Fifth National Climate Assessment: Chapter 14

Air Quality

Chapter 14. Air Quality

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Introduction

Good air quality is vital to human health and the environment. Ozone and fine particulate matter ($PM_{2.5}$) are air pollutants with widespread health and environmental effects that derive from emissions from a variety of natural and human-caused sources, including industry, power plants, vehicles, and agriculture. Ozone is a colorless gas that forms in the atmosphere from emissions of other compounds. At ground level, ozone is a powerful oxidant that, when inhaled, affects the respiratory and cardiovascular system, causing a wide range of health outcomes including lung damage and premature mortality.[1,2] It also damages crops and natural vegetation.[1,3] $PM_{2.5}$ is defined as airborne particles with a diameter of 2.5 micrometers and smaller—about 30 times smaller than the width of a human hair. These small particles can be inhaled into the lungs, leading to health problems including cardiovascular disease, adverse birth outcomes, neurological disease, and increased risk of death.[4,5,6,7,8,9,10] $PM_{2.5}$ is a complex mixture of solid and liquid substances,[11] including particles emitted directly from combustion and those formed in the atmosphere from gases emitted from natural and human sources. $PM_{2.5}$ also contributes to regional haze, which can impair enjoyment of scenic vistas, including in national parks.

Ground-level ozone and $PM_{2.5}$ have declined in the US due to programs that lowered emissions. From 2000 to 2020, extreme ozone levels (98th percentile) declined by 18%,[12] and annual average $PM_{2.5}$ concentrations declined by 41%.[13] Continued reductions in human-caused emissions are projected to bring still cleaner air in the US.[14,15]

Despite these improvements, in 2021 nearly 102 million people lived in areas where pollution levels exceeded health-based air quality standards.[13] Estimates of annual US deaths from exposure to ambient ozone and $PM_{2.5}$ range from about 60,000[16]—more deaths than from either motor vehicle accidents, kidney disease, breast cancer, or prostate cancer—to 260,000[17,18,19] or more,[20] valued at $750 billion to $3 trillion (in 2022 dollars).[21,22] Air pollution damages to US crops are estimated at approximately $12 billion annually (in 2022 dollars).[23] The negative impacts of air pollution are not distributed equally, with communities of color and low-income communities disproportionately burdened.[24,25]

Climate change, driven mainly by human greenhouse gas (GHG) emissions that are not harmful to breathe at typical atmospheric levels, affects air pollutant concentrations through multiple pathways (KM 14.1) including wildfire smoke (KM 14.2) and affects aeroallergens (KM 14.4), with effects on health. Air pollutants also affect climate (KM 3.1), and the main sources of air pollutants are also the main sources of GHG emissions, suggesting that there is opportunity to address climate and air quality goals simultaneously (KM 14.5). Current inequities in air pollution exposure may be alleviated or worsened by the impacts of climate change and actions to reduce GHG emissions (KM 14.3).

Key Message 14.1

Climate Change Will Hamper Efforts to Improve US Air Quality

Climate change is projected to worsen air quality in many US regions (*medium confidence*), thereby harming human health and increasing premature death (*very likely*, *high confidence*). Extreme heat events, which can lead to high concentrations of air pollution, are projected to increase in severity and frequency (*very likely*, *very high confidence*), and the risk of exposure to airborne dust and wildfire smoke will increase with warmer and drier conditions in some regions (*very likely*, *high confidence*). Reducing air pollution concentrations will unequivocally help protect human health in a changing climate.

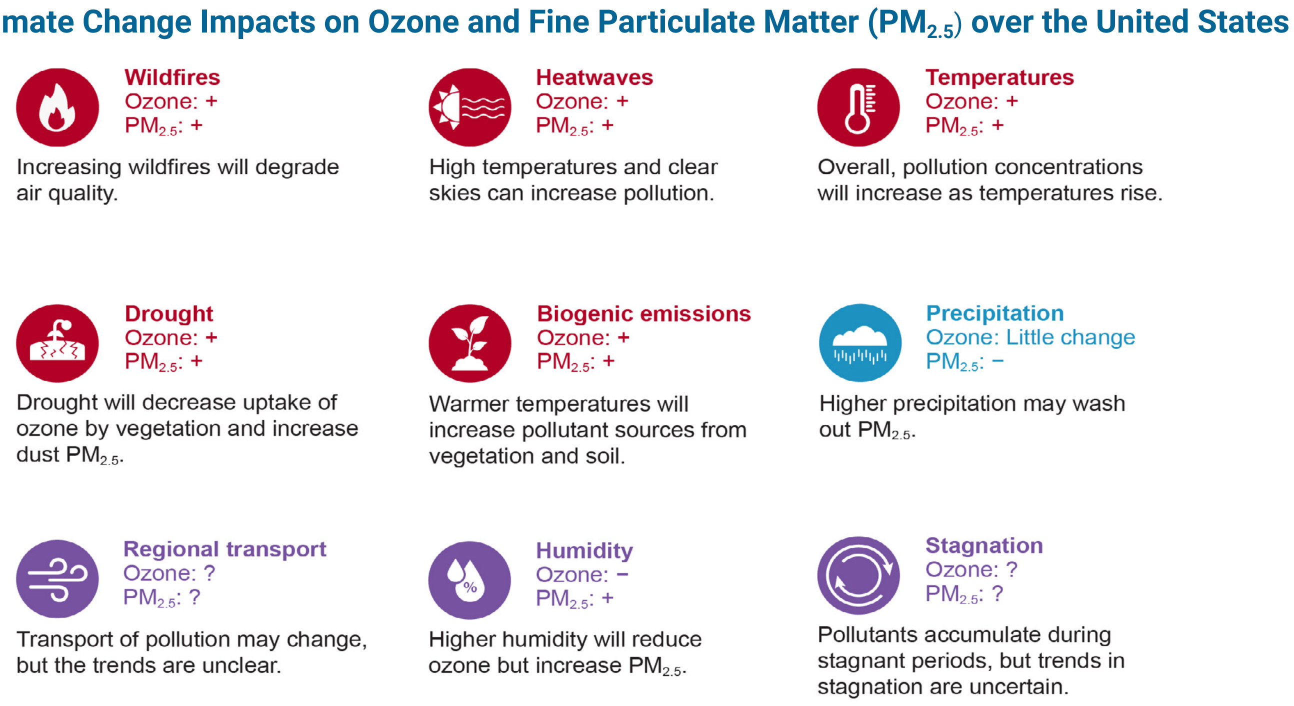
Air pollution concentrations are determined by natural and human-caused emissions and by atmospheric conditions, including temperature, humidity, and winds. Climate change is projected to worsen air quality in many regions, harming human health. Some of the largest increases in $PM_{2.5}$ and ozone exposure are expected in heat- and drought-prone regions (Figure 14.1) and in areas where vulnerable populations live (KM 14.3). For example, increasing heat and drought already contribute to more frequent wildfires and associated smoke episodes (KMs 14.2, 7.1). Severe climate change, with a US average warming of 9°–14°F, would increase annual US air pollution–related deaths by about 25,000 in 2100, relative to 2000.[26,27] This estimate assumes population growth but no change in emissions, including wildfire smoke. Given that wildfires and smoke $PM_{2.5}$ are projected to increase in a warmer climate (KM 14.2), this mortality rate may be an underestimate.

Climate change is expected to alter meteorology over the US in several ways that will directly degrade air quality (Figure 14.1). For example, ozone levels are higher on warm, sunny days because the chemical reactions that produce ozone speed up with temperature and sunlight. Exposure to these short-term ozone episodes has been linked to increased mortality.[28] Some gases that produce ozone and $PM_{2.5}$ come from soils and vegetation, and these emissions are sensitive to temperature and rainfall. Such processes typically lead to higher pollution levels during heatwaves, when exposure to $PM_{2.5}$ appears to be especially harmful.[29,30,31,32]

Local air pollution events are also strongly tied to large-scale weather patterns.[33,34,35,36] For example, cold fronts sweep clean air across the eastern US, clearing the air of pollution.[37] How climate change will affect these large-scale patterns is not well known. In the eastern US, the largest and most persistent pollution events often co-occur with extreme heat.[38] Air stagnation events, when weak winds provide little ventilation near the ground, promote pollution accumulation. Co-occurrences of heat and air stagnation are projected to increase with climate change.[39] Air pollution is also expected to worsen as the warm season lengthens, with greater pollution during the spring and autumn.[40,41] Other meteorological changes accompanying climate change may improve air quality. For example, increasing humidity may reduce ozone through chemical reactions, while increasing precipitation may remove $PM_{2.5}$ from the atmosphere (Figure 14.1).

Methane, a key GHG that contributes to near-term warming (KM 14.5), is a source of global background ozone when it undergoes chemical oxidation in the presence of nitrogen oxides.[42,43] Continued growth in methane emissions from wetlands and human activities would raise background ozone levels, including in winter (KM 3.1),[44,45] increasing the potential for a longer ozone season that begins earlier in the spring.[46] As with ozone episodes, long-term exposure to background ozone also increases mortality.[2,47]

The response of ozone and $PM_{2.5}$ to climate change—and their associated impacts on health—will vary regionally, reflecting the net balance of several complex chemical, meteorological, and small-scale processes, which vary spatially and over time (Figure 14.1).[48,49,50] Across the Midwest and Northeast, year-round ozone is expected to increase by 2035 under a very high scenario (RCP8.5).[51] In California and the Northeast, increasing temperatures under a moderate scenario (RCP4.5) would double the number of severe ozone episodes by the 2050s relative to the early 2000s,[52] with further increases in summer average ozone in these regions by 2100.[53] Projecting future $PM_{2.5}$ is complicated, as different types of $PM_{2.5}$ are expected to respond differently to changing climate.[51,54] Wildfires are expected to increase smoke $PM_{2.5}$ in the West and Alaska (KM 14.2). The rugged western topography makes it particularly susceptible to $PM_{2.5}$ increases, especially in winter when mountain valleys trap polluted air.[55] Declines in lake area in some areas of the mountainous West, driven mainly by human water use but also by changing climate, have exposed lakebeds and increased dust emissions.[56,57,58] These declines in lake area are projected to continue as temperatures rise and snowpack diminishes (KM 4.1), with further increases in dust.[59,60,61] In the arid Southwest, dust concentrations are expected to double by 2100, compared to 2010, due to warmer and drier conditions (KMs 6.1, 28.3, 28.4).[62,63] Multiple studies agree that climate change is expected to increase $PM_{2.5}$ concentrations in the Northeast.[40,49,64]



Climate Change Impacts on Ozone and Fine Particulate Matter ($PM_{2.5}$) over the United States

Wildfires
Ozone: +
$PM_{2.5}$: +

Increasing wildfires will degrade air quality.

