

Air Quality



Chapter 14. Air Quality

Authors and Contributors

Federal Coordinating Lead Author

Christopher G. Nolte, US Environmental Protection Agency

Chapter Lead Author

J. Jason West, University of North Carolina at Chapel Hill

Chapter Authors

Michelle L. Bell, Yale University

Arlene M. Fiore, Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences

Panos G. Georgopoulos, Rutgers University

Jeremy J. Hess, University of Washington

Loretta J. Mickley, Harvard University

Susan M. O'Neill, USDA Forest Service, Pacific Northwest Research Station

Jeffrey R. Pierce, Colorado State University

Robert W. Pinder, US Environmental Protection Agency

Sally Pusede, University of Virginia

Drew T. Shindell, Duke University

Sacoby M. Wilson, University of Maryland

Technical Contributors

William R. L. Anderegg, University of Utah

Bhargavi Chekuri, University of Colorado School of Medicine

Nina Gabrielle G. Domingo, Yale University

Isabella M. Dressel, University of Virginia

Stuart Illson, University of Washington

Jean-Francois Lamarque, National Center for Atmospheric Research

Yuhao Pan, unaffiliated

Robbie M. Parks, Columbia University

Muye Ru, Morgan Stanley

Cascade Tuholske, Montana State University

Review Editor

Neal Fann, US Environmental Protection Agency

Cover Art

Margaret Plumley

Recommended Citation

West, J.J., C.G. Nolte, M.L. Bell, A.M. Fiore, P.G. Georgopoulos, J.J. Hess, L.J. Mickley, S.M. O'Neill, J.R. Pierce, R.W. Pinder, S. Pusede, D.T. Shindell, and S.M. Wilson, 2023: Ch. 14. Air quality. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. <https://doi.org/10.7930/NCA5.2023.CH14>

Table of Contents

Introduction.....5

Key Message 14.1
Climate Change Will Hamper Efforts to Improve US Air Quality5

Key Message 14.2
**Increasing Wildfire Smoke Is Harming Human Health
and Catalyzing New Protection Strategies.....9**

Key Message 14.3
**Air Pollution Is Often Worse in Communities of Color
and Low-Income Communities11**

Box 14.1. Environmental Justice, Air Pollution,
and Climate Change: Houston, Texas 12

Key Message 14.4
Climate Change Is Worsening Pollen Exposures and Adversely Impacting Health 14

Key Message 14.5
**Policies Can Reduce Greenhouse Gas Emissions and
Improve Air Quality Simultaneously16**

Traceable Accounts.....20

Process Description 20

Key Message 14.1 20

Key Message 14.2 22

Key Message 14.3 23

Key Message 14.4 25

Key Message 14.5 26

References28

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 60,000¹⁶—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}: ?

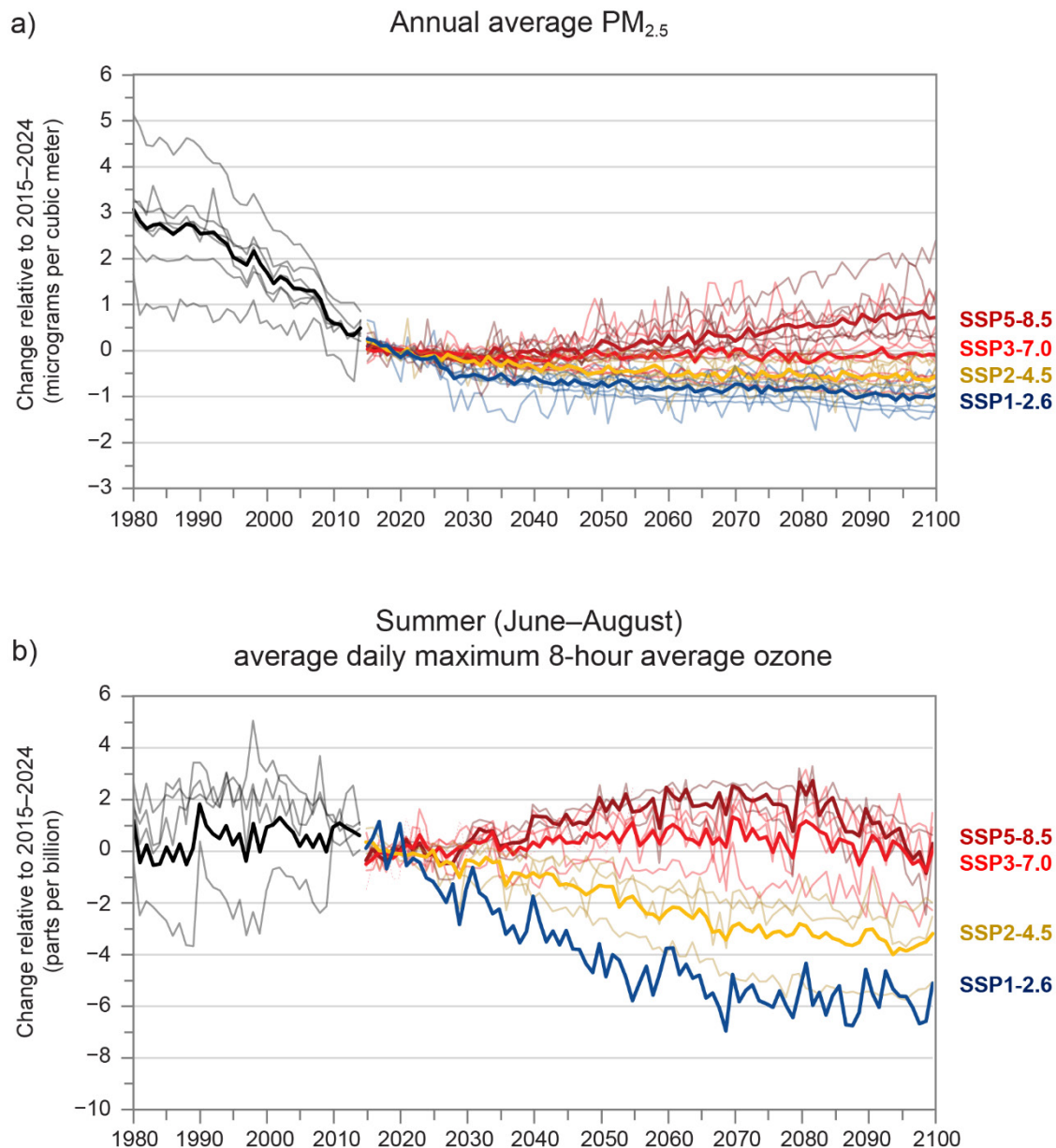
Pollutants accumulate during stagnant periods, but trends in stagnation are uncertain.

