13 Air Quality

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Air Quality

Carr Fire, Shasta County, California, August 2018

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels. This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death. Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests.

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities.

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens.

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality.

Executive Summary

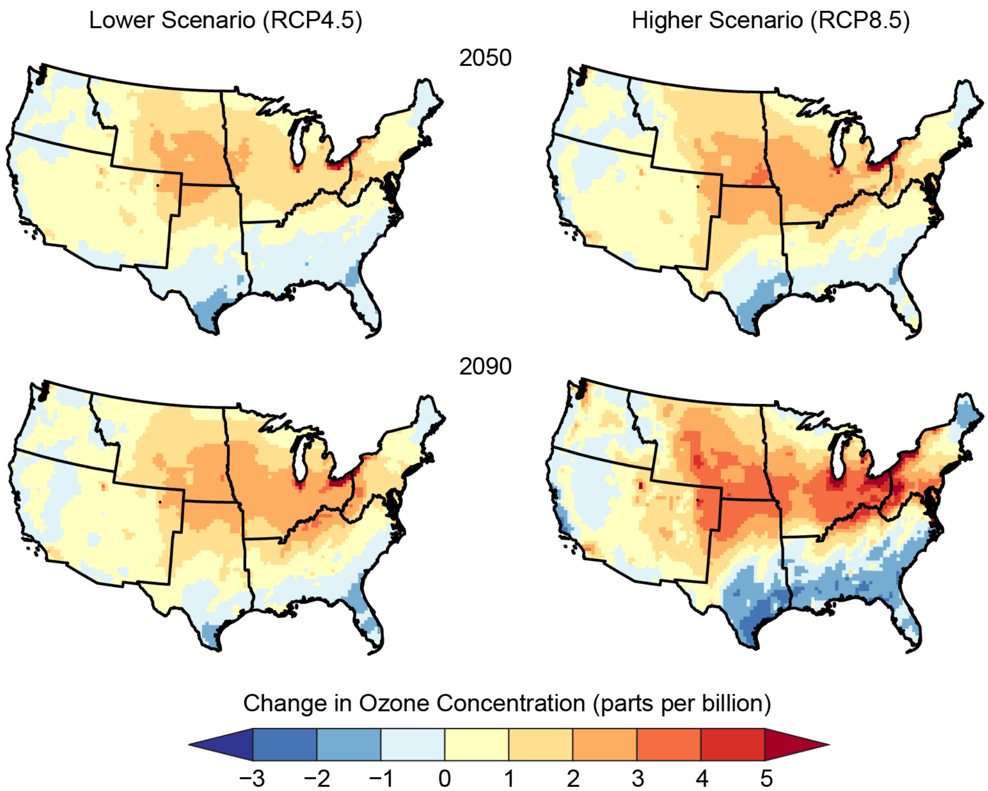
Unless offset by additional emissions reductions of ozone precursor emissions, there is high confidence that climate change will increase ozone levels over most of the United States, particularly over already polluted areas, thereby worsening the detrimental health and environmental effects due to ozone. The climate penalty results from changes in local weather conditions, including temperature and atmospheric circulation patterns, as well as changes in ozone precursor emissions that are influenced by meteorology. Climate change has already had an influence on ozone concentrations over the United States, offsetting some of the expected ozone benefit from reduced precursor emissions. The magnitude of the climate penalty over the United States could be reduced by mitigating climate change.

Climatic changes, including warmer springs, longer summer dry seasons, and drier soils and vegetation, have already lengthened the wildfire season and increased the frequency of large wildfires. Exposure to wildfire smoke increases the risk of respiratory disease, resulting in adverse impacts to human health. Longer fire seasons and increases in the number of large fires would impair both human health and visibility.

Climate change, specifically rising temperatures and increased carbon dioxide (CO_2) concentrations, can influence plant-based allergens, hay fever, and asthma in three ways: by increasing the duration of the pollen season, by increasing the amount of pollen produced by plants, and by altering the degree of allergic reactions to the pollen.

The energy sector, which includes energy production, conversion, and use, accounts for 84% of greenhouse gas (GHG) emissions in the United States as well as 80% of emissions of nitrogen oxides (NO_x) and 96% of sulfur dioxide, the major precursor of sulfate aerosol. In addition to reducing future warming, reductions in GHG emissions often result in co-benefits (other positive effects, such as improved air quality) and possibly some negative effects (disbenefits) (Ch. 29: Mitigation). Specifically, mitigating GHG emissions can lower emissions of particulate matter (PM), ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution.