Heatwaves
Ozone: +
$PM_{2.5}$: +

High temperatures and clear skies can increase pollution.

Temperatures
Ozone: +
$PM_{2.5}$: +

Overall, pollution concentrations will increase as temperatures rise.

Drought
Ozone: +
$PM_{2.5}$: +

Drought will decrease uptake of ozone by vegetation and increase dust $PM_{2.5}$.

Biogenic emissions
Ozone: +
$PM_{2.5}$: +

Warmer temperatures will increase pollutant sources from vegetation and soil.

Precipitation
Ozone: Little change
$PM_{2.5}$: −

Higher precipitation may wash out $PM_{2.5}$.

Regional transport
Ozone: ?
$PM_{2.5}$: ?

Transport of pollution may change, but the trends are unclear.

Humidity
Ozone: −
$PM_{2.5}$: +

Higher humidity will reduce ozone but increase $PM_{2.5}$.

Stagnation
Ozone: ?
$PM_{2.5}$: ?

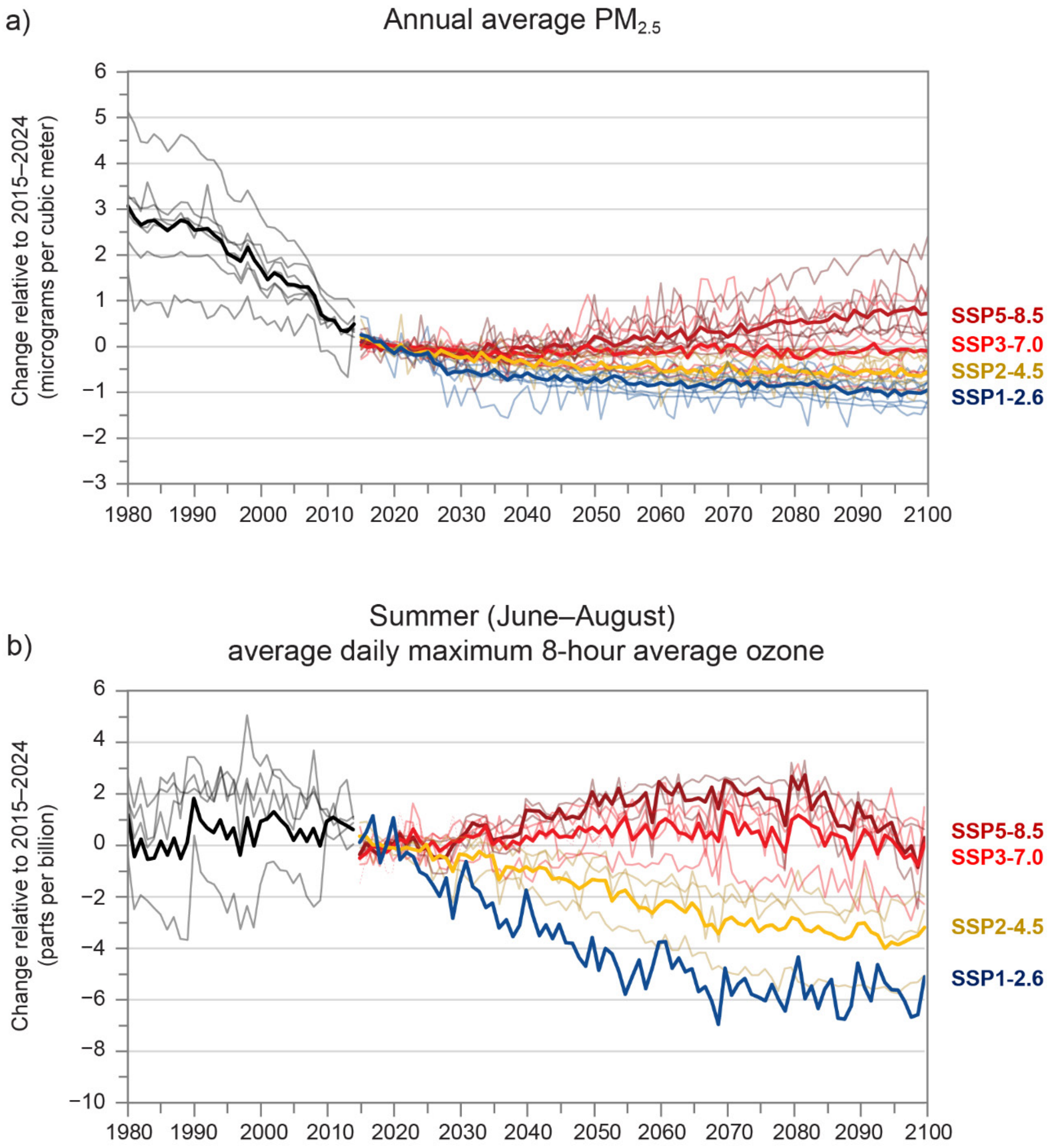
Pollutants accumulate during stagnant periods, but trends in stagnation are uncertain.

Climate change will have varying effects on ozone and fine particulate matter ($PM_{2.5}$) concentrations, including through impacts on weather-sensitive emissions.

Figure 14.1. Climate change is projected to alter concentrations of two key US air pollutants, ozone and $PM_{2.5}$, through several processes. Red icons signify increased ozone and $PM_{2.5}$, and the blue icon denotes decreased $PM_{2.5}$. Plus and minus signs indicate the expected pollutant response to climate-driven changes in meteorology. Question marks and purple icons denote uncertainty in either the response or in how the meteorological process will change with climate change. Given uncertainties and regional differences in pollution responses, the magnitude of these responses is not presented. Key Messages 14.1 and 14.2 provide more detailed descriptions of the mechanisms involved. Adapted from The Royal Society 2021[65] [CC BY 4.0].

The adverse effect of climate change on the air we breathe is known as the climate penalty on air quality, in which climate change counteracts some of the benefits expected from emissions reductions.[66] Figure 14.2 illustrates how air quality can vary under different scenarios of air pollution sources and GHGs in future decades. In general, climate change is expected to worsen air quality, although the actions that policymakers and communities take today could counteract this outcome. Steeper reductions in the human-caused emissions that contribute to ozone and $PM_{2.5}$ are expected to lessen this climate penalty and limit adverse health effects.[15,64,67,68]

Simulated Historical and Projected Changes in Fine Particulate Matter ($PM_{2.5}$) and Ozone



Reductions in human-caused emissions that contribute to ozone and fine particulate matter ($PM_{2.5}$) are expected to improve air quality in a changing climate.

Figure 14.2. Future air quality depends on both air pollution control measures and climate change. Modeled pollutant concentrations are shown averaged over the contiguous US, with the historical period in black and projections in various colors, for (**a**) annual average $PM_{2.5}$ and (**b**) summer (June–August) average daily maximum 8-hour average ozone, a metric of ozone pollution. Trends are shown relative to the 2015–2024 average value. Historical air quality improvements reflect clean air policies. Thick lines are multimodel average values. Thin lines show individual model simulations, indicating uncertainties from modeled processes and natural weather variability for each scenario. The focus on the contiguous states reflects the stronger influence from domestic emissions compared to other US regions (Alaska, Hawai‘i and the US-Affiliated Pacific Islands, and the US Caribbean), where the balance of processes contributing to pollution and responses to climate change are expected to differ. These projections do not include the expected strong influence of climate change on wildfire smoke. Model simulations are described by Turnock et al. 2020.[15] Figure credit: Massachusetts Institute of Technology. See figure metadata for additional contributors.

Key Message 14.2

Increasing Wildfire Smoke Is Harming Human Health and Catalyzing New Protection Strategies

Wildfires emit gases and fine particles that are harmful to human health, contributing to premature mortality, asthma, and other health problems (*very high confidence*). Climate change is contributing to increases in the frequency and severity of wildfires, thereby worsening air quality in many regions of the contiguous US and Alaska (*likely*, *high confidence*). Although large challenges remain, new communication and mitigation measures are reducing a portion of the dangers of wildfire smoke (*medium confidence*).