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 2021⁶⁵ [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}

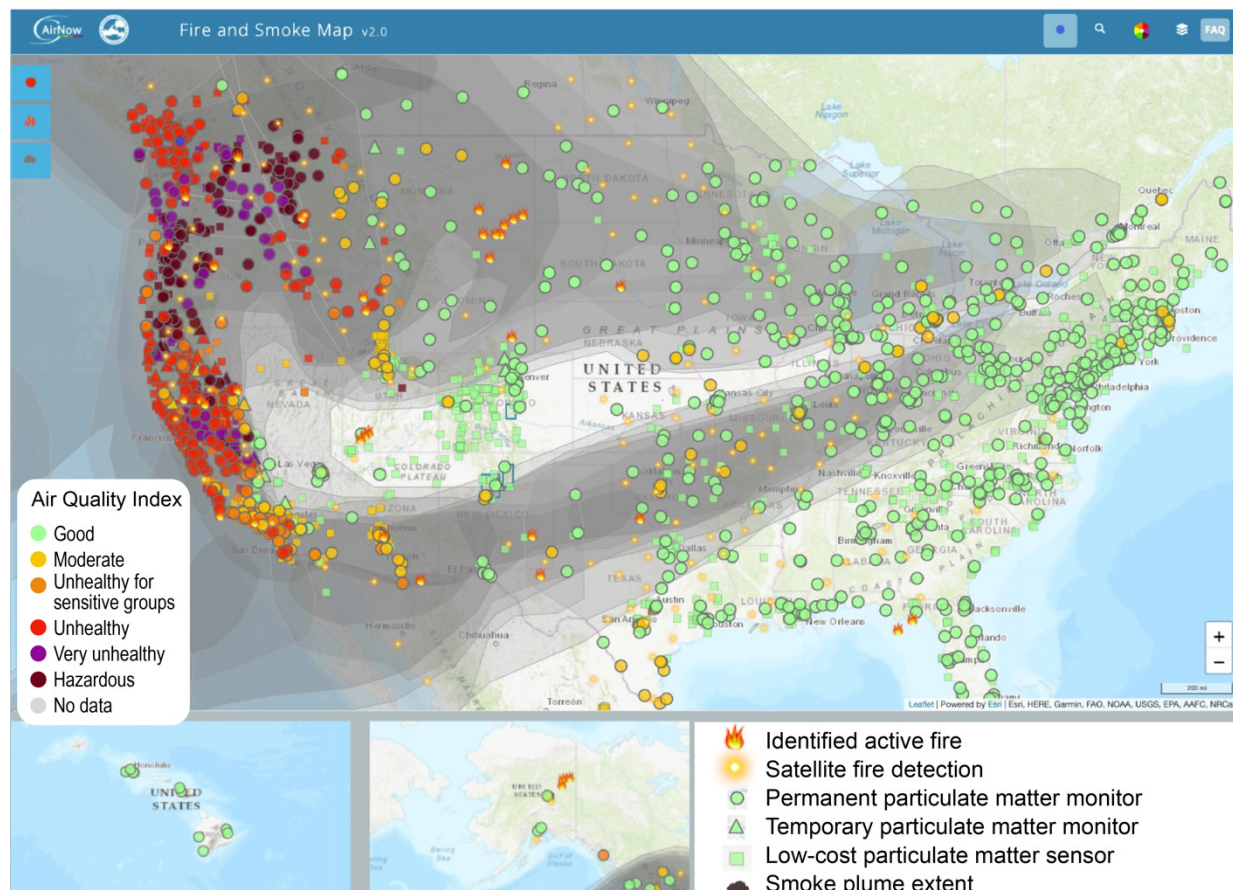
Wildfires emit PM_{2.5} and other air pollutants, including volatile organic compounds (VOCs), nitrogen oxides (which contribute to ozone generation in plumes), and toxic gaseous and particulate species.^{74,77} Since publication of the Fourth National Climate Assessment in 2018, studies have revealed 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 season¹⁰⁷ 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 exposure¹⁰⁹ 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 forecasts¹²² 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 (NO₂),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.

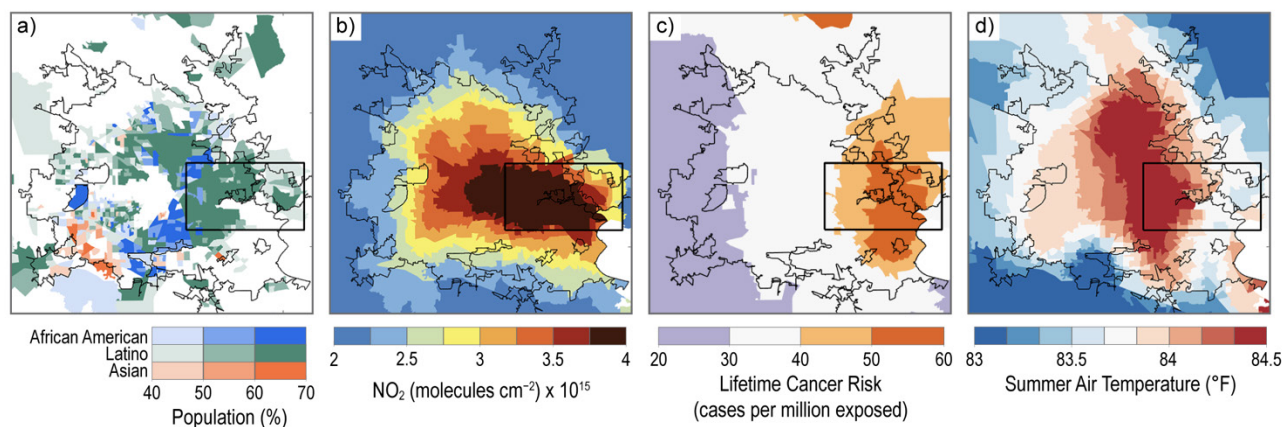
Air Pollution Exposure at Home in the Houston Ship Channel Region



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 (NO₂; 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 (CO₂) can increase pollen allergenicity.^{195,196,197}

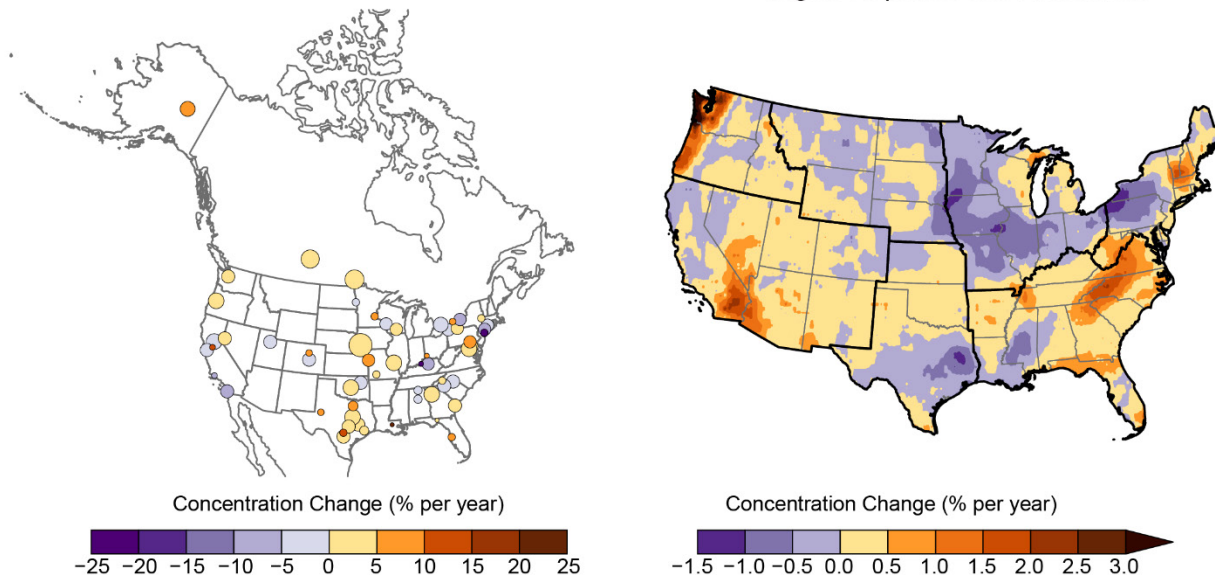
Multiple US regions have experienced longer, more intense pollen seasons, with earlier start dates and increased emissions and airborne loads over the past 30 years, increasing the potential for exposures (Figure 14.6; KM 22.2).^{187,194,196,198,199,200,201} For example, the season for ragweed pollen, 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-CO₂ 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

a) Observed long-term pollen trends

b)