Projected Changes in Summer Season Ozone



The maps show projected changes in summer averages of the maximum daily 8-hour ozone concentration (as compared to the 1995–2005 average). Summertime ozone is projected to change non-uniformly across the United States based on multiyear simulations from the Community Multiscale Air Quality (CMAQ) modeling system. Those changes are amplified under the higher scenario (RCP8.5) compared with the lower scenario (RCP4.5), as well as at 2090 compared with 2050. Data are not available for Alaska, Hawai'i, U.S.-Affiliated Pacific Islands, and the U.S. Caribbean. *From Figure 13.2 (Source: adapted from EPA 2017[1]).*

State of the Sector

Air quality is important for human health, vegetation, and crops as well as aesthetic considerations (such as visibility) that affect appreciation of the natural beauty of national parks and other outdoor spaces. Many of the processes that determine air quality are affected by weather (Figure 13.1). For example, hot, sunny days can increase ozone levels, while stagnant weather conditions can produce high concentrations of both ozone and particulate matter (PM). Ozone and PM are air pollutants that adversely affect human health and are monitored and regulated with national standards. Temperature, wind patterns, cloud cover, and precipitation, as well as the amounts and types of pollutants emitted into the air from human activities and natural sources, all affect air quality (Figure 13.1). Thus, climate-driven changes in weather, human activity, and natural emissions are all expected to impact future air quality across the United States.

These climate effects on air quality are not expected to occur uniformly at all locations. For example, as discussed in Chapter 2: Climate, precipitation is projected to increase in some regions of the country and decrease in other regions. Regions that experience excessive periods of drought and higher temperatures will have increased frequency of wildfires and more windblown dust from soils. At the same time, changes to temperatures and rainfall affect the types of crops that can be grown (Ch. 10: Ag & Rural) and the length of the growing season, the application of fertilizers and pesticides to crops, and ensuing transport and fate of those chemicals into the air, water, and soil. In the future, climate change is expected to alter the demand for heating and cooling of indoor spaces due to changes in temperatures. The resulting shift in fuel types and amounts used will modify the amount and composition of air pollutants emitted. Climate change can also increase the duration of the pollen season and the amount of pollen at some locations, as well as worsen respiratory health impacts due to pollen exposure. Despite the potential variability in regional impacts of climate change, there is evidence that climate change will increase the risk of unhealthy air quality in the future across the Nation in the absence of further air pollution control efforts (for other impacts of climate change on health, see Ch. 14: Human Health).

Since people spend most of their time inside buildings, indoor air quality is important for human health. Indoor air pollutants may come from interior sources or may be transported into buildings with outdoor air. If there are changes in airborne pollutants of outdoor origin, such as ozone, pollen, mold, and $PM_{2.5}$ (particulate matter less than 2.5 micrometers in diameter), there will be changes in indoor exposures to these contaminants.[2,3]

There is robust evidence from models and observations that climate change is worsening ozone pollution. The net effect of climate change on PM pollution is less certain than for ozone, but increases in smoke from wildfires and windblown dust from regions affected by drought are expected. The complex interactions of natural variability with changes in climate and emissions pose a significant challenge for air quality management. Some approaches to mitigating climate change could result in large near-term co-benefits for air quality.