Large wildfires have become more frequent in the western US in recent decades. While wildfires occur naturally, climate change and other human influences have increased their likelihood (Focus on Western Wildfires; KM 28.5; Figure A4.14).[69] Wildfires are projected to increase in many regions over the coming century (KM 27.2).[70,71,72,73] Smoke pollutants emitted by wildfires negatively impact human health, visibility, and solar energy generation.[74,75] Wildland fires are the largest contributors to $PM_{2.5}$ concentrations in some parts of the western US[74,76,77] and impact air quality across the US (Figure 14.3). These concentrations could increase, particularly in the western US, by the end of the century,[78] offsetting improvements from reduced human-caused air pollutant emissions.[71,79]

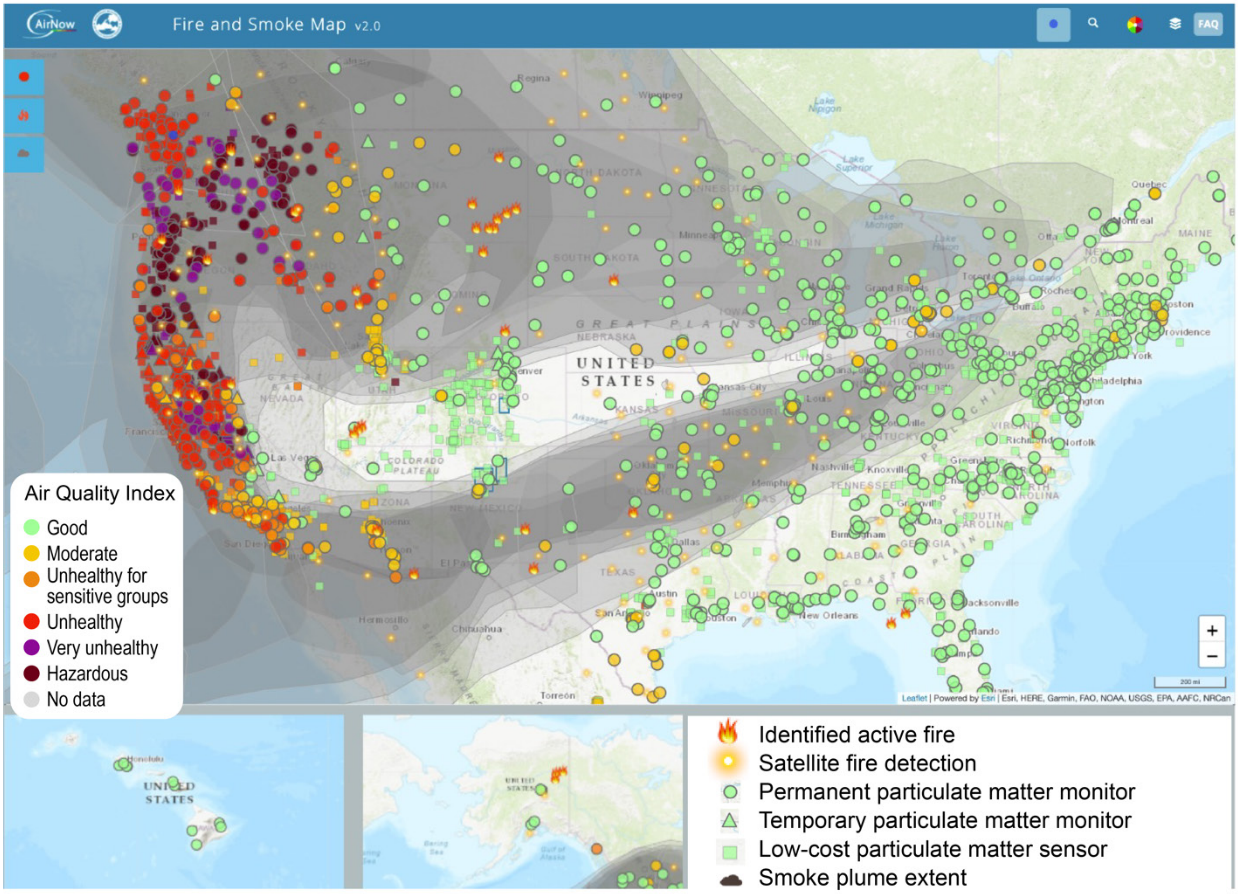
Wildfires emit $PM_{2.5}$ and other air pollutants, including volatile organic compounds (VOCs), nitrogen oxides (which contribute to ozone generation in plumes), and toxic gaseous and particulate species.[74,77] Since publication of the Fourth National Climate Assessment in 2018, studies have revealed factors influencing the smoke pollutant mixture, including the following: 1) smoke enhancements to ozone may be amplified when smoke mixes with urban pollution;[80,81] 2) chemical reactions in plumes change the composition of smoke $PM_{2.5}$ but generally not its amount;[82] and 3) hazardous VOC concentrations generally decrease with plume age due to chemical losses,[77] but structures burning in wildfires could emit additional toxic material, increasing health risks in the wildland–urban interface.[74,83,84] Finally, microbes emitted by fires and transported in smoke suggest that the region biologically affected by fires is more extensive than previously thought.[85,86,87]

Human exposure to smoke pollutants is associated with mortality, asthma, and other respiratory problems, as well as worse outcomes for birth, COVID-19 infection rates (Focus on COVID-19 and Climate Change), and emotional well-being.[88,89,90,91,92,93,94,95] Smoke exposure in the US presently contributes to 1,000–9,000 hospital and emergency department visits and 6,000–30,000 deaths annually.[96,97] Smoke can disproportionately impact certain racial, ethnic, occupational, and age-related subpopulations in both urban and rural areas (KM 22.2),[76,98,99,100] but the most impacted subpopulations are not consistent across studies. As future wildfire activity increases in some US regions, mortality rates and respiratory hospitalizations attributable to wildfires are also expected to increase (KM 27.5).[71,101]

Fire is a natural part of many ecosystems. Land managers use prescribed fire to promote ecosystem health and to reduce the vulnerability to severe fires (KMs 7.3, 28.5),[102] especially in a changing climate.[103,104] Indigenous communities have long used fire to steward their environments (KM 16.3).[105,106] Prescribed fire emissions vary greatly by region and season[107] but are typically much lower per acre than those from wildfires.[74] Prescribed fire activity could increase in some regions as land managers attempt to reduce the frequency, intensity, and spread of wildfires in a changing climate (KM 7.3).[103,104] Although air quality and health impacts are associated with prescribed fire smoke (KM 22.2),[108] well-designed prescribed fires targeted for specific locations have the potential to reduce overall smoke exposure[109] and health impacts of subsequent wildfires.[110,111]

Advances in remote sensing and improved smoke prediction systems,[112,113,114,115,116] combined with better communications strategies,[117] are helping protect the public from unhealthy smoke conditions (Figure 14.3). Smoke exposure reduction techniques, including masks and portable air filters, can help people limit the amount of $PM_{2.5}$ that is inhaled during a smoke event,[117,118,119,120,121] as well as pollen and other particulate air pollution. Smoke forecasters synthesize modeled, satellite, and monitoring data to create daily forecasts[122] that reach the general public, including underserved communities—for example, through Spanish translations. Communication of these forecasts and techniques to reduce smoke exposure occurs through interagency federal,[117,123] state, and Tribal programs, as well as social media. However, people tend to take protective actions, such as staying indoors and using air filters, in response to symptoms from exposure rather than take preventive measures.[124] More work would be needed to quantify and communicate the benefits of exposure-reduction actions.[125,126]

Impacts of Wildfire Smoke on Air Quality



Wildfire smoke affects air quality across the country.

Figure 14.3. Wildfire smoke can affect the daily lives of people across the country, as communicated in real time to the public on September 13, 2020, on the AirNow Fire and Smoke Map (https://fire.airnow.gov/). Monitors measuring particulate matter are color-coded by air quality index from green for good air quality to brown for hazardous. Here, unhealthy to hazardous air quality conditions are shown at multiple monitors (circle, triangle, and square icons) across the western US, and satellite imagery (gray) shows smoke extending across much of North America. On this day, the US Caribbean was free of smoke, and monitor or sensor data were not yet available, so the region is not shown. Data are not available for US-affiliated Pacific Islands. Adapted from EPA 2022.[127] Base map: Copyright © 2022 Esri and its licensors. All rights reserved.

Key Message 14.3

Air Pollution Is Often Worse in Communities of Color and Low-Income Communities

Communities of color, people with low socioeconomic status, and other marginalized populations are disproportionately harmed by poor air quality (*very high confidence*). In the coming decades, these same communities will, on average, face worsened cumulative air pollution burdens from climate change–driven hazards (*very likely*, *high confidence*). Decision-making focused on the fair distribution of air quality improvements, rather than on overall emissions reductions alone, is critical for reducing air pollution inequities (*high confidence*).

Air pollution disproportionately affects people of color and people with low socioeconomic status in both cities and rural places.[128,129,130,131] While air quality has improved over recent decades, air pollution disparities have persisted.[132,133,134,135,136,137] There is a clear pattern of more air pollution sources being located in communities of color and low-income neighborhoods. Diesel traffic exhaust is among the largest sources of air pollution inequalities in urban areas,[138] while other emitters, including industrial facilities,[25,139] prescribed agricultural burns,[140] concentrated animal feeding operations,[141,142,143,144,145] power generation,[146] and oil and gas infrastructure,[147,148] contribute to air pollution disparities in cities and rural environments. Racism in historical practices and policies has contributed to ongoing inequities, protecting White areas from pollution and disinvesting in and off-loading those costs onto communities of color, for example, through redlining and housing segregation.[149,150,151]

The health impacts of the unequal distribution of air pollution are magnified by factors including reduced access to nutrition, social and institutional support, and healthcare, as well as psychosocial stress from racism and poverty.[152] As a result, a given level of air pollution can cause more harm to people of color and those with lower socioeconomic status.[30,152,153,154] Environmental inequalities often overlap, such as exposure to both poor air quality and higher-than-average urban heat (KM 21.3).[155,156] Exposure to air pollution and high air temperatures in combination can worsen health outcomes.[29,30,157,158] Environmental inequalities also often compound in ways that exacerbate negative impacts; for example, reduced tree cover, common in urban communities of color,[159] intensifies urban heat (KM 12.2) and affects air quality (KM 14.1). Disparities in air-conditioning access[160,161] and other housing differences may increase infiltration of outdoor air pollution and wildfire smoke into homes and schools in communities of color and lower-income neighborhoods,[162] and low-income households may have less ability to adopt in-home air filtration.