Projected changes in
ragweed pollen concentrations

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. 2021¹⁹⁴ [CC BY 4.0]; (b) adapted from Ren et al. 2022²¹⁰ [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 systems²¹³ 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

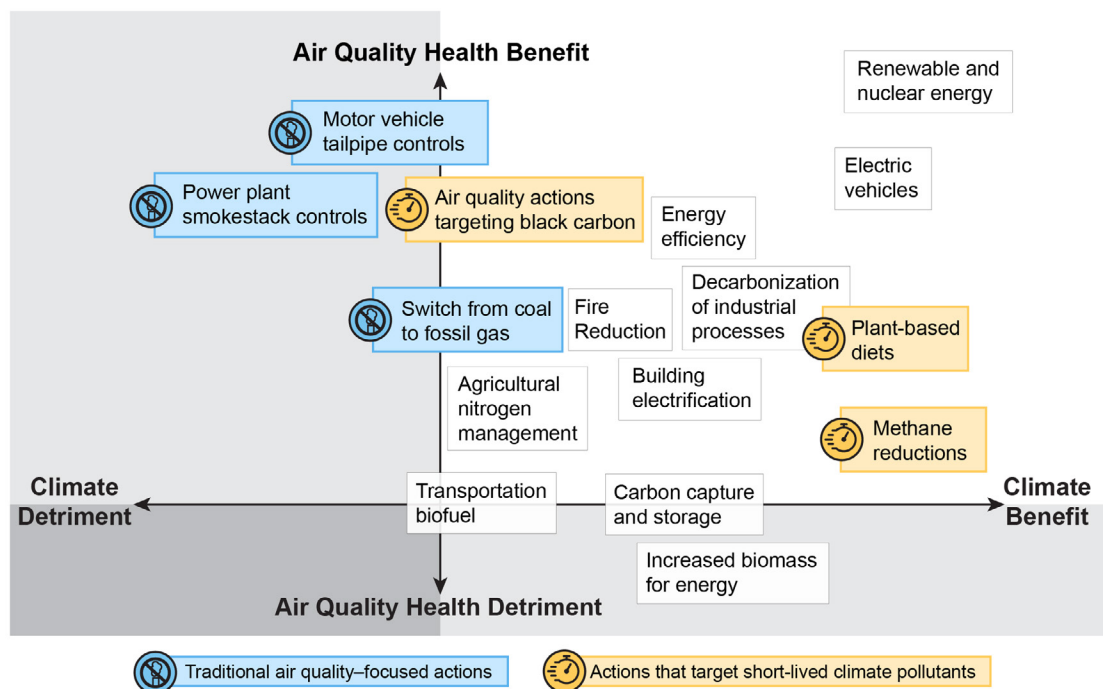
Substantial reductions in economy-wide greenhouse gas emissions would result in improved air quality and significant public health benefits (*very likely, high confidence*). For many actions, these benefits exceed the cost of greenhouse gas emission controls (*likely, high confidence*). Through coordinated 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 CO₂ emissions (*high confidence*).

Fossil fuel energy use is responsible for 92.1% of US CO₂ emissions²¹⁵ 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 quality²²⁴ and health benefits²²⁵ beyond what smokestack and tailpipe controls can provide.

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

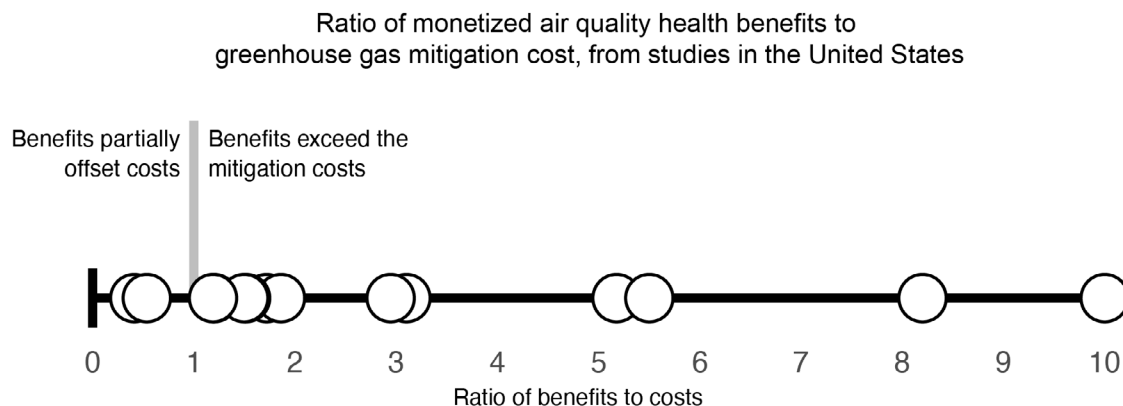


Many emissions-reduction actions can achieve multiple benefits for climate, air quality, and health.

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 CO₂ reduced is estimated to bring about health benefits²³¹ that are valued in 26 US studies from \$8 to \$430 (in 2022 dollars), with a median of \$100 per ton of CO₂ (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 CO₂.^{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 ton²⁴² 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 CO₂ 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 CO₂ 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 (NO₂)^{138,163,177,312} and in combination with models for PM_{2.5} and NO₂,^{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 campaigns²¹⁴ 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 GHGs²¹⁵ 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 III²²¹ 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 deaths²¹⁶ 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 CO₂). 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 pollutants²⁵² 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}