Pathways by Which Climate Change Will Influence Air Pollution

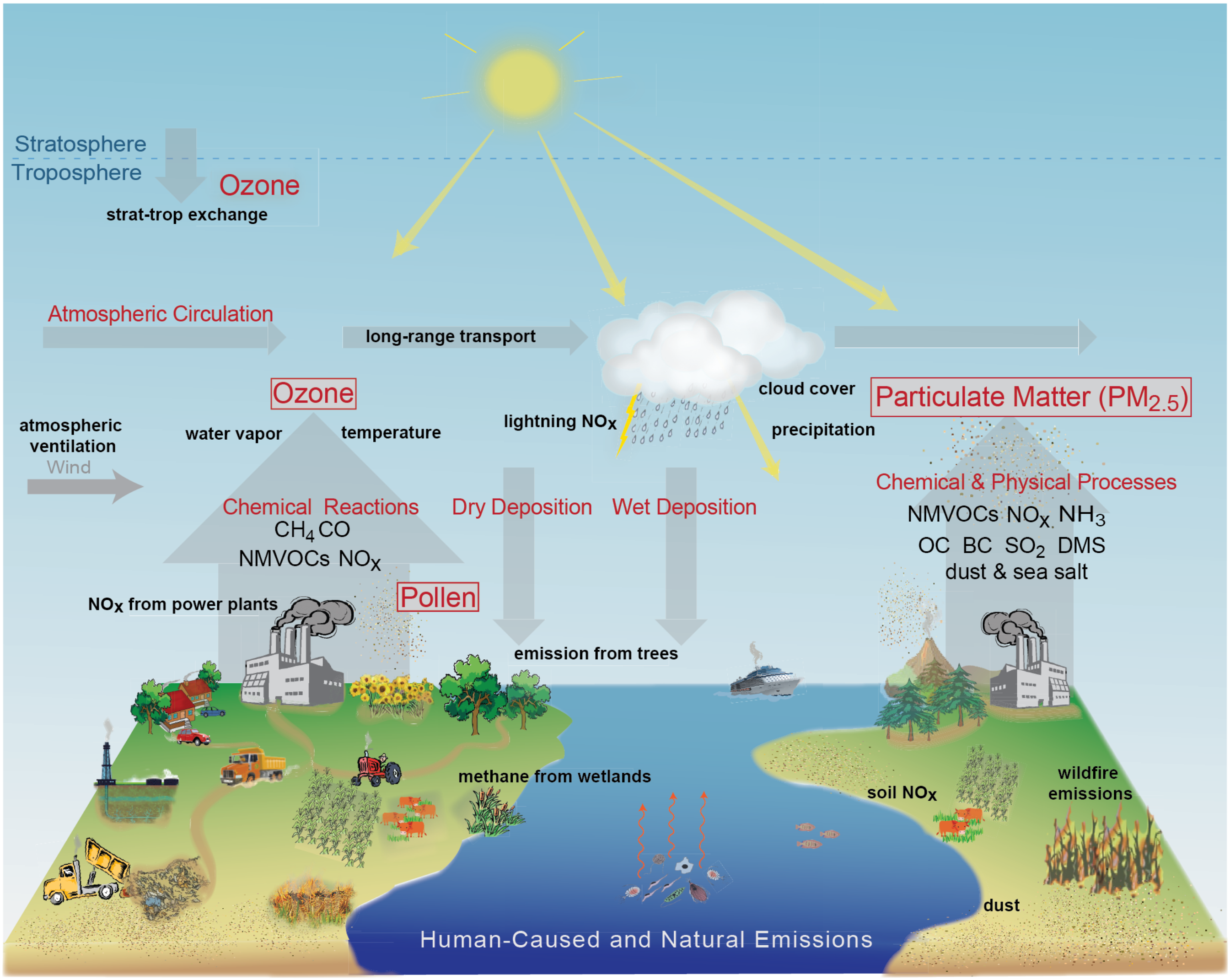


Figure 13.1: Climate change will alter (black bold text) chemical and physical interactions that create, remove, and transport air pollution (red text and gray arrows). Human activities and natural processes release precursors for ground-level ozone (O_3) and particulate matter with a diameter less than 2.5 micrometers ($PM_{2.5}$), including methane (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3), organic carbon (OC), black carbon (BC), and dimethyl sulfide (DMS); and direct atmospheric pollutants, including mineral dust, sea salt, pollen, spores, and food particles. Source: adapted from Fiore et al. 2015.[4] Reprinted by permission of the publisher (Taylor & Francis Ltd., http://www.tandfonline.com).

Air Pollution Health Effects

Ground-level ozone and particulate matter are common air pollutants that pose a serious risk to human health and the environment.[5,6] Short- and long-term exposure to these pollutants results in adverse respiratory and cardiovascular effects,[7] including premature deaths,[8] hospital and emergency room visits, aggravated asthma,[3,9] and shortness of breath.[10] Certain population groups, such as the elderly, children, and those with chronic illnesses, are especially susceptible to ozone and PM-related effects.[11,12,13]

A growing body of evidence indicates the harmful effects of short-term (i.e., daily) exposures to ground-level ozone vary with climate conditions, specifically temperature.[14,15,16,17,18] For a given level of ozone, higher temperatures increase the risk of ozone-related premature death.[14,19,20,21] However, the risk of premature death is likely to decrease as the prevalence of air conditioning increases, as is expected to occur with rising temperatures.[22] The extent to which the growing use of air conditioning will offset climate-induced increases in ozone-related premature death is unknown.

Ozone Air Quality

Ozone is not directly emitted but is formed in the atmosphere by reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Ozone concentrations depend on emissions of these two precursors as well as weather conditions such as temperature, humidity, cloud cover, and winds.[3] These emissions come from a variety of human sources, such as power plants and motor vehicles, and from natural sources, such as forests and wildfires (Figure 13.1). Additionally, ozone concentrations in one region may be influenced by the transport of either precursors or ozone itself from another region.[23,24]

Ozone levels in the United States are often highest in Southern California and the Northeast Corridor as well as around other large cities like Dallas, Houston, Denver, Phoenix, and Chicago,[25] and during extended episodes of extreme heat and sunshine.[26] Ozone air quality in the United States has improved dramatically over the past few decades due to NO_x and VOC emissions control efforts, despite population and economic growth.[27,28,29] Nationally, ozone concentrations have been reduced by 22% over the 1990 to 2016 period.[29] Nonetheless, in 2015 nearly 1 in 3 Americans were exposed to ozone values that exceeded the national standard determined by the U.S. Environmental Protection Agency (EPA) to be protective of human health.[29] Adverse human health impacts associated with exposure to ground-level ozone include premature death, respiratory hospital admissions, cases of aggravated asthma, lost days of school, and reduced productivity among outdoor workers.[30,31,32] Ozone pollution can also damage crops and plant communities, including forests, by reducing photosynthesis.[33]

Due in part to air pollutant regulations driven by the Clean Air Act, NO_x and VOC emissions from human sources should continue to decline over the next few decades.[34] These emissions reductions are designed to reduce ozone concentrations so that polluted areas of the country meet air quality standards. However, climate change will also influence future levels of ozone in the United States by altering weather conditions and impacting emissions from human and natural sources. The prevailing evidence strongly suggests that climate change alone introduces a climate penalty (an increase in air pollution resulting from climate change[35,36]) for ozone over most of the United States from warmer temperatures and increases in natural emissions.[3,4,37,38] This climate penalty will partially counteract the continued reductions in emissions of ozone precursors from human activities.