A 3.6°F (2°C) increase in average global temperatures relative to the 1986–2005 average is projected to worsen $PM_{2.5}$-related premature mortality for African Americans over age 65 by 40%–60% more than for people of other racial and ethnic groups.[155] This same temperature change is projected to cause substantially higher rates of $PM_{2.5}$-related asthma for African American children and smaller, but still disproportionate, increased rates for Latino, Asian, Pacific Islander, and American Indian and Alaska Native children. In New York City and Newark, New Jersey, projected trends in air stagnation are expected to worsen inequalities in concentrations of nitrogen dioxide (NO_2),[163] an air pollutant associated with asthma.[164,165] The impact of climate change on air quality–related inequalities may differ depending on the sources of pollution and whether pollutants are emitted directly or formed through chemistry (KM 14.1). However, climate change can increase cumulative and unequal air quality–related health burdens, such as from the combined effects of air pollution and temperature, even if air pollution itself does not worsen.[29,30,157,158]

Actions to address climate change through GHG regulation will also affect air quality, with the distribution of benefits dependent on the mitigation approach. Programs focusing on GHG sources with the lowest mitigation costs have had mixed impacts on air pollution equity.[166,167] In California, GHG regulation through carbon cap-and-trade increased emissions of combustion-related air pollutants in communities of color and low-income neighborhoods.[168] Approaches focused on lowering aggregate emissions across a large geographic region, or from a single emissions category, have been shown to be less effective than interventions aimed at reducing air pollution inequalities for a specific location.[169] Solutions can be designed to reduce disparities and overcome the challenges associated with GHG regulation.[170,171]

Box 14.1. Environmental Justice, Air Pollution, and Climate Change: Houston, Texas

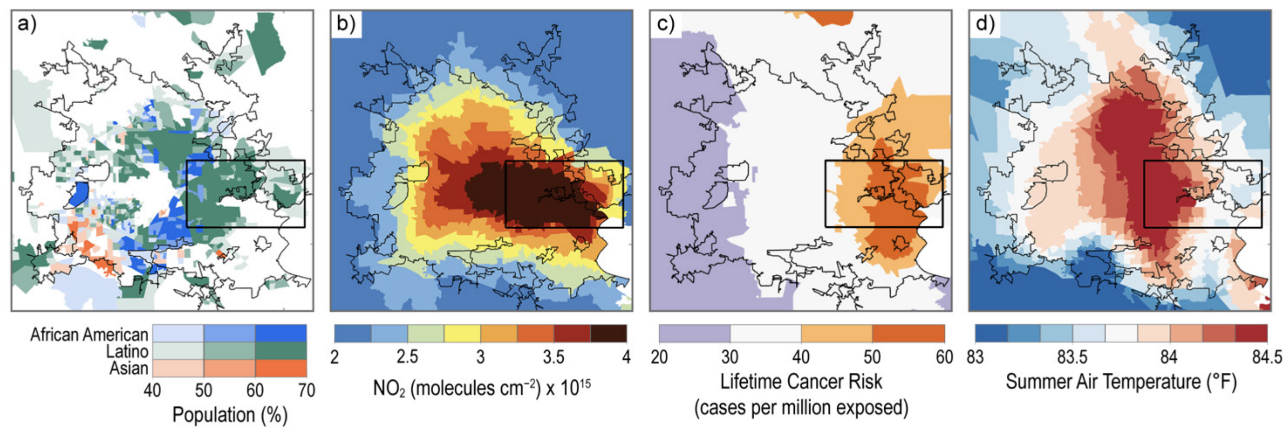
Houston's Ship Channel region is a patchwork of chemical refineries, freeways, homes, and playgrounds (Figure 14.4; Box 26.1). Air pollution levels along this busy industrial waterway, connecting downtown Houston to Galveston Bay, are among the highest in the city (Figure 14.5). Flares and odors are commonplace,[172,173,174] and community concerns about health impacts are often ignored. Many of Houston's African American, Latino, and working-class families live in the neighborhoods of the Ship Channel, where they are more likely to breathe harmful cancer-causing air pollution from diesel trucks and refineries.[138,175,176,177,178,179,180] Communities living at the fenceline of the petrochemical industry face ongoing vulnerabilities, such as dual exposure to air pollution and heat and endangerment from damages to petrochemical facilities caused by stronger hurricanes (KMs 9.2, 15.2). In 2017, Hurricane Harvey triggered widespread industrial releases of hazardous air pollutants throughout the Houston Ship Channel.[181,182,183] Houston is also the stage for foundational scholarship on environmental justice by Dr. Robert Bullard (KM 20.3), where community organizations lead work to reduce air pollution and make communities more resilient to climate change.

Air Pollution Exposure at Home in the Houston Ship Channel Region

Industries expose people living near the Ship Channel—often African American, Latino, and low-income residents—to harmful air pollution.

Figure 14.4. Nighttime industrial flaring exposes residents to air pollution near the Houston Ship Channel in the Deepwater community in Pasadena, Texas, a primarily African American, Latino, and low-income neighborhood. Photo credit: ©Cassandra Casados-Klein, Air Alliance Houston.

Air Pollution and Temperature Inequalities in Houston, Texas



Air pollution, its health impacts, and temperatures are unequally distributed across Houston, Texas.

Figure 14.5. Air quality and temperatures vary across Houston, Texas (urbanized area outlined in black). (**a**) For each neighborhood, the largest racial or ethnic group is shown: African American (blue), Latino (green), and Asian (orange). Higher-than-average levels of (**b**) nitrogen dioxide (NO_2; in 2019), (**c**) lifetime cancer risks associated with chronic air pollution exposure per million equally exposed people (2018), and (**d**) summer (June–August) air temperatures (2020) are found in neighborhoods that are primarily African American and Latino, especially those surrounding the Ship Channel (black box). There is variability in time and at very fine spatial scales that may not be captured here. Figure credit: University of Virginia, Columbia University, and Montana State University.

Key Message 14.4

Climate Change Is Worsening Pollen Exposures and Adversely Impacting Health

Increased allergen exposure damages the health of people who suffer from allergies, asthma, and chronic obstructive pulmonary disease (COPD) (*very high confidence*). Human-caused climate change has already caused some regions to experience longer pollen seasons and higher pollen concentrations (*very likely*, *high confidence*), and these trends are expected to continue as climate changes (*very likely*, *high confidence*). Increasing access to allergists, improved diagnosis and disease management, and allergy early warning systems may counteract the health impacts of increasing pollen exposure (*high confidence*).

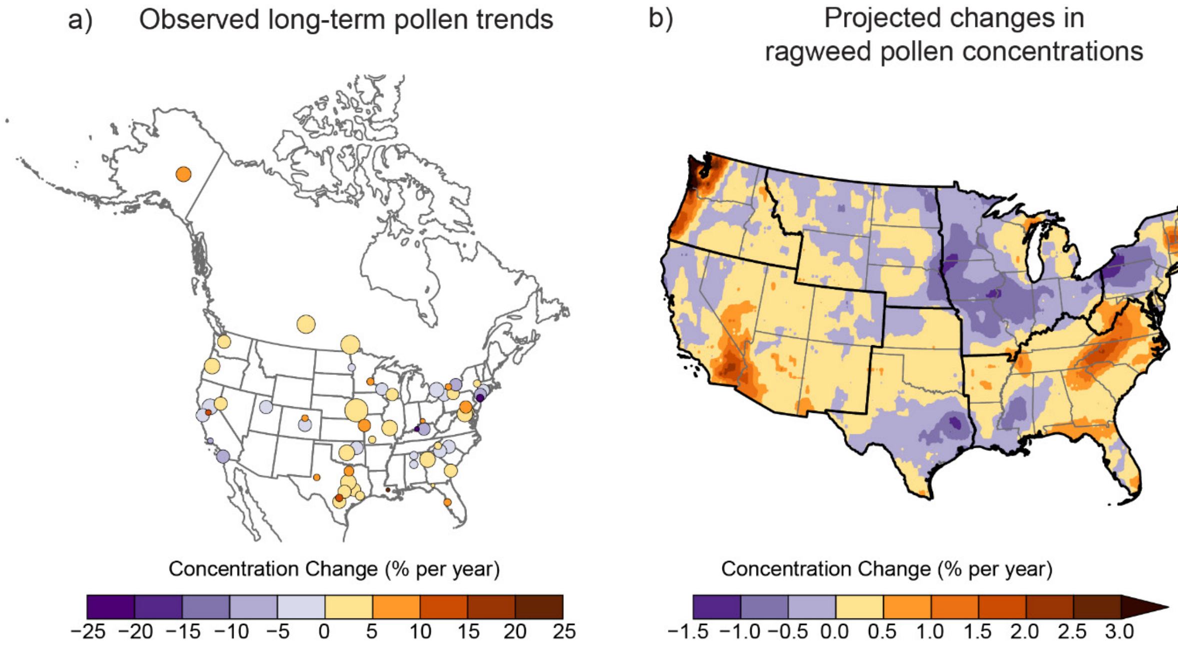
Allergic airway disease, including allergic rhinitis and asthma, is widespread in the US, is becoming more prevalent, and imposes a burden of several billion dollars in healthcare costs and lost productivity annually.[184] Exposure to allergenic pollens and molds (aeroallergens) triggers allergic disease development.[185,186,187] Co-exposure to aeroallergens and pollutants like ozone, nitrogen oxides, and $PM_{2.5}$ can exacerbate allergic airway disease symptoms.[188,189,190] Aeroallergen exposure can compromise the body's antiviral defenses, possibly increasing susceptibility to respiratory viral infections in both allergic and nonallergic people.[186,191] It is also probable that pollen exposure is associated with COPD mortality.[192] Pollen can also transport viruses.[193]

Local climate affects emissions of allergenic tree and grass pollens and fungal spores. Climate change is altering pollen season characteristics for allergen-producing trees during spring and for grasses and weeds during summer and fall.[194] Rising atmospheric carbon dioxide (CO_2) can increase pollen allergenicity.[195,196,197]

Multiple US regions have experienced longer, more intense pollen seasons, with earlier start dates and increased emissions and airborne loads over the past 30 years, increasing the potential for exposures (Figure 14.6; KM 22.2).[187,194,196,198,199,200,201] For example, the season for ragweed pollen, a significant allergen, has lengthened since the 1990s (Figure A4.13), and its range has expanded northward;[202] ragweed grows faster, flowers earlier, and produces more pollen in high-CO_2 areas.[196,203] With climate change, ragweed pollen is projected to increase in most regions (Figure 14.6) and to co-occur with high ozone more frequently.[204,205] Likewise, the number of days with total pollen concentrations exceeding thresholds for triggering allergies is projected to increase in most US regions.[204,206,207,208]

Increasing frequency and intensity of heatwaves, storms, and floods associated with climate change can also intensify aeroallergen exposures. Mold proliferation is increased by floods. Thunderstorms can exacerbate respiratory allergy and asthma in patients with hay fever, and similar phenomena have been observed for molds.[209]

Observed and Projected Pollen Changes Under Climate Change



Pollen has been increasing in many US regions and is projected to continue to increase as climate changes.