References

1. EPA, 2020: Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants (Final Report, Apr 2020). EPA/600/R-20/012. U.S. Environmental Protection Agency, Washington, DC. <https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=348522>
2. Turner, M.C., M. Jerrett, C.A. Pope, D. Krewski, S.M. Gapstur, W.R. Diver, B.S. Beckerman, J.D. Marshall, J. Su, D.L. Crouse, and R.T. Burnett, 2016: Long-term ozone exposure and mortality in a large prospective study. *American Journal of Respiratory and Critical Care Medicine*, **193** (10), 1134–1142. <https://doi.org/10.1164/rccm.201508-1633oc>
3. Emberson, L., 2020: Effects of ozone on agriculture, forests and grasslands. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **378** (2183), 20190327. <https://doi.org/10.1098/rsta.2019.0327>
4. Bell, M.L., K. Ebisu, B.P. Leaderer, J.F. Gent, H.J. Lee, P. Koutrakis, Y. Wang, F. Dominici, and R.D. Peng, 2014: Associations of PM_{2.5} constituents and sources with hospital admissions: Analysis of four counties in Connecticut and Massachusetts (USA) for persons ≥ 65 years of age. *Environmental Health Perspectives*, **122** (2), 138–144. <https://doi.org/10.1289/ehp.1306656>
5. Calderón-Garcidueñas, L. and A. Ayala, 2022: Air pollution, ultrafine particles, and your brain: Are combustion nanoparticle emissions and engineered nanoparticles causing preventable fatal neurodegenerative diseases and common neuropsychiatric outcomes? *Environmental Science & Technology*, **56** (11), 6847–6856. <https://doi.org/10.1021/acs.est.1c04706>
6. Dockery, D.W., F.E. Speizer, D.O. Stram, J.H. Ware, J.D. Spengler, and B.G. Ferris, 1989: Effects of inhalable particles on respiratory health of children. *American Review of Respiratory Disease*, **139** (3), 587–594. <https://doi.org/10.1164/ajrccm/139.3.587>
7. Johnson, N.M., A.R. Hoffmann, J.C. Behlen, C. Lau, D. Pendleton, N. Harvey, R. Shore, Y. Li, J. Chen, Y. Tian, and R. Zhang, 2021: Air pollution and children's health—A review of adverse effects associated with prenatal exposure from fine to ultrafine particulate matter. *Environmental Health and Preventive Medicine*, **26** (1), 72. <https://doi.org/10.1186/s12199-021-00995-5>
8. Krewski, D., M. Jerrett, R.T. Burnett, R. Ma, E. Hughes, Y. Shi, M.C. Turner, C.A. Pope, III, G. Thurston, E.E. Calle, and M.J. Thun, 2009: Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. HEI Research Report 140. Health Effects Institute, Boston, MA, 140 pp. <https://pubmed.ncbi.nlm.nih.gov/19627030/>
9. Ljungman, P.L.S., N. Andersson, L. Stockfelt, E.M. Andersson, J.N. Sommar, K. Eneroth, L. Gidhagen, C. Johansson, A. Lager, K. Leander, P. Molnar, N.L. Pedersen, D. Rizzuto, A. Rosengren, D. Segersson, P. Wennberg, L. Barregard, B. Forsberg, G. Sallsten, T. Bellander, and G. Pershagen, 2019: Long-term exposure to particulate air pollution, black carbon, and their source components in relation to ischemic heart disease and stroke. *Environmental Health Perspectives*, **127** (10), 107012. <https://doi.org/10.1289/ehp4757>
10. Yitshak-Sade, M., I. Kloog, J.D. Schwartz, V. Novack, O. Erez, and A.C. Just, 2021: The effect of prenatal temperature and PM_{2.5} exposure on birthweight: Weekly windows of exposure throughout the pregnancy. *Environment International*, **155**, 106588. <https://doi.org/10.1016/j.envint.2021.106588>
11. Hopke, P.K., Q. Dai, L. Li, and Y. Feng, 2020: Global review of recent source apportionments for airborne particulate matter. *Science of The Total Environment*, **740**, 140091. <https://doi.org/10.1016/j.scitotenv.2020.140091>
12. Wells, B., P. Dolwick, B. Eder, M. Evangelista, K. Foley, E. Mannshardt, C. Misenis, and A. Weishampel, 2021: Improved estimation of trends in U.S. ozone concentrations adjusted for interannual variability in meteorological conditions. *Atmospheric Environment*, **248**, 118234. <https://doi.org/10.1016/j.atmosenv.2021.118234>
13. EPA, 2022: Our Nation's Air: Trends Through 2020. U.S. Environmental Protection Agency. <https://gispub.epa.gov/air/trendsreport/2021>
14. EPA, 2022: Policy Assessment for the Reconsideration of the National Ambient Air Quality Standards for Particulate Matter. EPA-452/R-22-004. U.S. Environmental Protection Agency, Research Triangle Park, NC. https://www.epa.gov/system/files/documents/2022-05/Final%20Policy%20Assessment%20for%20the%20Reconsideration%20of%20the%20PM%20NAAQS_May2022_0.pdf

15. Turnock, S.T., R.J. Allen, M. Andrews, S.E. Bauer, M. Deushi, L. Emmons, P. Good, L. Horowitz, J.G. John, M. Michou, P. Nabat, V. Naik, D. Neubauer, F.M. O'Connor, D. Olivie, N. Oshima, M. Schulz, A. Sellar, S. Shim, T. Takemura, S. Tilmes, K. Tsigaridis, T. Wu, and J. Zhang, 2020: Historical and future changes in air pollutants from CMIP6 models. *Atmospheric Chemistry and Physics*, **20** (23), 14547–14579. <https://doi.org/10.5194/acp-20-14547-2020>
16. Murray, C.J.L., A.Y. Aravkin, P. Zheng, C. Abbafati, K.M. Abbas, et al., 2020: Global burden of 87 risk factors in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, **396** (10258), 1223–1249. [https://doi.org/10.1016/s0140-6736\(20\)30752-2](https://doi.org/10.1016/s0140-6736(20)30752-2)
17. Burnett, R., H. Chen, M. Szyszkowicz, N. Fann, B. Hubbell, C.A. Pope, J.S. Apte, M. Brauer, A. Cohen, S. Weichenthal, J. Coggins, Q. Di, B. Brunekreef, J. Frostad, S.S. Lim, H. Kan, K.D. Walker, G.D. Thurston, R.B. Hayes, C.C. Lim, M.C. Turner, M. Jerrett, D. Krewski, S.M. Gapstur, W.R. Diver, B. Ostro, D. Goldberg, D.L. Crouse, R.V. Martin, P. Peters, L. Pinault, M. Tjepkema, A. van Donkelaar, P.J. Villeneuve, A.B. Miller, P. Yin, M. Zhou, L. Wang, N.A.H. Janssen, M. Marra, R.W. Atkinson, H. Tsang, T.Q. Thach, J.B. Cannon, R.T. Allen, J.E. Hart, F. Laden, G. Cesaroni, F. Forastiere, G. Weinmayr, A. Jaensch, G. Nagel, H. Concin, and J.V. Spadaro, 2018: Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (38), 9592–9597. <https://doi.org/10.1073/pnas.1803222115>
18. Seltzer, K.M., D.T. Shindell, and C.S. Malley, 2018: Measurement-based assessment of health burdens from long-term ozone exposure in the United States, Europe, and China. *Environmental Research Letters*, **13** (10), 104018. <https://doi.org/10.1088/1748-9326/aae29d>
19. Shindell, D., M. Ru, Y. Zhang, K. Seltzer, G. Faluvegi, L. Nazarenko, G.A. Schmidt, L. Parsons, A. Challapalli, L. Yang, and A. Glick, 2021: Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (46), e2104061118. <https://doi.org/10.1073/pnas.2104061118>
20. Vohra, K., A. Vodonos, J. Schwartz, E.A. Marais, M.P. Sulprizio, and L.J. Mickley, 2021: Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research*, **195**, 110754. <https://doi.org/10.1016/j.envres.2021.110754>
21. EPA, 2023: Environmental Benefits Mapping and Analysis Program—Community Edition, User Manual. U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf
22. EPA, 2023: Estimating PM_{2.5}- and Ozone-Attributable Health Benefits, Technical Support Document for the 2022 PM_{2.5} NAAQS Reconsideration Proposal RIA. EPA-HQ-OAR-2019-0587. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-10/source-apportionment-tsd-oct-2021_0.pdf
23. McGrath, J.M., A.M. Betzelberger, S. Wang, E. Shook, X.-G. Zhu, S.P. Long, and E.A. Ainsworth, 2015: An analysis of ozone damage to historical maize and soybean yields in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (46), 14390–14395. <https://doi.org/10.1073/pnas.1509777112>
24. Marlier, M.E., K.I. Brenner, J.C. Liu, L.J. Mickley, S. Raby, E. James, R. Ahmadov, and H. Riden, 2022: Exposure of agricultural workers in California to wildfire smoke under past and future climate conditions. *Environmental Research Letters*, **17** (9), 094045. <https://doi.org/10.1088/1748-9326/ac8c58>
25. Tessum, C.W., D.A. Paoletta, S.E. Chambliss, J.S. Apte, J.D. Hill, and J.D. Marshall, 2021: PM_{2.5} pollutants disproportionately and systemically affect people of color in the United States. *Science Advances*, **7** (18), 4491. <https://doi.org/10.1126/sciadv.abf4491>
26. Fann, N.L., C.G. Nolte, M.C. Sarofim, J. Martinich, and N.J. Nassikas, 2021: Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, **4** (1), e2032064. <https://doi.org/10.1001/jamanetworkopen.2020.32064>
27. Saari, R.K., Y. Mei, E. Monier, and F. Garcia-Menendez, 2019: Effect of health-related uncertainty and natural variability on health impacts and cobenefits of climate policy. *Environmental Science & Technology*, **53** (3), 1098–1108. <https://doi.org/10.1021/acs.est.8b05094>
28. Bell, M.L., A. McDermott, S.L. Zeger, J.M. Samet, and F. Dominici, 2004: Ozone and short-term mortality in 95 US urban communities, 1987–2000. *JAMA: The Journal of the American Medical Association*, **292** (19), 2372–2378. <https://doi.org/10.1001/jama.292.19.2372>