Particulate Matter

Tiny liquid or solid particles suspended in the atmosphere are known as aerosols or particulate matter (PM). PM includes many different chemical components, such as sulfate, nitrate, organic and black carbon, mineral dust, and sea spray. Unlike ozone, PM can be either directly emitted or formed in the atmosphere. $PM_{2.5}$ refers to atmospheric PM with a diameter less than 2.5 micrometers. These particles are small enough to be inhaled deeply, and exposure to high concentrations can result in serious health impacts, including premature death, nonfatal heart attacks, and adverse birth outcomes.[5,39,40,41] $PM_{2.5}$ concentrations vary greatly with daily weather conditions,[42,43] depending particularly on wind speed (which affects the mixing of pollutants) and precipitation (which removes particles from the air).[4] Concentrations of $PM_{2.5}$ build up during long periods of low wind speeds, and they are reduced when weather fronts move air through a region.[4]

Wildfires not only emit gases that contribute to ozone formation[44,45,46,47,48] but they also are a major source of PM, especially in the western United States during the summer[49,50,51,52,53,54,55] and in the Southeast[48,56] (Ch. 6: Forests; Ch. 19: Southeast, Case Study “Prescribed Fire”; Ch. 24: Northwest; Ch. 25: Southwest). Wildfire smoke can worsen air quality locally,[57] with substantial public health impacts in regions with large populations near heavily forested areas.[56,58,59,60,61] Exposure to wildfire smoke increases the incidence of respiratory illnesses, including asthma, chronic obstructive pulmonary disease, bronchitis, and pneumonia.[62] Smoke can decrease visibility[63] and can be transported hundreds of miles downwind, often crossing national boundaries.[54,64,65,66,67,68,69]

Climate change is expected to impact atmospheric PM concentrations in numerous ways.[38,70] Changing weather patterns, including increased stagnation,[71,72] altered frequency of weather fronts,[73,74] more frequent heavy rain events,[43] changing emissions from vegetation[75,76] and human sources,[77] and increased evaporation of some aerosol components[78] will all affect PM concentrations. In addition, more frequent and longer droughts would lengthen the wildfire season[79,80,81] and result in larger wildfires[82,83] and increased dust emissions in some areas.[84] Projections of regional precipitation changes show considerable variation across models and thus remain highly uncertain.[85] Accurately assessing how $PM_{2.5}$ concentrations will respond to the changing climate is difficult due to these complex and highly spatially variable interactions.

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels. This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death. Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests.

Unless offset by additional reductions of ozone precursor emissions, there is high confidence that climate change will increase ozone levels over most of the United States, particularly over already polluted areas,[3,86] thereby worsening the detrimental health and environmental effects due to ozone. Although competing meteorological effects determine local ozone levels, temperature is often the largest single driver.[87] The climate penalty[35,36] results from changes in local weather conditions, including temperature and atmospheric circulation patterns,[4,88] as well as changes in ozone precursor emissions that are influenced by meteorology.[75,76,77] Climate change has already had an influence on ozone concentrations over the United States, offsetting some of the expected ozone benefit from reduced precursor emissions.[89,90] Assessments of climate change impacts on ozone trends are complicated by year-to-year changes in weather conditions[91] and require multiple years of model information to estimate the potential range of effects.[92] Besides being affected by climate change, future ozone levels in the United States will also be affected greatly by domestic emissions of ozone precursors as well as by international emissions of ozone precursors and global methane levels. Studies suggest that climate change will decrease the sensitivity of regional ozone air quality to intercontinental sources.[93]

$PM_{2.5}$ accounts for most of the health impacts due to air pollution in the United States,[94] and small changes in average concentrations have large implications for public health. Without consideration of climate effects, concentrations of $PM_{2.5}$ in the United States are projected to decline through 2040 due to ongoing emissions control efforts.[34] $PM_{2.5}$ is highly sensitive to weather conditions, including temperature, humidity, wind speed, and rainfall. The effects of climate change on the timing, intensity, duration, and frequency of rainfall are highly uncertain, influencing both the removal of $PM_{2.5}$ from air and the incidence of wildfires and their associated emissions. Accordingly, the net impact of climate-driven weather changes on $PM_{2.5}$ concentrations is less certain than for ozone.[3,4,43,70] However, some studies have indicated that even without considering increased wildfire frequency, climate change will cause a small but important increase in $PM_{2.5}$ over North America.[95,96] The impact of climate change on the $PM_{2.5}$ contribution from intercontinental sources, which depends strongly on projected changes in precipitation, remains highly uncertain.[24]

The health impacts of climate-induced changes in air quality may be reduced by various adaptation measures. For example, as local authorities issue air quality alerts, people may reduce their exposure to air pollution by postponing outdoor activities and staying indoors (for further information on the role of adaptation in reducing climate-related health risks, see Ch. 14: Human Health, KM 3).