Figure 14.6. (**a**) Observed long-term pollen increases are shown as the linear trend of total annual pollen at 60 stations (1990–2018). (**b**) Modeled projected changes in average airborne ragweed pollen concentrations in 2047, relative to 2004, are shown for climate change conditions under a very high scenario (RCP8.5). Yellow and red shades indicate increases in pollen concentrations, and circle size in panel (a) reflects the number of years of data at each station. Observations are not available for many US states and affiliated territories, and the modeled projection does not include non-contiguous US states and territories. There is a net increase in concentration overall, with marked increases in certain areas and declines in others. (a) Adapted from Anderegg et al. 2021[194] [CC BY 4.0]; (b) adapted from Ren et al. 2022[210] [CC BY 4.0].

Allergic airway disease is underdiagnosed, and many therapies are underutilized.[211] Increasing access to allergists and diagnostic tests can help clarify what exposures drive allergies for individuals and aid in developing therapeutic plans including medical and immune therapies.[212] Staying indoors and wearing masks to reduce exposure, as well as avoidance of allergens through early warning systems[213] and other public health campaigns, can also reduce impacts.[214] Understanding of climatic influences on pollen exposures can inform diagnosis and disease management, but it remains unclear whether these and other advances can blunt the health impact of increased aeroallergen exposures as the climate warms.

Key Message 14.5

Policies Can Reduce Greenhouse Gas Emissions and Improve Air Quality Simultaneously

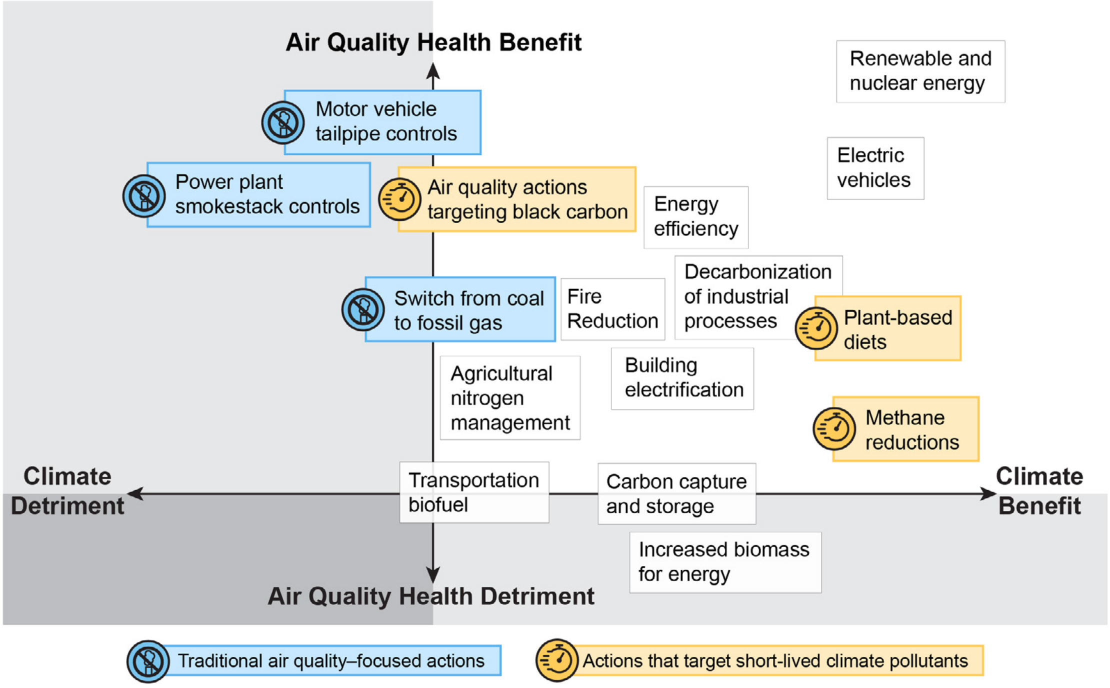
Substantial reductions in economy-wide greenhouse gas emissions would result in improved air quality and significant public health benefits (*very likely*, *high confidence*). For many actions, these benefits exceed the cost of greenhouse gas emission controls (*likely*, *high confidence*). Through coordinated actions emphasizing reduced fossil fuel use, improved energy efficiency, and reductions in short-lived climate pollutants, the US has an opportunity to greatly improve air quality while substantially reducing its climate impact, approaching net-zero CO_2 emissions (*high confidence*).

Fossil fuel energy use is responsible for 92.1% of US CO_2 emissions[215] and the majority of $PM_{2.5}$-induced deaths.[20,216] Consequently, actions to control GHGs, including reductions in energy demand or shifts toward cleaner energy sources, typically reduce air pollutant emissions from the same sources, benefiting air quality and health.

By contrast, actions that have substantially improved US air quality since 1990 generally did not reduce GHG emissions, as they focused on technologies that remove air pollutant emissions from power plants, industrial facilities, and vehicles but do not reduce fossil fuel consumption—and some actions increased fossil fuel use and GHG emissions (Figure 14.7).[215,217,218] In the past decade, fuel switching from coal toward renewables (wind and solar) and lower-emitting sources (fossil gas) has reduced emissions of both GHGs and air pollutants.[219,220]

To further improve air quality, more stringent smokestack and tailpipe controls on fossil fuel sources may be chosen. Alternatively, GHG mitigation scenarios that meet the long-term temperature goal of the Paris Agreement and approach net-zero emissions this century replace fossil fuels with cleaner energy sources and reduce overall energy use (Figure 14.7; KM 32.2).[221,222,223] This clean energy transition would provide air quality[224] and health benefits[225] beyond what smokestack and tailpipe controls can provide.

Potential for Emissions-Reduction Actions to Achieve Air Quality and Climate Benefits

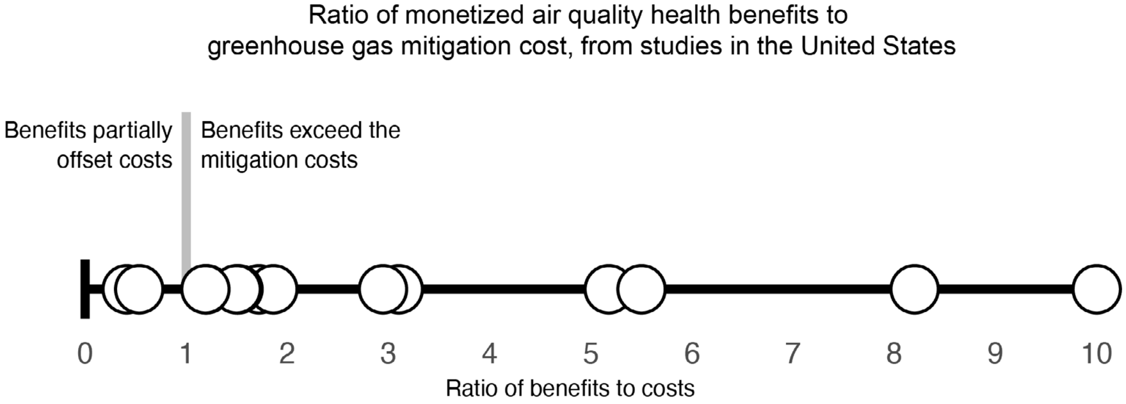


Many emissions-reduction actions can achieve multiple benefits for climate, air quality, and health.

Figure 14.7. Environmental policies to mitigate emissions will affect both air quality and climate change, and actions can be coordinated to address both problems simultaneously. Blue boxes show mitigation actions aimed at conventional air pollution controls; orange boxes show actions targeted at short-lived climate pollutants; and white boxes show other types of actions. Emissions-reduction actions in the upper right have greater air quality and climate benefits. Box position indicates the relative potential of actions, from most detrimental to most beneficial, and should not be interpreted quantitatively (e.g., that one action has twice the potential of another). The size of the boxes indicates some uncertainty, with actions in boxes straddling an axis being uncertain in the direction of the effect. Addressing climate change requires moving to the actions on the right-hand side of the figure, where many options simultaneously improve air quality. Figure credit: EPA, University of North Carolina at Chapel Hill, and Duke University.