29. Chen, K., K. Wolf, S. Breitner, A. Gasparrini, M. Stafoggia, E. Samoli, Z.J. Andersen, G. Bero-Bedada, T. Bellander, F. Hennig, B. Jacquemin, J. Pekkanen, R. Hampel, J. Cyrus, A. Peters, and A. Schneider, 2018: Two-way effect modifications of air pollution and air temperature on total natural and cardiovascular mortality in eight European urban areas. *Environment International*, **116**, 186–196. <https://doi.org/10.1016/j.envint.2018.04.021>
30. Kioumourtzoglou, M.A., J. Schwartz, P. James, F. Dominici, and A. Zanobetti, 2016: PM_{2.5} and mortality in 207 US cities: Modification by temperature and city characteristics. *Epidemiology*, **27** (2), 221–227. <https://doi.org/10.1097/ede.0000000000000422>
31. Yitshak-Sade, M., J.F. Bobb, J.D. Schwartz, I. Kloog, and A. Zanobetti, 2018: The association between short and long-term exposure to PM_{2.5} and temperature and hospital admissions in New England and the synergistic effect of the short-term exposures. *Science of The Total Environment*, **639**, 868–875. <https://doi.org/10.1016/j.scitotenv.2018.05.181>
32. Zanobetti, A. and A. Peters, 2015: Disentangling interactions between atmospheric pollution and weather. *Journal of Epidemiology and Community Health*, **69** (7), 613–615. <https://doi.org/10.1136/jech-2014-203939>
33. Kerr, G.H., D.W. Waugh, S.D. Steenrod, S.A. Strode, and S.E. Strahan, 2020: Surface ozone-meteorology relationships: Spatial variations and the role of the jet stream. *Journal of Geophysical Research: Atmospheres*, **125** (21), e2020JD032735. <https://doi.org/10.1029/2020jd032735>
34. Kerr, G.H., D.W. Waugh, S.A. Strode, S.D. Steenrod, L.D. Oman, and S.E. Strahan, 2019: Disentangling the drivers of the summertime ozone-temperature relationship over the United States. *Journal of Geophysical Research: Atmospheres*, **124** (19), 10503–10524. <https://doi.org/10.1029/2019jd030572>
35. Previdi, M. and A.M. Fiore, 2019: The importance of sampling variability in assessments of ENSO-PM_{2.5} relationships: A case study for the south central United States. *Geophysical Research Letters*, **46** (12), 6878–6884. <https://doi.org/10.1029/2019gl082250>
36. Sun, W., P. Hess, G. Chen, and S. Tilmes, 2019: How waviness in the circulation changes surface ozone: A viewpoint using local finite-amplitude wave activity. *Atmospheric Chemistry and Physics*, **19** (20), 12917–12933. <https://doi.org/10.5194/acp-19-12917-2019>
37. Leibensperger, E.M., L.J. Mickley, and D.J. Jacob, 2008: Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change. *Atmospheric Chemistry and Physics*, **8** (23), 7075–7086. <https://doi.org/10.5194/acp-8-7075-2008>
38. Schnell, J.L. and M.J. Prather, 2017: Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (11), 2854–2859. <https://doi.org/10.1073/pnas.1614453114>
39. Zhang, J., Y. Gao, K. Luo, L.R. Leung, Y. Zhang, K. Wang, and J. Fan, 2018: Impacts of compound extreme weather events on ozone in the present and future. *Atmospheric Chemistry and Physics*, **18** (13), 9861–9877. <https://doi.org/10.5194/acp-18-9861-2018>
40. Trail, M., A.P. Tsimpidi, P. Liu, K. Tsigaridis, J. Rudokas, P. Miller, A. Nenes, Y. Hu, and A.G. Russell, 2014: Sensitivity of air quality to potential future climate change and emissions in the United States and major cities. *Atmospheric Environment*, **94**, 552–563. <https://doi.org/10.1016/j.atmosenv.2014.05.079>
41. Zhang, Y. and Y. Wang, 2016: Climate-driven ground-level ozone extreme in the fall over the southeast United States. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (36), 10025–10030. <https://doi.org/10.1073/pnas.1602563113>
42. Butler, T., A. Lupascu, and A. Nalam, 2020: Attribution of ground-level ozone to anthropogenic and natural sources of nitrogen oxides and reactive carbon in a global chemical transport model. *Atmospheric Chemistry and Physics*, **20** (17), 10707–10731. <https://doi.org/10.5194/acp-20-10707-2020>
43. Fiore, A.M., D.J. Jacob, B.D. Field, D.G. Streets, S.D. Fernandes, and C. Jang, 2002: Linking ozone pollution and climate change: The case for controlling methane. *Geophysical Research Letters*, **29** (19), 25-1–25-4. <https://doi.org/10.1029/2002gl015601>
44. Clifton, O.E., A.M. Fiore, G. Correa, L.W. Horowitz, and V. Naik, 2014: Twenty-first century reversal of the surface ozone seasonal cycle over the northeastern United States: Reversal of the NE US high-O₃ season. *Geophysical Research Letters*, **41** (20), 7343–7350. <https://doi.org/10.1002/2014gl061378>