The magnitude of the climate penalty over the United States could be reduced by mitigating climate change.[1,90,97] For example, Figure 13.2 shows results from one study[1] projecting the change in summertime ozone resulting from two different future scenarios (RCP8.5 and RCP4.5) (see the Scenario Products section of App. 3 for additional information about these scenarios) at 2050 and 2090, with human emissions of ozone precursors held constant. Due to climate change, ozone is projected to increase over a broad portion of the United States. Mitigating climate change globally (for instance, following RCP4.5 rather than RCP8.5) would reduce the impact on ozone, resulting in fewer adverse health effects, including 500 fewer premature deaths per year due to ozone in 2090.[1]

Projected Changes in Summer Season Ozone

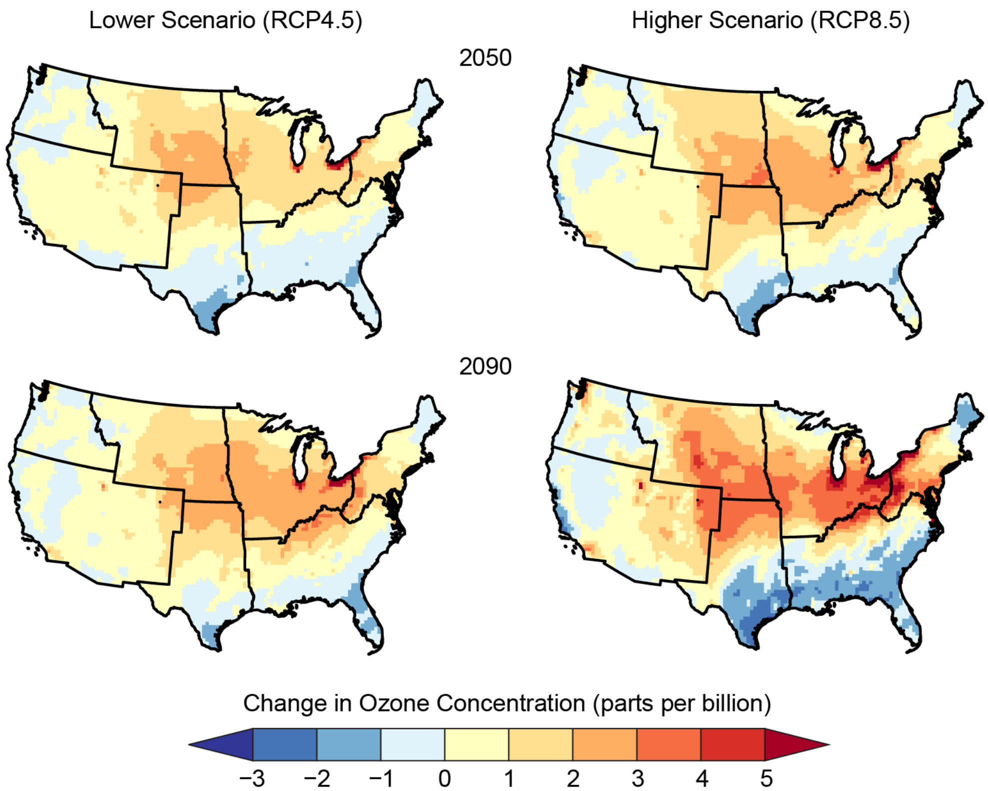


Figure 13.2: The maps show projected changes in summer averages of the maximum daily 8-hour ozone concentration (as compared to the 1995–2005 average). Summertime ozone is projected to change non-uniformly across the United States based on multiyear simulations from the Community Multiscale Air Quality (CMAQ) modeling system. Those changes are amplified under the higher scenario (RCP8.5) compared with the lower scenario (RCP4.5), as well as at 2090 compared with 2050. Data are not available for Alaska, Hawai'i, U.S.-Affiliated Pacific Islands, and the U.S. Caribbean. Source: adapted from EPA 2017.[1]

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities.

Climatic changes, including warmer springs, longer summer dry seasons, and drier soils and vegetation, have already lengthened the wildfire season[79,80,81,98] (Ch. 6: Forests) and increased the frequency of large wildfires.[82,83]

Human-caused climate change is estimated to have doubled the area of forest burned in the western United States from 1984 to 2015.[99] Projections indicate that the wildfire frequency and burned area in North America will continue to increase over the 21st century due to climate change.[100,101,102,103,104,105,106]

Wildfires and prescribed fires contribute to ozone formation[44,107] and are major sources of PM, together comprising about 40% of directly emitted $PM_{2.5}$ in the United States in 2011.[34] Exposure to wildfire smoke increases the risk of respiratory disease and mortality.[56,60,62] Longer fire seasons and increases in the number of large fires would impair both human health[108] and visibility.[54,63] Wildfires are projected to become the principal driver of summertime

$PM_{2.5}$ concentrations, offsetting even large reductions in emissions of $PM_{2.5}$ precursors.[54,109]

Opportunities for outdoor recreational activities are also vulnerable to changes in the frequency and intensity of wildfires due to climate change. Climate change-induced increases in wildfire smoke events are likely to reduce the amount and quality of time spent in outdoor activities (Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 4). More accurate forecasting of smoke events may mitigate some of the negative effects through changes in timing of outdoor activities.

Forests are actively managed, and the frequency and severity of wildfire occurrence in the future will not be determined solely by climate factors. Humans affect fire activity in many ways, including increasing ignitions and conducting controlled burns and fire suppression.[110,111] Forest management decisions may outweigh the impacts of climate change on both forest ecosystems and air quality.[112]

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens.