Economy-wide GHG reductions are expected to decrease emissions of air pollutants emitted from the same sources, resulting in benefits for air quality and health (KMs 13.3, 32.4).[226,227,228,229,230] Each metric ton of CO_2 reduced is estimated to bring about health benefits[231] that are valued in 26 US studies from $8 to $430 (in 2022 dollars), with a median of $100 per ton of CO_2 (see Traceable Accounts for details on relevant studies), mainly from avoided premature death. These health benefits can significantly offset or exceed implementation costs for many GHG mitigation measures (Figure 14.8). Since health benefits exceed costs in most studies, these GHG reductions are economically beneficial, even without accounting for other benefits of slowing climate change. Estimates of these benefits vary across many studies because of differences in mitigation actions considered, methods of assessing emissions, pollutant concentrations and health impacts, and mortality valuation.[232] Most studies have typically evaluated mortality while neglecting morbidity impacts, such as preterm births, restricted activity days, and hospitalizations,[233] and therefore may underestimate the full health benefits of GHG reductions. However, some individual actions, including biomass energy and carbon capture and storage, may provide small air quality benefits or even worsen air quality (Figure 14.7; KM 5.3).[234] Lastly, GHG mitigation policies may alleviate or worsen inequities in air pollution exposure, depending on their design (KMs 14.3, 32.4).

Air Quality and Health Benefits Estimates in the US, Relative to Costs



Air quality health benefits alone exceed or significantly offset the costs of greenhouse gas reductions.

Figure 14.8. Controls on greenhouse gas (GHG) emissions also reduce air pollutant emissions from the same sources (often fossil fuel combustion), improving air quality and saving lives. Each circle denotes the results from a study in the US during 2013–2022. These studies find that the value of health benefits significantly offset or in most cases exceed the GHG emissions control costs, apart from other benefits of slowing climate change. Figure credit: EPA, University of North Carolina at Chapel Hill, and Duke University.

The air quality benefits of GHG controls by reducing co-emitted air pollutants occur mainly locally and regionally and nearly immediately following emissions reductions.[19,235] By contrast, benefits of slowing climate change, including lessening the impacts of climate change on air quality (KM 14.1), are long term and distributed globally. Recognizing these air quality health benefits strengthens incentives for local, state, and national actions to reduce GHG emissions.[236]

Indoor air quality can also be affected by GHG reduction actions, as some methods for improving building energy efficiency decrease ventilation, which can increase mold and degrade indoor air quality.[237] Newer approaches to building design improve energy efficiency while meeting temperature control and indoor air quality needs.[238] More widespread application of these approaches can reduce energy use, mitigate GHG emissions, and improve indoor air quality (KM 12.3).

Climate mitigation actions focused on short-lived climate pollutants (SLCPs) can also improve local air quality. Reducing SLCPs, including methane, black carbon, and ozone, directly improves air quality and reduces the near-term rate of warming, affecting climate more quickly than reductions in long-lived GHGs like CO_2.[239,240] Methane directly contributes to warming and increases ozone air pollution globally.[42,241] The social cost of methane is estimated at around $2,200 (in 2022 dollars) per metric ton[242] when accounting for impacts via climate change. Other estimates that also include health impacts of ozone are higher (about $4,600 to $9,200 per metric ton in 2022 dollars), with over half of that from ozone health impacts.[243,244,245] VOCs and carbon monoxide (CO) form ozone in the atmosphere, and reducing their emissions benefits both climate and air quality. Nitrogen oxides also contribute to ozone but have a net cooling influence by shortening methane's lifetime and forming $PM_{2.5}$.[240,246] Together, global emissions of methane, VOCs, CO, and black carbon have contributed about 1.5°F to global average warming in 2019, compared to about 1.4°F from CO_2 increases (KM 3.1).[247]

Most forms of $PM_{2.5}$ cool the climate, and removing them exacerbates climate warming (KMs 2.1, 3.1), as seen from historical sulfur dioxide reductions to improve air quality.[248,249,250,251] If $PM_{2.5}$ reductions are undertaken together with CO_2 and SLCP reductions, this short-term warming may be outweighed, leading to a net cooling.[252,253] Carbon particles, mostly from fires and burning fossil fuels, cause a mix of warming and cooling effects.[240] Of these, black carbon is the component that contributes most to warming, and actions targeting sources that emit relatively more black carbon, like diesel engines, are expected to best reduce warming while improving air quality. Ammonia, which contributes to $PM_{2.5}$ and is growing in relative importance as a $PM_{2.5}$ source, comes mostly from agriculture.[254] Agricultural ammonia and methane emissions can be reduced by more efficient use of fertilizer[255,256] and adopting healthier plant-based diets.[244,257] Finally, air pollutants can influence regional climate such as through changes in clouds and precipitation, and black carbon can increase snowmelt, which affects water resources (KM 4.1).[258]

Traceable Accounts

Process Description

Authors were selected to provide diversity in topical focus areas and to align expertise with the anticipated topics for the chapter, as well as for geographic and racial diversity. All authors are recognized experts in climate change and air quality, including in the focus areas of the chapter.

The author team met online roughly every two weeks to discuss the organization of topics, main points to emphasize, and the many logistical questions related to writing the chapter. The author team agreed on five key topics as the focus of the chapter, reflected in the Zero Order Draft (ZOD). The ZOD was made publicly available, and a public engagement workshop was held on January 18, 2022, where the author team gathered public comments on the ZOD. All written public comments on the ZOD were reviewed by the author team, and responses were provided for each. Similarly, the author team responded to comments received on multiple drafts that followed.

Key Messages were developed by small author teams, who were responsible for developing the content of each topic area, and discussed among all authors. The team achieved consensus on the wording of the Key Messages for the Third Order Draft through group meetings to discuss this text specifically. Following comments on drafts of the Fourth Order Draft, the team made small revisions to the Key Messages, and these were discussed among authors to again achieve consensus.

Key Message 14.1

Climate Change Will Hamper Efforts to Improve US Air Quality

Description of Evidence Base

An extensive literature base documents air quality modeling of the response of ozone and fine particulate matter ($PM_{2.5}$) to future climate change. Comparison across studies, however, is challenging due to the use of different scenarios, time periods, metrics, and process representations in the modeling systems. The chemistry of both ozone and $PM_{2.5}$ is complex, which adds to the difficulty of predicting the influence of climate change on air quality. Source gases of ozone and $PM_{2.5}$ include methane, carbon monoxide, nitrogen oxides, non-methane volatile organic compounds, sulfur dioxide, ammonia, and dimethyl sulfide; types of $PM_{2.5}$ directly emitted into the atmosphere include black carbon, organic carbon, mineral dust, sea salt, pollen, and spores.

The literature using observations to infer process-level relationships between air pollutants and climate is growing and includes links with temperature, precipitation, winds, and near-surface mixing.[39,259,260] However, observational records are relatively short (a few decades at best), and isolating responses to meteorology requires disentangling air pollution responses to large emissions perturbations over the observing period to reveal the influence of climate change and variability. Air pollution trends in recent decades in some urban areas and at the regional scale are well established based on high-quality monitoring.[13,261] A large literature base employs a wide range of methods to attribute observed trends and variability to anthropogenic emissions versus meteorological variability. Highly resolved spatial distributions needed to assess community-level exposure are sparse but growing, and new observations from satellites and low-cost sensors will prove useful in this regard. For example, the Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite instrument, launched in April 2023, promises to provide hourly, fine-spatial information about US pollution.[262,263]

Many processes involving interactions between climate and air quality have been the foci of major lab, field, and modeling efforts (e.g., wildfires) or represent fundamental physics (e.g., the increase in water vapor as temperatures rise), and new work since the Fourth National Climate Assessment (NCA4) was published in 2018 further strengthens this deep evidence base. Such processes and their impacts on air pollution in a changing climate are illustrated in Figure 14.1. Wildfires are a key example of how feedbacks from the biosphere are expected to increase air pollution in future years (KM 14.2).[264] An increased frequency of heatwaves will also lead to more extreme levels of ozone and $PM_{2.5}$ (KM 2.2),[38,265,266] while warmer average temperatures will increase seasonal mean daily maximum 8-hour average (MDA8) ozone and $PM_{2.5}$ concentrations.[49,51,260] The source gases of ozone and $PM_{2.5}$ from plants and soils are expected to increase with warmer and drier conditions,[259,267,268,269] thus degrading air quality. In addition, as plants wither and die during drought, ozone that would otherwise be deposited on leaves may accumulate in the atmosphere,[270,271] although this process is less well studied. Other processes may lead to lower pollution in a warmer climate. Some studies project that annual average precipitation, which removes $PM_{2.5}$, will increase across much of the United States by 2100,[272] but not all studies agree.[273] Basic physics explains why atmospheric humidity will rise with temperature, and the chemical reactions governing ozone destruction will increase with humidity, reducing ozone in unpolluted regions.[68,274] In contrast, greater humidity is expected to worsen $PM_{2.5}$ air quality in some regions.[275] Finally, future trends in the regional transport of pollution or in the frequency of weather patterns like stagnation will have consequences for US air pollution, but these trends are not well established across the US.[276,277,278]

Efforts to model the net response of US air quality to climate change have taken two main approaches, with some studies focusing on the impact from climate change alone[27,41,49,50,51,52,68,279] and other studies including the influences of both climate change and changing emissions from human sources of ozone and $PM_{2.5}$, such as fossil fuel combustion.[26,39,45,67] Some studies compare the combined effects of emissions and climate change with climate change alone.[44,46] There is general agreement across these studies that climate change will degrade US air quality in many regions with high concentrations of pollutants. Summertime average surface ozone is expected to increase across much of the northern and eastern United States[26,51] and during heatwaves in populous areas already affected by pollution.[53] Surface $PM_{2.5}$ is also projected to increase in areas prone to wildfires (KM 14.2) or dust events,[63] but there is less agreement on the response of $PM_{2.5}$ elsewhere.[50,51,54,280]

