. Although indoor fine PM levels from wildfires are typically lower than outdoors (about 50%), because people spend most of their time indoors, most of their exposure to and health effects from wildfire particles (about 80%) will come from particles inhaled

Dampness and mold in U.S. homes are linked to approximately 4.6 million cases of worsened asthma.

Research Highlight: Residential Infiltration and Indoor Air

Importance: Indoor and outdoor air are constantly mixing as air flows through small cracks and openings in buildings (infiltration) in addition to any open doors, windows, and vents. Infiltration or air exchange is driven by differences in barometric pressure, as a result of wind, and of the temperature difference between indoor and outdoor air. The greater this air exchange, the more similar the composition of indoor and outdoor air. Lower air exchange rates accentuate the impact of indoor sources while reducing that of some outdoor pollution. As climate change increases the average temperature of outdoor air, while indoor air continues to be maintained at the same comfortable temperatures, infiltration driven by temperature differences will change as well, modifying exposure to indoor and outdoor air pollution sources.

Objective: Project the relative change in infiltration and its effects on exposure to indoor and outdoor air pollution sources for different climates in the United States, between a late-20th century reference and the middle of the current century, in typical detached homes.

Method: The infiltration change projected for 2040–2070 compared to 1970–2000 was modeled for typical single-family residences in urban areas, using temperatures and wind speeds from eight global–regional model combinations for nine U.S. cities (Atlanta, Boston, Chicago, Houston, Los Angeles, Minneapolis, New York, Phoenix, and Seattle). This analysis compares a building to itself, removing the effects of individual building characteristics on infiltration. Indoor temperatures were assumed unchanged between these two periods. Further details can be found in Ilacqua et al. 2015.[131]

Results: Because current average yearly temperatures across the contiguous United States are generally below comfortable indoor temperatures, model results indicate that, under future warmer temperatures, infiltration is projected to decrease by about 5%, averaged across cities, seasons, and climate models. Exposure to some pollutants emitted indoors would correspondingly increase, while exposure to some outdoor air pollutants would decrease to some extent. Projections vary, however, among location, seasons, and climate models. In the warmer cities, infiltration during summer months would rise by up to 25% in some models, raising peak exposures to ozone and other related pollutants just when their concentrations are typically highest. Predictions of different models are less consistent for summer months, however, displaying more uncertainty (average modeling relative range of 14%) for summer than for the rest of the year, and in fact not all models predict summer infiltration increases. Modeling uncertainty for the rest of the year is lower than in the summer (relative range less than 6%).

Conclusions: This study shows the potential shifts in residential exposure to indoor and outdoor air pollution sources driven by a changing climate.[131] These conclusions can be applied to small buildings, including single-family homes, row houses, and small offices. Potential adaptations intended to promote energy efficiency by reducing the leakage area of buildings will enhance the effect of decreasing infiltration and increasing exposure to indoor sources. Because of its novelty and lack of additional evidence, the study results should be considered as suggestive of an emerging issue. If replicated by other studies, these findings would add to the evidence on the potential for climate change to alter indoor air quality and further emphasize the impact of indoor air sources on human health. The overall implications of these findings for exposure to ambient and indoor air pollution remain uncertain at present, as they need to be considered along with other determinants of air exchange, such as window-opening behavior, whose relationship with climate change remains poorly characterized.

indoors.[130] Climate-induced changes in indoor-outdoor temperature differences may somewhat reduce the overall intake of outdoor pollutants into buildings for certain regions and seasons (see “Research Highlight: Residential Infiltration and Indoor Air”).[131]

Most exposures to high levels of ozone occur outdoors; however, indoor exposures, while lower, occur for much longer time periods. Indoors, ozone concentrations are usually about 10% to 50% of outdoor concentrations; however, since people spend most of their time indoors, most of their exposure to ozone is from indoor air.[130] Thus, about 45% to 75% of a person’s overall exposure to ozone will occur indoors.[132] About half of the health effects resulting from any outdoor increases in ozone (see Section "Ground-Level Ozone" on page 72) will be due to indoor ozone exposures.[130] The elderly and children are particularly sensitive to short-term ozone exposure; however, they may spend even more time indoors than the general population and consequently their exposure to ozone is at lower levels for longer periods than the general public.[133, 134] In addition, ozone entering a building reacts with some organic compounds to produce secondary indoor air pollutants. These reactions lower indoor ozone concentrations but introduce new indoor air contaminants, including other respiratory irritants.[135]