45. Gao, Y., J.S. Fu, J.B. Drake, J.F. Lamarque, and Y. Liu, 2013: The impact of emission and climate change on ozone in the United States under representative concentration pathways (RCPs). *Atmospheric Chemistry and Physics*, **13** (18), 9607–9621. <https://doi.org/10.5194/acp-13-9607-2013>
46. Rieder, H.E., A.M. Fiore, O.E. Clifton, G. Correa, L.W. Horowitz, and V. Naik, 2018: Combining model projections with site-level observations to estimate changes in distributions and seasonality of ozone in surface air over the U.S.A. *Atmospheric Environment*, **193**, 302–315. <https://doi.org/10.1016/j.atmosenv.2018.07.042>
47. Jerrett, M., R.T. Burnett, C.A. Pope, K. Ito, G. Thurston, D. Krewski, Y. Shi, E. Calle, and M. Thun, 2009: Long-term ozone exposure and mortality. *The New England Journal of Medicine*, **360** (11), 1085–1095. <https://doi.org/10.1056/nejmoa0803894>
48. Lu, X., L. Zhang, and L. Shen, 2019: Meteorology and climate influences on tropospheric ozone: A review of natural sources, chemistry, and transport patterns. *Current Pollution Reports*, **5** (4), 238–260. <https://doi.org/10.1007/s40726-019-00118-3>
49. Shen, L., L.J. Mickley, and L.T. Murray, 2017: Influence of 2000–2050 climate change on particulate matter in the United States: Results from a new statistical model. *Atmospheric Chemistry and Physics*, **17** (6), 4355–4367. <https://doi.org/10.5194/acp-17-4355-2017>
50. Silva, R.A., J.J. West, J.-F. Lamarque, D.T. Shindell, W.J. Collins, G. Faluvegi, G.A. Folberth, L.W. Horowitz, T. Nagashima, V. Naik, Steven T. Rumbold, K. Sudo, T. Takemura, D. Bergmann, P. Cameron-Smith, R.M. Doherty, B. Josse, I.A. MacKenzie, David S. Stevenson, and G. Zeng, 2017: Future global mortality from changes in air pollution attributable to climate change. *Nature Climate Change*, **7** (9), 647–651. <https://doi.org/10.1038/nclimate3354>
51. Nolte, C.G., T.L. Spero, J.H. Bowden, M.S. Mallard, and P.D. Dolwick, 2018: The potential effects of climate change on air quality across the conterminous US at 2030 under three Representative Concentration Pathways. *Atmospheric Chemistry and Physics*, **18** (20), 15471–15489. <https://doi.org/10.5194/acp-18-15471-2018>
52. Shen, L., L.J. Mickley, and E. Gilleland, 2016: Impact of increasing heat waves on U.S. ozone episodes in the 2050s: Results from a multimodel analysis using extreme value theory. *Geophysical Research Letters*, **43** (8), 4017–4025. <https://doi.org/10.1002/2016gl068432>
53. Schnell, J.L., M.J. Prather, B. Josse, V. Naik, L.W. Horowitz, G. Zeng, D.T. Shindell, and G. Faluvegi, 2016: Effect of climate change on surface ozone over North America, Europe, and East Asia. *Geophysical Research Letters*, **43** (7), 3509–3518. <https://doi.org/10.1002/2016gl068060>
54. Westervelt, D.M., L.W. Horowitz, V. Naik, A.P.K. Tai, A.M. Fiore, and D.L. Mauzerall, 2016: Quantifying PM_{2.5}-meteorology sensitivities in a global climate model. *Atmospheric Environment*, **142**, 43–56. <https://doi.org/10.1016/j.atmosenv.2016.07.040>
55. Baasandorj, M., S.W. Hoch, R. Bares, J.C. Lin, S.S. Brown, D.B. Millet, R. Martin, K. Kelly, K.J. Zarzana, C.D. Whiteman, W.P. Dube, G. Tonnesen, I.C. Jaramillo, and J. Sohl, 2017: Coupling between chemical and meteorological processes under persistent cold-air pool conditions: Evolution of wintertime PM_{2.5} pollution events and N₂O₅ observations in Utah's Salt Lake Valley. *Environmental Science & Technology*, **51** (11), 5941–5950. <https://doi.org/10.1021/acs.est.6b06603>
56. Carling, G.T., D.P. Fernandez, K.A. Rey, C.A. Hale, M.M. Goodman, and S.T. Nelson, 2020: Using strontium isotopes to trace dust from a drying Great Salt Lake to adjacent urban areas and mountain snowpack. *Environmental Research Letters*, **15** (11), 114035. <https://doi.org/10.1088/1748-9326/abbfc4>
57. Jones, B.A. and J. Fleck, 2020: Shrinking lakes, air pollution, and human health: Evidence from California's Salton Sea. *Science of The Total Environment*, **712**, 136490. <https://doi.org/10.1016/j.scitotenv.2019.136490>
58. Wurtsbaugh, W.A., C. Miller, S.E. Null, R.J. DeRose, P. Wilcock, M. Hahnenberger, F. Howe, and J. Moore, 2017: Decline of the world's saline lakes. *Nature Geoscience*, **10** (11), 816–821. <https://doi.org/10.1038/ngeo3052>
59. Duffy, P.B., C.B. Field, N.S. Diffenbaugh, S.C. Doney, Z. Dutton, S. Goodman, L. Heinzerling, S. Hsiang, D.B. Lobell, L.J. Mickley, S. Myers, S.M. Natali, C. Parmesan, S. Tierney, and A.P. Williams, 2019: Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases. *Science*, **363** (6427), 5982. <https://doi.org/10.1126/science.aat5982>
60. Hall, D.K., D.S. O'Leary, N.E. DiGirolamo, W. Miller, and D.H. Kang, 2021: The role of declining snow cover in the desiccation of the Great Salt Lake, Utah, using MODIS data. *Remote Sensing of Environment*, **252**, 112106. <https://doi.org/10.1016/j.rse.2020.112106>