Many epidemiological health studies have identified a wide range of adverse health outcomes following exposure to wildfire smoke and dust, as well as to ozone and particulate matter. Such adverse outcomes are expected to generally increase in response to ongoing climate change.[26]

Major Uncertainties and Research Gaps

Uncertainties remain in how meteorology will respond to climate change in different regions of the United States and how these meteorological responses, in turn, will trigger changes in different air pollutants. While it is well established that rising methane will increase background ozone at the surface, there is uncertainty in the spatial patterns of this response tied to nitrogen oxides emissions, including from ship plumes.[42,281] Climate variability tends to dominate the uncertainty in shorter-range projections (thin lines in Figure 14.2).[282,283,284] Health responses to the combined impacts of exposure to multiple pollutants and other climate change impacts (heat, flooding) are not well quantified. Extensive research into the relative toxicity of $PM_{2.5}$ mixtures has not consistently shown that any particular source or component is more strongly related to health effects than total $PM_{2.5}$ mass.[285]

The lack of systematic information available from chemistry–climate models for US air quality complicates the assessment of future change. For example, Figure 14.2 makes use of the most comprehensive set of coordinated simulations with international climate models that include the atmospheric chemistry necessary for projections of future air quality. There are different numbers of models with simulations available for each scenario. Specifically, seven models simulated $PM_{2.5}$ for both the historical simulations and four future air pollutant emissions and climate scenarios during 2015–2100 (see Table 3 in the Guide to the Report). In contrast, for ground-level ozone, fewer models (one to five depending on scenario) archived the hourly ground-level ozone needed to calculate the MDA8 metric used to assess compliance with the National Ambient Air Quality Standards. In Figure 14.2, thick lines show the average of all available model simulations for each scenario, with each simulation shown individually by the thin lines. A list of the individual models that produced each scenario in Figure 14.2, together with the simulated fields, are available in the metadata. Models and simulations are further described by Turnock et al. (2020).[15]

In more recent studies, progress is being made in quantifying different sources of uncertainty in emissions scenarios and future projections for US air quality, including separately determining the uncertainty associated with model mechanisms and with naturally arising climate variability.[259,286,287]

Description of Confidence and Likelihood

The overall assessment of *medium confidence* that climate change is projected to worsen US air quality in many US regions reflects uncertainty in the net ozone and $PM_{2.5}$ responses to climate change across different regions.[48,49,50,51,54,68,280] The evidence for air pollution impacts on health is well established from epidemiological and toxicological studies,[4,7,9,10] supporting a *very likely*, *high confidence* assessment. There is *very high confidence* and it is *very likely* that climate change will increase the intensity and frequency of extreme heat (KM 2.2).[247] Observational evidence, theoretical understanding, and modeling studies all support an assessment of *high confidence* that increasing frequency of warmer and drier conditions will *very likely* raise the risk of exposure to airborne dust and wildfire smoke in some regions.[62,63,69,288]

Key Message 14.2

Increasing Wildfire Smoke Is Harming Human Health and Catalyzing New Protection Strategies

Description of Evidence Base

This section was based on a review of the recent peer-reviewed literature. Many studies detail the harmful health effects of wildfire smoke on human health. A growing weight of evidence indicates that wildfires and associated air quality impacts will increase in the future with a warming climate, but the interactions are complex and regionally driven. Our understanding of smoke exposure and health impacts has been aided by combinations of surface and satellite-based observations, as well as model simulations.[289,290] Smoke prediction (forecast) systems are a useful mitigation tool,[121] and the number of them online, along with many science improvements, has grown in recent years across North America.[112,114,115,291,292,293,294]

Since NCA4, particularly impactful wildfire smoke years have driven the development of new communication and smoke mitigation measures. The authors highlight the growing base of information on how the public can protect itself before and during a wildfire, such as that found in the EPA Smoke-Ready Toolbox (https://www.epa.gov/smoke-ready-toolbox-wildfires), as well as the development of wildfire smoke mitigation programs by many states and Tribes, in addition to federal programs.[295,296,297,298] Evidence shows that social media plays an important role in communicating mitigation measures. For example, smoke blogs in many western states are a nexus of information.[299,300,301,302]

Major Uncertainties and Research Gaps

Uncertainties in future smoke exposure are intrinsically tied to the uncertainties in future wildfires. Hence, improvements in future wildfire projections will reduce uncertainties in future smoke exposure. Related to this is the uncertainty regarding how future use of prescribed fire as a management tool for wildfire mitigation and ecosystem health will affect smoke at regional and national extents. Finally, quantification of how Indigenous fire practices influence smoke both historically and into the future will also reduce this uncertainty.

Uncertainties remain in our understanding of the health effects of smoke-specific particulate matter and the impacts of cumulative smoke exposure over many years. Research investigating indoor concentrations during wildfire smoke events is preliminary, and there is a specific need to understand how indoor concentrations vary between socioeconomic groups during wildfire smoke events. Research quantifying the effectiveness of smoke mitigation measures and other health protection interventions is limited, and relying on personal interventions such as wearing face masks, filtering indoor air, and staying indoors can have limitations.[303,304]

Description of Confidence and Likelihood

There is *very high confidence* that wildfires emit gases and fine particulate matter that are harmful to human health based on epidemiological and toxicological studies.[74,77,88,89,90,91,92,93,94,95] Many studies document the effects of short-term acute exposures on respiratory healthcare outcomes (Liu et al. 2015; Reid et al. 2016[92,93] and references therein). Less quantified but also of concern are the effects of long-term lower-level exposure.[92,93] A growing weight of evidence supports the *likely*, *high confidence* assessment that with a warming climate, wildfires and associated air quality impacts will increase in the future in many regions of the contiguous US and Alaska, but the fire-climate interactions are complex and regionally driven, and the extent to which human management actions will influence future wildfire activity is unknown (Ch. 7). Since NCA4, particularly impactful wildfire smoke years have driven the development of new communication and smoke mitigation measures.[117,118,119,120,121] Advancements in the science in models and observational data are also leading to products to help inform the public.[112,113,114,115,116,154] However, these developments may not be enough to substantially reduce exposure, especially for all demographic groups.[125,126] This uncertainty in exposure reduction leads to the assessment of *medium confidence* in the efficacy of these measures and the conclusion that challenges remain.

Key Message 14.3

Air Pollution Is Often Worse in Communities of Color and Low-Income Communities

Description of Evidence Base

This section is based on a review of peer-reviewed scientific literature, focusing on work published in the last decade. It has been repeatedly shown that communities of color, low-income communities, and other marginalized groups are disproportionately exposed to and harmed by air pollution.[25,30,132,133,134,135,136,137,138,139,140,141,142,143,144,145,146,147,148,152,153,154,155] Over the last 10 years, there has been an emphasis on developing and applying new measurements and models to describe air pollution inequalities and, in some cases, on deepening commitments to community-engaged scholarship. Improved monitoring and modeling have advanced tools for distinguishing pollutant differences within and between neighborhoods, whereas research over previous decades was largely based on analyses of source proximity and/or health impacts. A new generation of sensors, costing a few hundred dollars each, is supporting collaborative air quality and exposure research and producing actionable results.[305,306,307,308,309,310,311] In addition, recent advances in satellite remote sensing are enabling more detailed observations of neighborhood-level pollution inequalities, with satellite measurements being used directly in the case of nitrogen dioxide (NO_2)[138,163,177,312] and in combination with models for $PM_{2.5}$ and NO_2,[133,134,135,313,314] with additional information, especially on daytime temporal variability, anticipated with the launch of TEMPO. Machine learning and regression models are filling observational gaps and improving estimates of unequal exposures.[129,134,313,315] Current understanding of air pollution health impact disparities is also improving through neighborhood-level datasets on disease rates.[133,314] Chemical transport models, which are standard research and air quality decision-making tools that account for key chemical and physical processes, have only begun to be used for neighborhood-level environmental justice applications because of model resolution challenges.[316,317] That said, neighborhoods are typically larger than the spatial gradients of primary pollutants, and emissions sources are often clustered in overburdened communities. As a result, models with very-fine-scale spatial resolution (hundreds of meters) may not always be needed to describe neighborhood-level inequalities,[163,318] further opening the range of tools applicable to describing and understanding air pollution inequalities. As air pollution datasets evolve, they reinforce what communities with environmental justice concerns have been saying for decades.

Major Uncertainties and Research Gaps

While patterns of inequities related to air pollution sources, exposure, and associated adverse health impacts are well established, we lack tools that fully describe neighborhood-level distributions of a wide variety of pollutants harmful to health, such as air toxins, and of pollutant mixtures. Air pollution exposures also occur in the home, in classrooms, and at work, and there is little research simultaneously considering outdoor, indoor, and occupational exposures. To date, researchers have largely focused on producing high spatial resolution air pollution maps, and as a result, there is far less knowledge of the temporal variability and source patterns driving air pollution inequalities. Without also capturing this temporal variability, it is difficult to incorporate issues of inequalities in broader air quality and climate change decision-making.[163] Equity-related questions are not a common feature of air pollution–climate research, partly because of computational limitations on model spatial resolution and partly because of disciplinary and regulatory divides in the fields of air quality and environmental justice. There is limited research on how greenhouse gas (GHG) mitigation actions have differential impacts on air quality affecting different communities, but there is clear evidence that without considering equity, GHG regulations can adversely affect air quality in communities of color and communities with low-socioeconomic status.[168]