Climate-related increases in droughts and dust storms may result in increases in indoor transmission of dust-borne pathogens, as the dust penetrates the indoor environment. Dust contains particles of biologic origin, including pollen and bacterial and fungal spores. Some of the particles are allergenic.[136] Pathogenic fungi and bacteria can be found in dust both indoors and outdoors.[137] For example, in the southwestern United States, spores from the fungi *Coccidiodes*, which can cause valley fever, are found indoors.[138] The geographic range where *Coccidiodes* is commonly found is increasing. Climate changes, including increases in droughts and temperatures, may be contributing to this spread and to a rise in valley fever (see Ch. 4: Extreme Events).

Legionnaires' disease is primarily contracted from aerosolized water contaminated with *Legionella* bacteria.[139] *Legionella* bacteria are naturally found outdoors in water and soil; they are also known to contaminate treated water systems in buildings,[140] as well as building cooling systems such as swamp coolers or cooling towers.[141] *Legionella* can also be found indoors inside plumbing fixtures such as showerheads, faucets, and humidifiers.[142, 143] *Legionella* can cause outbreaks of a pneumonia known as Legionnaire's disease, which is a potentially fatal infection.[144] Exposure can occur indoors when a spray or mist of contaminated water is inhaled, including mist or spray from showers and swamp coolers.[145] The spread of *Legionella* bacteria can be affected by regional environmental factors.[116] Legionnaires' disease is known to follow a seasonal pattern, with more cases in late summer and autumn, potentially due to warmer and damper conditions.[146, 147] Cases of Legionnaires' disease are rising in the United States, with an increase of 192% from 2000 to 2009.[148, 149] If climate change results in sustained higher temperatures and damper conditions in some areas, there could be increases in the spread and transmission of *Legionella*.

Contaminants Generated Indoors

Although research directly linking indoor dampness and climate change is not available, information on building science, climate change, and outdoor environmental factors that affect indoor air quality can be used to project how climate change may influence indoor environments.[130] Climate change could result in increased indoor dampness in at least two ways: 1) if there are more frequent heavy precipitation events and other severe weather events (including high winds, flooding, and winter storms) that result in damage to buildings, allowing water or moisture entry; and 2) if outdoor humidity rises with climate change, indoor humidity and the potential for condensation and dampness will likely rise. Outdoor humidity is usually the largest contributor to indoor dampness on a yearly basis.[127]

Increased indoor dampness and humidity will in turn increase indoor mold, dust mites, bacteria, and other bio-contamination indoors, as well as increase levels of volatile organic compounds (VOCs) and other chemicals resulting from the off-gassing of damp or wet building materials.[116, 119, 150] Dampness and mold in U.S. homes are linked to approximately 4.6 million cases of worsened asthma and between 8% and 20% of several common respiratory infections, such as acute bronchitis.[151, 152] If there are climate-induced rises in indoor dampness, there could be increases in adverse health effects related to dampness and mold, such as asthma exacerbation.

Additionally, power outages due to more frequent extreme weather events such as flooding could lead to a number of health effects (see Ch 4: Extreme Events). Heating, ventilation, and air conditioning (HVAC) systems will not function without power; therefore, many buildings could have difficulty maintaining indoor temperatures or humidity. Loss of ventilation, filtration, air circulation, and humidity control can lead to indoor mold growth and increased levels of indoor contaminants,[153] including VOCs such as formaldehyde.[119, 154, 155, 156] Power outages are also associated with increases in hospital visits from carbon monoxide (CO) poisoning, primarily due to the incorrect use of backup and portable generators that contaminate indoor air with carbon monoxide.[135] Following floods, CO poisoning is also associated with the improper indoor use of wood-burning appliances and other combustion appliances designed for use outdoors.[157] There were at least nine deaths from carbon monoxide poisoning related to power outages from 2000 to 2009.[158]