61. Wang, J., C. Song, J.T. Reager, F. Yao, J.S. Famiglietti, Y. Sheng, G.M. MacDonald, F. Brun, H.M. Schmied, R.A. Marston, and Y. Wada, 2018: Recent global decline in endorheic basin water storages. *Nature Geoscience*, **11** (12), 926–932. <https://doi.org/10.1038/s41561-018-0265-7>
62. Achakulwisut, P., S.C. Anenberg, J.E. Neumann, S.L. Penn, N. Weiss, A. Crimmins, N. Fann, J. Martinich, H. Roman, and L.J. Mickley, 2019: Effects of increasing aridity on ambient dust and public health in the U.S. Southwest under climate change. *GeoHealth*, **3** (5), 127–144. <https://doi.org/10.1029/2019gh000187>
63. Li, Y., L.J. Mickley, and J.O. Kaplan, 2021: Response of dust emissions in southwestern North America to 21st century trends in climate, CO₂ fertilization, and land use: Implications for air quality. *Atmospheric Chemistry and Physics*, **21** (1), 57–68. <https://doi.org/10.5194/acp-21-57-2021>
64. Fiore, A.M., V. Naik, and E.M. Leibensperger, 2015: Air quality and climate connections. *Journal of the Air & Waste Management Association*, **65** (6), 645–685. <https://doi.org/10.1080/10962247.2015.1040526>
65. The Royal Society, 2021: Effects of Net-Zero Policies and Climate Change on Air Quality. The Royal Society, London, UK, 106 pp. <https://royalsociety.org/topics-policy/projects/air-quality-climate-change/>
66. Wu, S., L.J. Mickley, E.M. Leibensperger, D.J. Jacob, D. Rind, and D.G. Streets, 2008: Effects of 2000–2050 global change on ozone air quality in the United States. *Journal of Geophysical Research: Atmospheres*, **113** (D6). <https://doi.org/10.1029/2007jd008917>
67. Nolte, C.G., T.L. Spero, J.H. Bowden, M.C. Sarofim, J. Martinich, and M.S. Mallard, 2021: Regional temperature–ozone relationships across the U.S. under multiple climate and emissions scenarios. *Journal of the Air & Waste Management Association*, **71** (10), 1251–1264. <https://doi.org/10.1080/10962247.2021.1970048>
68. Zanis, P., D. Akritidis, S. Turnock, V. Naik, S. Szopa, A.K. Georgoulas, S.E. Bauer, M. Deushi, L.W. Horowitz, J. Keeble, P. Le Sager, F.M. O'Connor, N. Oshima, K. Tsigaridis, and T. van Noije, 2022: Climate change penalty and benefit on surface ozone: A global perspective based on CMIP6 earth system models. *Environmental Research Letters*, **17** (2), 024014. <https://doi.org/10.1088/1748-9326/ac4a34>
69. Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (42), 11770–11775. <https://doi.org/10.1073/pnas.1607171113>
70. Abatzoglou, J.T., D.S. Battisti, A.P. Williams, W.D. Hansen, B.J. Harvey, and C.A. Kolden, 2021: Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment*, **2** (1), 227. <https://doi.org/10.1038/s43247-021-00299-0>
71. Ford, B., M. Val Martin, S.E. Zelasky, E.V. Fischer, S.C. Anenberg, C.L. Heald, and J.R. Pierce, 2018: Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. *GeoHealth*, **2** (8), 229–247. <https://doi.org/10.1029/2018gh000144>
72. Liu, Y., Y. Liu, J. Fu, C.-E. Yang, X. Dong, H. Tian, B. Tao, J. Yang, Y. Wang, Y. Zou, and Z. Ke, 2022: Projection of future wildfire emissions in western USA under climate change: Contributions from changes in wildfire, fuel loading and fuel moisture. *International Journal of Wildland Fire*, **31** (1), 1–13. <https://doi.org/10.1071/wf20190>
73. Stambaugh, M.C., R.P. Guyette, E.D. Stroh, M.A. Struckhoff, and J.B. Whittier, 2018: Future southcentral US wildfire probability due to climate change. *Climatic Change*, **147** (3–4), 617–631. <https://doi.org/10.1007/s10584-018-2156-8>
74. Jaffe, D.A., S.M. O'Neill, N.K. Larkin, A.L. Holder, D.L. Peterson, J.E. Halofsky, and A.G. Rappold, 2020: Wildfire and prescribed burning impacts on air quality in the United States. *Journal of the Air & Waste Management Association*, **70** (6), 583–615. <https://doi.org/10.1080/10962247.2020.1749731>
75. Juliano, T.W., P.A. Jiménez, B. Kosović, T. Eidhammer, G. Thompson, L.K. Berg, J. Fast, A. Motley, and A. Polidori, 2022: Smoke from 2020 United States wildfires responsible for substantial solar energy forecast errors. *Environmental Research Letters*, **17** (3), 034010. <https://doi.org/10.1088/1748-9326/ac5143>
76. Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara, 2021: The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (2), e2011048118. <https://doi.org/10.1073/pnas.2011048118>
77. O'Dell, K., R.S. Hornbrook, W. Permar, E.J.T. Levin, L.A. Garofalo, E.C. Apel, N.J. Blake, A. Jarnot, M.A. Pothier, D.K. Farmer, L. Hu, T. Campos, B. Ford, J.R. Pierce, and E.V. Fischer, 2020: Hazardous air pollutants in fresh and aged western US wildfire smoke and implications for long-term exposure. *Environmental Science & Technology*, **54** (19), 11838–11847. <https://doi.org/10.1021/acs.est.0c04497>

78. Xie, Y., M. Lin, B. Decharme, C. Delire, L.W. Horowitz, D.M. Lawrence, F. Li, and R. Séférian, 2022: Tripling of western US particulate pollution from wildfires in a warming climate. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (14), e2111372119. <https://doi.org/10.1073/pnas.2111372119>
79. McClure, C.D. and D.A. Jaffe, 2018: US particulate matter air quality improves except in wildfire-prone areas. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (31), 7901–7906. <https://doi.org/10.1073/pnas.1804353115>
80. Brey, S.J. and E.V. Fischer, 2016: Smoke in the city: How often and where does smoke impact summertime ozone in the United States? *Environmental Science & Technology*, **50** (3), 1288–1294. <https://doi.org/10.1021/acs.est.5b05218>
81. Buysse, C.E., A. Kaulfus, U. Nair, and D.A. Jaffe, 2019: Relationships between particulate matter, ozone, and nitrogen oxides during urban smoke events in the western US. *Environmental Science & Technology*, **53** (21), 12519–12528. <https://doi.org/10.1021/acs.est.9b05241>
82. Hodshire, A.L., A. Akherati, M.J. Alvarado, B. Brown-Steiner, S.H. Jathar, J.L. Jimenez, S.M. Kreidenweis, C.R. Lonsdale, T.B. Onasch, A.M. Ortega, and J.R. Pierce, 2019: Aging effects on biomass burning aerosol mass and composition: A critical review of field and laboratory studies. *Environmental Science & Technology*, **53** (17), 10007–10022. <https://doi.org/10.1021/acs.est.9b02588>
83. Boaggio, K., S.D. LeDuc, R.B. Rice, P.F. Duffney, K.M. Foley, A.L. Holder, S. McDow, and C.P. Weaver, 2022: Beyond particulate matter mass: Heightened levels of lead and other pollutants associated with destructive fire events in California. *Environmental Science & Technology*, **56** (20), 14272–14283. <https://doi.org/10.1021/acs.est.2c02099>
84. CARB, 2021: Camp Fire Air Quality Data Analysis. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/2021-07/Camp_Fire_report_July2021.pdf
85. Hauser, N., K.C. Conlon, A. Desai, and L.N. Kobziar, 2021: Climate change and infections on the move in North America. *Infection and Drug Resistance*, **14**, 5711–5723. <https://doi.org/10.2147/idr.s305077>
86. Kobziar, L.N., M.R.A. Pingree, H. Larson, T.J. Dreaden, S. Green, and J.A. Smith, 2018: Pyroaerobiology: The aerosolization and transport of viable microbial life by wildland fire. *Ecosphere*, **9** (11), e02507. <https://doi.org/10.1002/ecs2.2507>
87. Kobziar, L.N., D. Vuono, R. Moore, B.C. Christner, T. Dean, D. Betancourt, A.C. Watts, J. Aurell, and B. Gullett, 2022: Wildland fire smoke alters the composition, diversity, and potential atmospheric function of microbial life in the aerobiome. *ISME Communications*, **2** (1), 8. <https://doi.org/10.1038/s43705-022-00089-5>
88. Abdo, M., I. Ward, K. O'Dell, B. Ford, J.R. Pierce, E.V. Fischer, and J.L. Crooks, 2019: Impact of wildfire smoke on adverse pregnancy outcomes in Colorado, 2007–2015. *International Journal of Environmental Research and Public Health*, **16** (19), 3720. <https://doi.org/10.3390/ijerph16193720>
89. Chen, G., Y. Guo, X. Yue, S. Tong, A. Gasparrini, M.L. Bell, B. Armstrong, J. Schwartz, J.J.K. Jaakkola, A. Zanobetti, E. Lavigne, P.H. Nascimento Saldiva, H. Kan, D. Royé, A. Milojevic, A. Overcenco, A. Urban, A. Schneider, A. Entezari, A.M. Vicedo-Cabrera, A. Zeka, A. Tobias, B. Nunes, B. Alahmad, B. Forsberg, S.-C. Pan, C. Íñiguez, C. Ameling, C. De la Cruz Valencia, C. Åström, D. Houthuijs, D. Van Dung, E. Samoli, F. Mayvaneh, F. Sera, G. Carrasco-Escobar, Y. Lei, H. Orru, H. Kim, I.-H. Holobaca, J. Kyselý, J.P. Teixeira, J. Madureira, K. Katsouyanni, M. Hurtado-Díaz, M. Maasikmets, M.S. Ragettli, M. Hashizume, M. Stafoggia, M. Pascal, M. Scortichini, M. de Sousa Zanotti Stagliorio Coelho, N. Valdés Ortega, N.R.I. Rytí, N. Scovronick, P. Matus, P. Goodman, R.M. Garland, R. Abrutsky, S.O. Garcia, S. Rao, S. Fratianni, T.N. Dang, V. Colistro, V. Huber, W. Lee, X. Seposo, Y. Honda, Y.L. Guo, T. Ye, W. Yu, M.J. Abramson, J.M. Samet, and S. Li, 2021: Mortality risk attributable to wildfire-related PM_{2.5} pollution: A global time series study in 749 locations. *The Lancet Planetary Health*, **5** (9), e579–e587. [https://doi.org/10.1016/s2542-5196\(21\)00200-x](https://doi.org/10.1016/s2542-5196(21)00200-x)
90. Dodd, W., P. Scott, C. Howard, C. Scott, C. Rose, A. Cunsolo, and J. Orbinski, 2018: Lived experience of a record wildfire season in the Northwest Territories, Canada. *Canadian Journal of Public Health*, **109** (3), 327–337. <https://doi.org/10.17269/s41997-018-0070-5>
91. Doubleday, A., J. Schulte, L. Sheppard, M. Kadlec, R. Dhammapala, J. Fox, and T. Busch Isaksen, 2020: Mortality associated with wildfire smoke exposure in Washington state, 2006–2017: A case-crossover study. *Environmental Health*, **19** (1), 4. <https://doi.org/10.1186/s12940-020-0559-2>
92. Liu, J.C., G. Pereira, S.A. Uhl, M.A. Bravo, and M.L. Bell, 2015: A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environmental Research*, **136**, 120–132. <https://doi.org/10.1016/j.envres.2014.10.015>