Description of Confidence and Likelihood

There is *very high confidence* that communities of color, low-income communities, and other marginalized populations, on average, live in greater proximity to emissions sources, experience higher levels of air pollution, and are disproportionately harmed by poor air quality[25,129,138,152,153,319]—this has been repeatedly shown for decades. The author team assigns *very likely*, *high confidence* to the statement that these same communities will disproportionately face worsened cumulative air pollution burdens from climate change–driven hazards. Regarding the likelihood, there are two facets to consider concerning how climate change will affect air pollution inequity: 1) how the amount and distribution of air pollution will differ in the future and 2) how the health impacts of air pollution exposures will vary with climate change. There is less research on how the amount and distribution of air quality (i.e., air pollution inequalities) will change in the future,[155,163] with varying effects possible depending on which control strategies are employed and whether pollutants are directly emitted into the atmosphere or formed in the atmosphere through chemistry. The likelihood and confidence statements are largely based on the second facet—because of well-documented inequalities in the distribution of other climate-sensitive environmental benefits and harms (KMs 9.2, 12.2, 15.2) and because of other forms of structural racism affecting the impacts of air pollution on health and well-being,[152,156] hence the *high confidence*. The cumulative burdens of air pollution with other climate change-driven hazards are *very likely* to increase in the coming decades in the absence of equity-focused emission controls. The author team assigns *high confidence* to the statement that equity-focused decision-making is critical for reducing air pollution inequities, as it has been borne out over decades of improved air quality across the US that air pollution disparities persist.[132,133,134,135,136,137] Sector, market, and pollutant threshold-based controls have been shown to have smaller equity benefits than location-specific interventions,[169] with California's GHG market serving as a real-world demonstration that GHG controls have the potential to worsen air pollution inequalities.[168]

Key Message 14.4

Climate Change Is Worsening Pollen Exposures and Adversely Impacting Health

Description of Evidence Base

This section was based on a review of the recent peer-reviewed literature. A large number of articles using new data and tools have been published in the past few years, and some have provided insight into the attribution of observed shifts in pollen metrics to anthropogenic climate change.

Recent developments have enhanced our understanding of climatic influences on pollen. These include improved understanding of plant phenology,[203,320,321,322,323] improved measurements of aeroallergen concentrations,[194,201,324] new modeling platforms for pollen emissions and transport,[204,205,207,325,326] novel analytics tools for recognizing pollen patterns,[327,328] automatic analysis of pollen types,[329,330] and remotely sensed data on meteorology, air quality, and phenology.[321,331,332] In addition to these methodological advances that allow for greater insight into factors influencing aeroallergen distribution and concentration, climatic influences are becoming clearer as the climate shifts further, and longer time series allow for greater confidence in the correlations observed.

Strategies for reducing the impact of allergic airway disease by avoiding and reducing pollen exposure,[213] which can be facilitated through public health campaigns[214] and taking medications to reduce immune response intensity,[212] have been established for years. More recent literature has highlighted gaps in diagnosing and treating allergic airway disease.[211]

Major Uncertainties and Research Gaps

There are several papers suggesting overall trends in pollen season and concentrations for total pollen and ragweed, but there is limited evidence for specific taxa, and there is less literature on climate change impacts on indoor and outdoor mold exposure. There is also limited evidence linking changes in health impacts with changes in exposure; however, there is abundant evidence that allergic respiratory disease is driven by exposure, so there is a strong presumption of a link. There is relatively limited information on the health equity impacts of changes in pollen exposure and on the effectiveness of early warning systems in reducing symptom burden. Lastly, there is little information quantifying the likelihood that investments in adaptation can fully close the adaptation gap and negate climate change–attributable shifts in allergic airway disease.

Description of Confidence and Likelihood

There is *very high confidence* in the linkage between aeroallergen exposure and the development and intermittent exacerbation of allergic airway disease and, by extension, that increased aeroallergen exposure damages the health of people who suffer from allergic airway disease.[185,186,187,188,189,190,192] There is *high confidence* and it is *very likely* that human-caused climate change, particularly warming, has already changed the patterns of pollen seasons based on both observational studies in North America as well as modeling studies assessing the influence of anthropogenic climate change compared against a counterfactual without anthropogenic climate forcing (Figure 14.6).[187,194,196,198,199,200,201] This evidence demonstrates that shifts in pollen concentrations vary by region. There is *high confidence* and it is *very likely* that as the climate changes further, these trends will continue and that further shifts in aeroallergen concentrations and distribution will depend on the rate at which the climate changes and, in particular, the rate of warming in a given location (Figure 14.6).[204,206,207,208,210] Based on past experience with managing allergic airway disease, there is *high confidence* that the health impacts associated with increased pollen from climate change can be counteracted fully or in part through improvements including increasing access to allergists, improved diagnosis and disease management, and allergy early warning systems.[211,212,213,214]

Key Message 14.5

Policies Can Reduce Greenhouse Gas Emissions and Improve Air Quality Simultaneously

Description of Evidence Base

The author team made use of the existing literature, emphasizing studies published since NCA4 but also referencing some classic papers published before 2018. The author team emphasizes here how decisions to control GHG emissions often have effects on air pollutant emissions. Similarly, decisions to control air pollutant emissions may influence GHG emissions. The author team therefore highlights the opportunity to control both types of emissions simultaneously through reductions in fossil fuels use, addressing both air pollution and climate change. Conclusions are informed by historical changes in emissions in the US and elsewhere, particularly the actions to implement air quality regulations through controls on smokestack emissions from power plants and large industries and controls on tailpipe emissions from motor vehicles. A fuller array of possible actions is presented in Figure 14.7, which emphasizes the capacity for actions to affect emissions of both air pollutants and GHGs in the near-term (targeting 2030), without explicit consideration for the cost-effectiveness of actions. Figure 14.7 does not present the potential for emissions reductions quantitatively, as the author team is not aware that this has been analyzed previously for the US. Rather the author team used information from several key sources to inform where boxes are placed in Figure 14.7, including US emissions inventories for GHGs[215] and air pollutants,[333] which constrain the potential reductions of some actions. Estimates of the global GHG mitigation capacity from the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) Working Group III[221] help quantify the capacity for reduction, although these estimates are not specifically for the US, and estimates specifically for US energy system actions are from Figure 32.22. Estimates of sector contributions to US air pollution–related deaths[216] are also used, as are qualitative estimates of the effects of GHG reductions on air pollution in the United Kingdom.[65] Using these sources of information, emissions-reduction actions are put in order separately along the two axes in Figure 14.7 and then plotted. In some cases, minor changes in the order are made to fit the boxes on the figure. The boxes themselves are intended to communicate that there is some uncertainty in the emissions reductions, including boxes that straddle an axis, indicating uncertainty in the sign of the influence. Box positions should not be interpreted quantitatively (e.g., inferring that emissions-reduction capacity for one action is twice that of another action). Actions considered include those emphasized in past emissions reductions and considered for future action in the US, and not all possible actions can be included here. The analysis also focuses on technology actions rather than policy approaches (cap-and-trade, incentives for clean technology) used to achieve these goals.

There are many studies of the air quality and human health benefits due to the co-pollutant emission reductions from GHG mitigation actions.[226,227,228,229,230,231] The author team surveyed the literature and found 26 studies that either directly reported or contained enough information to quantify the monetary value of human health benefits from improved air quality per ton of mitigated GHG emissions. In some cases, it was necessary to contact the authors to ensure that the data were being interpreted correctly. These 26 studies form the basis of the range presented in the text ($8 to $430 in 2022 dollars, with a median of $100 per metric ton of CO_2). The estimates of human health benefits and costs from these studies span a range of two orders of magnitude because of different methods used, geographical scope, time periods analyzed, and GHG reduction actions considered. Figure 14.8 presents results from the subset of these studies that included both the air quality human health benefits and GHG mitigation costs. A complete list of the 26 studies and their reported values is available in the metadata for Figure 14.8.

Discussion of short-lived climate pollutants has a strong foundation in past research, as summarized in the IPCC AR6,[240] although some significant uncertainties remain in the magnitude of global anthropogenic radiative forcing for some of these species and in the net effects on climate from reductions of short-lived climate pollutants[252] in the United States in particular.

On the subject of social costs, since this chapter is about the link between climate change and air quality, it seemed appropriate to use costs that include both climate change and air pollution.[244] As the text states, "over half of [the value is] from ozone health impacts," so it is clear that this differs from commonly used costs, such as those produced by the US Government's Interagency Working Group on the Social Cost of Greenhouse Gases for use in regulations, which include only damages related to climate changes.[334]

Major Uncertainties and Research Gaps

Whereas there are new global modeling studies estimating air pollutant concentrations in future Shared Socioeconomic Pathway (SSP) scenarios, including the impacts of climate change on air quality, no study has yet downscaled these simulations to the United States for studying air pollution impacts. There is a gap in research that critically assesses how air pollution is projected to change in the US under scenarios that lead to decarbonization and approach net-zero emissions. There is also limited research in quantifying the effects of actions considered on both GHG and air pollutant emissions, as well as their costs and potential for emissions reductions, since much of the literature available focuses on GHG reductions without estimates of concurrent air pollutant emissions reductions.

Description of Confidence and Likelihood

There is *high confidence* and it is *very likely* that broad policies to reduce greenhouse gas emissions economy-wide in the United States will reduce air pollutant emissions and benefit air quality and health, although some individual actions may not achieve these benefits (Figure 14.7).[227,230,231] Many studies have estimated the air quality and human health benefits of greenhouse gas reduction actions, most of which have found that monetized benefits exceed the costs of greenhouse gas controls (see Figure 14.8 and associated metadata), when premature mortality is monetized using methods commonly used in the United States,[22] such as those used by the EPA. Therefore, there is *high confidence* that monetized health benefits would exceed costs for many greenhouse gas reduction actions, and it is *likely* that many specific actions will also have health benefits exceeding costs.[19,226,229] Based on several individual studies, there is *high confidence* that pursuing actions that emphasize reduced fossil fuel use, improved energy efficiency, and reductions in short-lived climate pollutants would not only put the United States on a trajectory that would substantially reduce GHG emissions and approach net-zero emissions (KM 32.4) but also substantially improve air quality and health.[224,231]

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