Climate factors can influence populations of rodents that produce allergens and can harbor pathogens such as hantaviruses, which can cause Hantavirus Pulmonary Syndrome. Hantaviruses can be spread to people by rodents that infest buildings,[159] and limiting indoor exposure is a key strategy to prevent the spread of hantavirus.[160] Climate change may increase rodent populations in some areas, including indoors, particularly when droughts are followed by periods of heavy rain (see Ch. 4: Extreme Events) and with increases in temperature and rainfall.[161] Also, extreme weather events such as heavy rains and flooding may drive some rodents to relocate indoors.[162] Increases in rodent populations may result in increased indoor exposures to rodent allergens and related health effects.[159, 163, 164] In addition, climate factors may also influence the prevalence of hantaviruses in rodents.[163, 164] This is a complex dynamic, because climate change may influence rodent populations, ranges, and infection rates.

3.5 Populations of Concern

Certain groups of people may be more susceptible to harm from air pollution due to factors including age, access to healthcare, baseline health status, or other characteristics.[60] In the contiguous United States, Blacks or African-Americans, women, and the elderly experience the greatest baseline risk from air pollution.[165] The young, older adults, asthmatics, and people whose immune systems are compromised are more vulnerable to indoor air pollutants than the general population.[166] Lower socioeconomic status and housing disrepair have been associated with higher indoor allergen exposures, though higher-income populations may be more exposed to certain allergens such as dust mites.[167, 168]

Nearly 6.8 million children in the United States are affected by asthma, making it a major chronic disease of childhood.[169] It is also the main cause of school absenteeism and hospital admissions among children.[83] In 2008, 9.3% of American children age 2 to 17 years were reported to have asthma.[169] The onset of asthma in children has been linked to early allergen exposure and viral infections, which act in concert with genetic susceptibility.[170] Children can be particularly susceptible to allergens due to their immature respiratory and immune systems, as well as indoor or outdoor activities that contribute to aeroallergen exposure (see Table 1).[170, 171, 172, 173]

Minority adults and children also bear a disproportionate burden associated with asthma as measured by emergency department visits, lost work and school days, and overall poorer health status (see Table 1).[175, 176] Twice as many Black children had asthma-related emergency department visits and hospitalizations compared with White children. Fewer Black and Hispanic children reported using preventative medication like inhaled corticosteroids (ICS) as compared to White children. Black and Hispanic children also had more poorly controlled asthma symptoms, leading to increased emergency department visits and greater use of rescue medications rather than routine daily use of ICS, regardless of symptom control.[173, 177]

Percentage of population with active asthma, by year and selected characteristics: United States, 2001 and 2010.

Characteristic	Year 2001 %	Year 2010 %
Total	**7.3**	**8.4**
Gender		
Male	6.3	7.0
Female	8.3	9.8
Race		
White	7.2	7.8
Black	8.4	11.9
Other	7.2	8.1
Ethnicity		
Hispanic	5.8	7.2
Non-Hispanic	7.6	8.7
Age		
Children (0-17)	8.7	9.3
Adults (18 and older)	6.9	8.2
Age Group		
0-4 years	5.7	6.0
5-14 years	9.9	10.7
15-34 years	8.0	8.6
35-64 years	6.7	8.1
65 years and older	6.0	8.1
Region		
Northeast	8.3	8.8
Midwest	7.5	8.6
South	7.1	8.3
West	6.7	8.3
Federal Poverty Threshold		
Below 100%	9.9	11.2
100% to < 250%	7.7	8.7
250% to < 450%	6.8	8.2
450% or higher	6.6	7.1

Source: Moorman et al. 2012[174]

Table 1: A recent study of children in California found that racial and ethnic minorities are more affected by asthma.[175] Among minority children, the prevalence of asthma varies with the highest rates among Blacks and American Indians/Alaska Natives (17%), followed by non-Hispanic or non-Latino Whites (10%), Hispanics (7%), and Asian Americans (7%).