Climate change, specifically rising temperatures and increased CO_2 concentrations, can influence plant-based allergens, hay fever, and asthma in three ways: by increasing the duration of the pollen season, by increasing the amount of pollen produced by plants, and by altering the degree of allergic reactions to pollen.

Seasonally, airborne allergen (aeroallergen) exposure in the United States begins with the release of tree pollen in the spring. Between the 1950s and the early 2000s, warming winters and earlier arrival of springs have resulted in earlier flowering of oak trees.[113] Projected increases in CO_2 induce earlier and greater seasonal pollen production in pine trees[114] and oak trees.[115] For summer pollen producers, such as weeds and grasses, the effect of warming temperatures on earlier flowering is less evident. However, the allergen content of timothy grass pollen increases with concurrent increases in ozone and CO_2.[116] For common ragweed, the primary fall aeroallergen, greenhouse studies simulating increased temperature and CO_2 concentrations resulted in earlier flowering, greater floral numbers, increased pollen production, and enhanced allergen content of the pollen.[117,118,119,120] Regional and continental studies indicate that ragweed growth and pollen production increase with urban-induced increases in temperature and CO_2. Ragweed pollen season exposure varies as a function of latitude and delayed autumnal frosts in North America.[119,121] In addition to pollen, aeroallergens are also generated by molds. Plants are often affected, since they can serve as hosts for fungi. For example, projected end-of-century CO_2 concentrations would substantially increase the number of allergenic spores produced from timothy grass.[122]

Although warming temperatures and rising CO_2 levels clearly increase aeroallergen prevalence, the link between exposure and health impacts is less well established. However, hay fever prevalence has been associated with exposure to annual and seasonal extreme heat events.[123] Furthermore, climate-induced changes in oak pollen are projected to increase the number of asthma-related emergency department visits in the Northeast, Southwest, and Midwest.[115]

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality.

The energy sector, which includes energy production, conversion, and use, accounts for 84% of greenhouse gas (GHG) emissions[124] as well as 80% of emissions of NO_x and 96% of sulfur dioxide, the major precursor of sulfate aerosol.[125] In addition to reducing future warming, reductions in GHG emissions often result in co-benefits (other positive effects, such as improved air quality) and possibly some negative effects (disbenefits) (Ch. 29: Mitigation). Specifically, mitigating GHGs can lower emissions of PM, ozone and PM precursors, and other hazardous pollutants, reducing the risks to human health from air pollution.[97,126,127,128,129,130] However, the magnitude of air quality co-benefits depends on a number of factors. Areas with higher levels of air pollution have more potential for air quality co-benefits compared to areas where emission controls have been enacted and air pollution levels have been reduced.[131] Different approaches to GHG mitigation yield different reductions, or in some cases, increases in ozone and PM precursors.[132] For example, diesel vehicles emit less GHGs than gasoline-powered vehicles, but without correctly operating pollution-control devices, diesel vehicles emit more particles and ozone precursors and thus contribute more to air quality human health risks.[133]

In addition to co-benefits from sources that emit multiple pollutants, mitigating individual GHGs could yield co-benefits. For example, methane is both a GHG and a slowly reactive ozone precursor that contributes to global background surface ozone concentrations. Some monitoring stations in remote parts of the western United States have recorded rising ozone concentrations, resulting in part from increased global methane levels.[90] The magnitude of the human health benefit of lowering ozone levels via methane mitigation is substantial and is similar in value to the climate change benefits.[134,135] Additionally, PM influences climate on local to global scales by affecting the radiation balance of the Earth,[23,136] so controlling emissions of PM and its precursors would not only yield direct human health benefits via reduced exposure but also avoid or minimize local meteorological conditions that lead to a buildup of pollutants.[137]

Acknowledgments

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Opening Image Credit

Carr Fire, Shasta County, California: Sgt. Lani O. Pascual/U.S. Army National Guard.

Traceable Accounts

Process Description

Due to limited resources and requirements imposed by the Federal Advisory Committee Act, the decision was made that this chapter would be developed using an all-federal author team. The author team was selected based on expertise in climate change impacts on air quality; several of the chapter authors were authors of the "Air Quality Impacts" chapter of the U.S. Global Change Research Program's (USGCRP) Climate and Health Assessment.[3] This chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors via weekly teleconferences and email exchanges. The authors considered inputs and comments submitted by the public; the National Academies of Sciences, Engineering, and Medicine; and federal agencies.

Key Message 1

Increasing Risks from Air Pollution

More than 100 million people in the United States live in communities where air pollution exceeds health-based air quality standards. Unless counteracting efforts to improve air quality are implemented, climate change will worsen existing air pollution levels (*likely, high confidence*). This worsened air pollution would increase the incidence of adverse respiratory and cardiovascular health effects, including premature death (*high confidence*). Increased air pollution would also have other environmental consequences, including reduced visibility and damage to agricultural crops and forests (*likely, very high confidence*).