Children living in poverty were 1.75 times more likely to be hospitalized for asthma than their non-poor counterparts. When income is accounted for, no significant difference was observed in the rate of hospital admissions by race or ethnicity. This income effect may be related to access and use of health care and appropriate use of preventive medications such as ICS.[178]

People with preexisting medical conditions—including hypertension, diabetes, and chronic obstructive pulmonary disorder—are at greater risk for outdoor air pollution-related health effects than the general population.[179] Populations with irregular heartbeats (atrial fibrillation) who were exposed to air pollution and high temperatures experience increased risk.[165] People who live or work in buildings without air conditioning and other ventilation controls or in buildings that are unable to withstand extreme precipitation or flooding events are at greater risk of adverse health effects. Other health risks are related to exposures to poor indoor air quality from mold and other biological contaminants and chemical pollutants emitted from wet building materials. While the presence of air conditioning has been found to greatly reduce the risk of ozone-related deaths, communities with a higher percentage of unemployment and a greater population of Blacks are at greater risk.[59]

3.6 Research Needs

In addition to the emerging issues identified above, the authors highlight the following potential areas for additional scientific and research activity on air quality. Understanding of future air quality and the ability to model future health impacts associated with air quality changes—particularly $PM_{2.5}$ impacts—will be enhanced by improved modeling and projections of climate-dependent variables like wildfires and land-use patterns, as well as improved modeling of ecosystem responses to climate change. Improved collection of data on aeroallergen concentrations in association with other ecosystem variables will facilitate research and modeling of related health impacts.

Future assessments can benefit from research activities that:

- enhance understanding of how interactions among climate-related factors, such as temperature or relative humidity, aeroallergens, and air pollution, affect human health, and how to attribute health impacts to changes in these different risk factors;

- improve the ability to model and project climate change impacts on the formation and fate of air contaminants and quantify the compounded uncertainty in the projections; and

- identify the impacts of changes in indoor dampness, such as mold, other biological contaminants, volatile organic compounds, and indoor air chemistry on indoor air pollutants and health.

Supporting Evidence

PROCESS FOR DEVELOPING CHAPTER

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops, teleconferences, and email exchanges. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, and Federal agencies. For additional information on the overall report process, see Appendices 2 and 3.

In addition, the author team held an all-day meeting at the U.S. Environmental Protection Agency National Center for Environmental Assessment in Crystal City, Virginia, on October 15, 2014, to discuss the chapter and develop initial drafts of the Key Findings. A quorum of the authors participated and represented each of the three sections of the chapter—outdoor air quality, aeroallergens, and indoor air quality. These discussions were informed by the results of the literature review as well as the research highlights focused on outdoor air quality and indoor air quality. The team developed Key Finding 2 in response to comments from the National Research Council review panel and the general public.

The Key Findings for outdoor ozone, wildfires, and aeroallergen impacts reflect strong empirical evidence linking changes in climate to these outcomes. When characterizing the human health impacts from outdoor ozone, the team considered the strength of the toxicological, clinical, and epidemiological evidence evaluated in the Ozone Integrated Science Assessment.[39] Because there is increasing evidence that climate change will increase the frequency and intensity of wildfire events, this outcome was included as a key finding, despite the inability to quantify this impact with the available tools and data. Because altered patterns of precipitation and increasing levels of CO_2 are anticipated to promote the level of aeroallergens, this outcome is also included as a Key Finding. Finally, because the empirical evidence linking climate change to indoor air quality was more equivocal, we identified this topic as an emerging issue.

KEY FINDING TRACEABLE ACCOUNTS

Exacerbated Ozone Health Impacts

Key Finding 1: Climate change will make it harder for any given regulatory approach to reduce ground-level ozone pollution in the future as meteorological conditions become increasingly conducive to forming ozone over most of the United States *[Likely, High Confidence]*. Unless offset by additional emissions reductions of ozone precursors, these climate-driven increases in ozone will cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms *[Likely, High Confidence].*

Description of evidence base

The Intergovernmental Panel on Climate Change (IPCC) has concluded that warming of the global climate system is unequivocal and that continued increases in greenhouse gas emissions will cause further temperature increases.[5, 35] At the same time, there is a well-established relationship between measured temperature and monitored peak ozone levels in the United States.[1, 25] Numerous climate and air quality modeling studies have also confirmed that increasing temperatures, along with other changes in meteorological variables, are likely to lead to higher peak ozone levels in the future over the United States,[7, 37] if ozone precursor emissions remain unchanged.