Description of evidence base

It is well established that air pollutants pose a serious risk to human health and the environment.[5,6] Short- and long-term exposure to pollutants such as ozone or $PM_{2.5}$ results in premature deaths,[8] hospital and emergency room visits, aggravated asthma,[3,9] and shortness of breath.[10] Numerous air quality modeling studies have assessed the potential impacts of a changing climate on future ozone and particulate matter levels in the United States.[4,37,38,70,86] These studies examine simulations conducted with a broad ensemble of global and regional climate models under various potential climate scenarios. For ozone, these model assessments consistently project higher future levels commensurate with warmer climates, independent of varying individual model assumptions. This model consensus strengthens confidence in the projected signal. Additionally, well-established data analyses have shown a strong positive correlation between temperature and ozone at many locations in the United States.[87,89] Although competing meteorological effects determine local ozone levels, temperature is often the single largest meteorological driver. This present-day signal also bolsters confidence in the conclusion that warmer climates will be associated with higher ozone. There are also modeling and observational studies that demonstrate that ozone precursor emissions from natural[75] and human sources[77] increase with temperature. In aggregate, the consistency in the ozone response to past and projected future climate across a large volume of analyses provides high confidence that ozone air pollution will likely be worsened in a warmer climate. For particulate matter, the model assessments exhibit greater variability in terms of future concentration differences projected to result from meteorological changes in a warmer climate.[3,4,43,70] The reduced certainty in the response of $PM_{2.5}$ concentrations (particulate matter, or PM, less than 2.5 micrometers in diameter) to changing meteorological drivers is the result of the multiple pathways toward $PM_{2.5}$ formation and the variable influence of meteorological factors on each of those different pathways.[5] Most of these model assessments have not considered the impact of changes in PM from changes in wildfires or windblown dust because they are difficult to quantify. Studies that have included projections of future wildfire incidences have concluded that climate-driven increases in wildfire activity are *likely*, with wildfires becoming an increasingly important source of $PM_{2.5}$[63,108,109] and degrading visibility.[54] Finally, there is ample observational evidence that decreasing ozone and particulate precursor emissions would reduce pollutant levels.[28,29]

Major uncertainties

Model simulations of future air quality indicate that climate warming generally increases ground-level ozone across the United States (see Figure 13.2), but results differ spatially and in the magnitude of the projected signal.[90,138,139,140,141] Because meteorological influences on ozone formation can vary to some degree by location (for example, wind direction may be paramount in locations affected primarily by ozone transport), a few areas may experience lower ozone levels.[4] Future ozone levels over the United States will depend not only on the severity of the climate change impacts on meteorology favorable for ozone accumulation but also on any measures to reduce ozone precursor emissions, introducing further uncertainty. Even larger uncertainties exist with respect to the climate impacts on $PM_{2.5}$, where the future concentrations will depend on changes in a suite of meteorological factors, which in some cases (for example, precipitation) are more difficult to quantify.

Description of confidence and likelihood

There is *high confidence* that rising temperatures will *likely* increase future ozone levels in many parts of the United States in response to climate change. There is greater uncertainty that a warmer climate will increase future $PM_{2.5}$ levels over the United States. Ultimately, the actual ozone and $PM_{2.5}$ changes between the present and the future at any given location will depend on the local climate impacts on meteorology and pollutant emission controls in that region. There is *very high confidence* that reducing ozone precursor emissions and $PM_{2.5}$ precursors and/or direct emissions will *likely* lead to improved air quality in the future, thus mitigating adverse climate effects.

Key Message 2

Increasing Impacts of Wildfires

Wildfire smoke degrades air quality, increasing the health risks to tens of millions of people in the United States. More frequent and severe wildfires due to climate change would further diminish air quality, increase incidences of respiratory illness from exposure to wildfire smoke, impair visibility, and disrupt outdoor recreational activities (*very likely, high confidence*).

Description of evidence base

Wildfire smoke worsens air quality through its direct emissions to the atmosphere as well as through chemical reactions of those pollutants with sunlight and other pollutants. Exposure to wildfire smoke increases the risk of exacerbating respiratory illnesses in tens of millions of people in vulnerable population groups across the United States.[62] Several studies have indicated that climate change has already led to longer wildfire seasons,[79] increased frequency of large wildfires,[82,83] and increased area of forest burned.[99] Additional studies project that climate change will cause wildfire frequency and burned area in North America to increase over the 21st century.[81,100,101,102,103,104,105,106] Increased emissions from wildfires may offset the benefits of large reductions in emissions of $PM_{2.5}$ precursors.[54,109] There is a broad and consistent evidence base leading to a high confidence conclusion that the increasing impacts of wildfire are very likely. Increases in wildfire smoke events due to climate change would reduce opportunities for outdoor recreational activities (Ch. 22: N. Great Plains, KM 3; Ch. 24: Northwest, KM 4).

Major uncertainties

Humans affect fire activity in many ways, including increasing ignitions as well as conducting controlled burns and fire suppression activities.[110,111] The frequency and severity of wildfire occurrence in the future will be largely determined by forest management practices and climate adaptation measures, which are very uncertain. Housing development practices and changes in the urban–forest interface are also important factors for future wildfire occurrence and for the extent to which associated smoke emissions impair air quality and result in adverse health effects. The composition of the pollutants contained in wildfire smoke and their chemical reactions are highly dependent on a variety of environmental factors, so projecting and quantifying the effects of wildfire smoke on specific pollutants can be particularly challenging. Exposure to wildfire smoke may also increase the risk of cardiovascular illness, but additional data are required to quantify this risk.[62] More accurate forecasting of wildfire smoke events may mitigate health impacts and reduced opportunities for outdoor recreational activities through changes in timing of those activities.