Risk assessments using concentration–response relationships from the epidemiological literature and modeled air quality data have projected substantial health impacts associated with climate-induced changes in air quality.[14, 42, 43, 44, 46, 50] This literature reports a range of potential changes in ozone-related, non-accidental mortality due to modeled climate change between the present and 2030 or 2050, depending upon the scenario modeled, the climate and air quality models used, and assumptions about the concentration–response function and future populations. Many of the studies suggest that tens to thousands of premature deaths could occur in the future due to climate change impacts on air quality.[14, 42] At the same time, hundreds of thousands of days of missed school and hundreds of thousands to millions of cases of acute respiratory symptoms also result from the climate-driven ozone increases in the United States.[14]

Major uncertainties

Climate projections are driven by greenhouse gas emission scenarios, which vary substantially depending on assumptions for economic growth and climate change mitigation policies. There is significant internal variability in the climate system, which leads to additional uncertainties in climate projections, particularly on a regional basis. Ozone concentrations also depend on emissions that are influenced indirectly by climate change (for example, incidence of wildfires, changes in energy use, energy technology choices), which further compounds the uncertainty. Studies projecting human health impacts apply concentration–response relationships from existing epidemiological studies characterizing historical air quality changes; it is unclear how future changes in the relationship between air quality, population exposure, and baseline health may affect the concentration–response relationship. Finally, these studies do not account for the possibility of a physiological interaction between air pollutants and temperature, which could lead to increases or decreases in air pollution-related deaths and illnesses.

Assessment of confidence and likelihood based on evidence

Given the known relationship between temperature and ozone, as well as the numerous air quality modeling studies that suggest climate-driven meteorological changes will yield conditions more favorable for ozone formation in the future, there is **high confidence** that ozone levels will **likely** increase due to climate change, unless offset by reductions in ozone precursor emissions. Based on observed relationships between ozone concentrations and human health responses, there is **high confidence** that any climate-driven increases in ozone will **likely** cause additional cases of premature mortality, as well as increasingly frequent cases of hospital visits and lost school days due to respiratory impacts.

Increased Health Impacts from Wildfires

Key Finding 2: Wildfires emit fine particles and ozone precursors that in turn increase the risk of premature death and adverse chronic and acute cardiovascular and respiratory health outcomes [*Likely*, *High Confidence*]. Climate change is projected to increase the number and severity of naturally occurring wildfires in parts of the United States, increasing emissions of particulate matter and ozone precursors and resulting in additional adverse health outcomes [*Likely, High Confidence*].

Description of evidence base

The harmful effects of PM concentrations on human health have been well-documented, and there is equally strong evidence linking wildfires to higher PM concentrations regionally. Recent studies have established linkages between wildfire incidence and adverse health outcomes in the nearby population.[70, 71] Though projections of climate change impacts on precipitation patterns are less certain than those on temperature, there is greater agreement across models that precipitation will decrease in the western United States.[74] Rising temperatures, decreasing precipitation, and earlier springtime onset of snowmelt are projected to lead to increased frequency and severity of wildfires.[22, 75, 77]

Major uncertainties

Future climate projections, especially projections of precipitation, are subject to considerable uncertainty. Land management practices, including possible adaptive measures taken to mitigate risk, could alter the frequency and severity of wildfires, the emissions from wildfires, and the associated human exposure to smoke.

Assessment of confidence and likelihood based on evidence

Given the known association between PM and health outcomes and between wildfires and PM concentrations, there is **high confidence** that an increase in wildfire frequency and severity will **likely** lead to an increase in adverse respiratory and cardiac health outcomes. Based on the robustness of the projection by global climate models that precipitation amounts will decrease in parts of the United States, and that summer temperatures will increase, there is **high confidence** that the frequency and severity of wildfire occurrence will **likely** increase, particularly in the western United States.