Description of confidence and likelihood

There is *high confidence* that rising temperatures and earlier spring snowmelt will *very likely* result in lengthening the wildfire season in portions of the United States, leading to an increased frequency of wildfires and associated smoke. There is *very high confidence* that increasing exposure to wildfire smoke, which contains particulate matter, will increase adverse health impacts. It is *likely* that smoke from wildfires will reduce visibility and disrupt outdoor recreational activities.

Key Message 3

Increases in Airborne Allergen Exposure

The frequency and severity of allergic illnesses, including asthma and hay fever, are likely to increase as a result of a changing climate. Earlier spring arrival, warmer temperatures, changes in precipitation, and higher carbon dioxide concentrations can increase exposure to airborne pollen allergens. (*Likely, High Confidence*)

Description of evidence base

Considerable evidence supports the conclusion that climate change and rising levels of CO_2 affect key aspects of aeroallergen biology, including the production, temporal distribution, and potential allergenicity of aeroallergens.[142,143,144,145,146] This evidence includes historical trends indicating that climate change has altered seasonal exposure times for allergenic pollen.[113] These changes in exposure times are associated with rising CO_2 levels, higher temperatures, changes in precipitation (which can extend the start or duration of pollen release times), and the amount of pollen released, the allergenicity of the pollen, and the spatial distribution of that pollen.[117,118,119,147]

Specific changes in weather patterns or extremes are also likely to contribute to the exacerbation of allergy symptoms. For example, thunderstorms can induce spikes in aeroallergen concentrations and increase the incidence and severity of asthma and other allergic disease.[148,149] However, the specific mechanism for intensification of weather and allergic disease is not entirely understood.

Overall, climate change and rising CO_2 levels are likely to increase exposure to aeroallergens and contribute to the severity and prevalence of allergic disease, including asthma.[115] There is consistent and compelling evidence that exposure to aeroallergens poses a significant health risk in regard to the occurrence of asthma, hay fever, sinusitis, conjunctivitis, hives, and anaphylaxis.[150,151,152,153] Finally, there is evidence that synergies between aeroallergens and air pollution, especially particulate matter, may increase health risks for individuals who are simultaneously exposed.[154,155,156]

Major uncertainties

While specific climate- and/or CO_2-induced links to aeroallergen biology are evident, allergic diseases develop in response to complex and multiple interactions, including genetic and non-genetic factors, a developing immune system, environmental exposures (such as ambient air pollution or weather conditions), and socioeconomic and demographic factors. Overall, the role of these factors in eliciting a health response has not been entirely elucidated. However, recent evidence suggests that climate change and aeroallergens are having a discernible impact on public health.[123,157]

There are a number of areas where additional information is needed, including regional variation in climate and aeroallergen production; specific links between aeroallergens and related diseases, particularly asthma; the need for standardized approaches to determine exposure times and pollen concentration; and uncertainty regarding the role of CO_2 on allergenicity.

Description of confidence and likelihood

The scientific literature shows that there is *high confidence* that changes in climate, including rising temperatures and altered precipitation patterns as well as rising levels of atmospheric CO_2, will increase the concentration, allergenicity, season length, and spatial distribution of a number of aeroallergens. These changes in aeroallergen exposure are, in turn, *likely* to impact allergic disease.

Key Message 4

Co-Benefits of Greenhouse Gas Mitigation

Many emission sources of greenhouse gases also emit air pollutants that harm human health. Controlling these common emission sources would both mitigate climate change and have immediate benefits for air quality and human health. Because methane is both a greenhouse gas and an ozone precursor, reductions of methane emissions have the potential to simultaneously mitigate climate change and improve air quality. (*Very Likely, Very High Confidence*)

Description of evidence base

Decades of experience in air quality management have resulted in a detailed accounting of the largest emission sources of greenhouse gases (GHGs) and precursors of ozone and PM. The cost and effectiveness of emission control technologies for the largest emissions sources are well understood. By combining these emission and control technology data with energy system modeling tools, the potential to achieve benefits to air quality while mitigating GHG emissions under a range of scenarios has been quantified in numerous studies.

Major uncertainties

A wide range of values have been reported for the magnitude of air quality co-benefits. Much of this variability can be attributed to differences in the mix of co-benefits included in the analysis and the time period under consideration. The largest sources of uncertainty are the cost paths of different energy technologies over time and the extent to which policy choices impact the evolution of these costs and the availability of different energy technologies.

Description of confidence and likelihood

There is *very high confidence* that emissions of ozone and PM precursors could be reduced by reducing combustion sources of CO_2. Reducing emissions of ozone and PM precursors would be *very likely* to reduce ozone and PM pollution, which would *very likely* result in fewer adverse health effects from air pollution. There is *very high confidence* that controlling methane emissions would also reduce ozone formation rates, which would also *very likely* lead to lower ozone levels.

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