Worsened Allergy and Asthma Conditions

Key Finding 3: Changes in climate, specifically rising temperatures, altered precipitation patterns, and increasing concentrations of atmospheric carbon dioxide, are expected to contribute to increases in the levels of some airborne allergens and associated increases in asthma episodes and other allergic illnesses [*High Confidence*].

Description of evidence base

There is a large body of evidence supporting the observation that climate change will alter the production, allergenicity, distribution, and timing of aeroallergens. Historical trends show that climate change has led to changes in the length of the growing season for certain allergenic pollens. Climate change also contributes to changes in allergic illnesses as greater concentrations of CO_2, together with higher temperatures and changes in precipitation, extend the start or duration of the growing season, increase the quantity and allergenicity of pollen, and expand the spatial distribution of pollens.[84, 91, 92, 93, 94] While the role of weather on the initiation or exacerbation of allergic symptoms in sensitive persons is not entirely understood,[86, 107] increases in intensity and frequency of rainfall and storminess over the coming decades is expected to be associated with spikes in aeroallergen concentrations and the potential for related increases in the number and severity of allergic illnesses.[108, 109]

These changes in exposure to aeroallergens contribute to the severity and prevalence of allergic disease in humans. Given that aeroallergen exposure is not the sole, or even necessarily the most significant, factor associated with allergic illnesses, that relationship is part of a complex pathway that links exposure to aeroallergens to the prevalence of allergic illnesses.[81] There is consistent and robust evidence that aeroallergen exposure contributes significantly to the occurrence of asthma episodes, hay fever, sinusitis, conjunctivitis, hives, and anaphylaxis.[84, 88] There is also compelling evidence that allergic diseases develop in response to complex and multiple interactions among both genetic and non-genetic factors, including a developing immune system, environmental exposures (such as ambient air pollution or weather conditions), and socioeconomic and demographic factors.[85, 86, 87] Finally, there is evidence that potential non-linear interactions between aeroallergens and ambient air pollutants is likely to increase health risks for people who are simultaneously exposed.[87, 88, 106, 108, 110, 111, 112, 113, 114]

Major uncertainties

The interrelationships between climate variability and change and exposure to aeroallergens are complex. Where they exist, differences in findings from across the relevant scientific literature may be due to study designs, references to certain species of pollen, geographic characteristics, climate variables, and degree of allergy sensitization.[104] There are also uncertainties with respect to the role of climate change and the extent and nature of its effects as they contribute to aeroallergen-related diseases, especially asthma.[91] Existing uncertainties can be addressed through the development of standardized approaches for measuring exposures and tracking outcomes across a range of allergic illnesses, vulnerable populations, and geographic proximity to exposures.[82]

Assessment of confidence and likelihood based on evidence
The scientific literature suggests that there is **high confidence** that changes in climate, including rising temperatures and altered precipitation patterns, will affect the concentration, allergenicity, season length, and spatial distribution of a number of aeroallergens, and these changes are expected to impact the prevalence of some allergic diseases, including asthma attacks.

DOCUMENTING UNCERTAINTY

This assessment relies on two metrics to communicate the degree of certainty in Key Findings. See Appendix 4: Documenting Uncertainty for more on assessments of likelihood and confidence.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Likelihood
Very Likely
≥ 9 in 10
Likely
≥ 2 in 3
As Likely As Not
≈ 1 in 2
Unlikely
≤ 1 in 3
Very Unlikely
≤ 1 in 10

PHOTO CREDITS

Pg. 69 –Girl with inhaler : © Stephen Welstead/LWA/Corbis

Pg. 70–Firefighters walking in smoke: © Ted Soqui/Corbis

Pg. 72–Ragweed pollen: Courtesy of Roy Morsch/Corbis

Pg. 74–L.A. smog: © Ringo Chiu/ZUMA Press/Corbis

Pg. 77 –Girl with inhaler : © Stephen Welstead/LWA/Corbis

Pg. 79–Moldy archway: Courtesy of Bart Everson/flickr

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