93. Reid, C.E., M. Brauer, F.H. Johnston, M. Jerrett, J.R. Balmes, and C.T. Elliott, 2016: Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, **124** (9), 1334–1343. <https://doi.org/10.1289/ehp.1409277>
94. Schwarz, L., A. Dimitrova, R. Aguilera, R. Basu, A. Gershunov, and T. Benmarhnia, 2022: Smoke and COVID-19 case fatality ratios during California wildfires. *Environmental Research Letters*, **17** (1), 014054. <https://doi.org/10.1088/1748-9326/ac4538>
95. Zhou, X., K. Josey, L. Kamareddine, M.C. Caine, T. Liu, L.J. Mickley, M. Cooper, and F. Dominici, 2021: Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States. *Science Advances*, **7** (33), 8789. <https://doi.org/10.1126/sciadv.abi8789>
96. Fann, N., B. Alman, R.A. Broome, G.G. Morgan, F.H. Johnston, G. Pouliot, and A.G. Rappold, 2018: The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. *Science of The Total Environment*, **610–611**, 802–809. <https://doi.org/10.1016/j.scitotenv.2017.08.024>
97. O'Dell, K., K. Bilsback, B. Ford, S.E. Martenies, S. Magzamen, E.V. Fischer, and J.R. Pierce, 2021: Estimated mortality and morbidity attributable to smoke plumes in the United States: Not just a western US problem. *GeoHealth*, **5** (9), e2021GH000457. <https://doi.org/10.1029/2021gh000457>
98. Liu, J.C., A. Wilson, L.J. Mickley, K. Ebisu, M.P. Sulprizio, Y. Wang, R.D. Peng, X. Yue, F. Dominici, and M.L. Bell, 2017: Who among the elderly is most vulnerable to exposure to and health risks of fine particulate matter from wildfire smoke? *American Journal of Epidemiology*, **186** (6), 730–735. <https://doi.org/10.1093/aje/kwx141>
99. Navarro, K.M., M.T. Kleinman, C.E. Mackay, T.E. Reinhardt, J.R. Balmes, G.A. Broyles, R.D. Ottmar, L.P. Naher, and J.W. Domitrovich, 2019: Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. *Environmental Research*, **173**, 462–468. <https://doi.org/10.1016/j.envres.2019.03.060>
100. Woo, S.H.L., J.C. Liu, X. Yue, L.J. Mickley, and M.L. Bell, 2020: Air pollution from wildfires and human health vulnerability in Alaskan communities under climate change. *Environmental Research Letters*, **15** (9), 094019. <https://doi.org/10.1088/1748-9326/ab9270>
101. Liu, J.C., L.J. Mickley, M.P. Sulprizio, X. Yue, R.D. Peng, F. Dominici, and M.L. Bell, 2016: Future respiratory hospital admissions from wildfire smoke under climate change in the Western US. *Environmental Research Letters*, **11** (12), 124018. <https://doi.org/10.1088/1748-9326/11/12/124018>
102. Stevens, J.T., B.M. Collins, J.W. Long, M.P. North, S.J. Prichard, L.W. Tarnay, and A.M. White, 2016: Evaluating potential trade-offs among fuel treatment strategies in mixed-conifer forests of the Sierra Nevada. *Ecosphere*, **7** (9), e01445. <https://doi.org/10.1002/ecs2.1445>
103. Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake, 2021: Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications*, **31** (8), e02432. <https://doi.org/10.1002/eap.2432>
104. USFS, 2022: Confronting the Wildlife Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests. FS-1187a. U.S. Department of Agriculture, Forest Service. <https://www.fs.usda.gov/sites/default/files/Confronting-Wildfire-Crisis.pdf>
105. Larson, E.R., K.F. Kipfmüller, and L.B. Johnson, 2021: People, fire, and pine: Linking human agency and landscape in the Boundary Waters Canoe Area Wilderness and beyond. *Annals of the American Association of Geographers*, **111** (1), 1–25. <https://doi.org/10.1080/24694452.2020.1768042>
106. Long, J.W., F.K. Lake, and R.W. Goode, 2021: The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecology and Management*, **500**, 119597. <https://doi.org/10.1016/j.foreco.2021.119597>
107. Larkin, N.K., S.M. Raffuse, S. Huang, N. Pavlovic, P. Lahm, and V. Rao, 2020: The comprehensive fire information reconciled emissions (CFIRE) inventory: Wildland fire emissions developed for the 2011 and 2014 U.S. national emissions inventory. *Journal of the Air & Waste Management Association*, **70** (11), 1165–1185. <https://doi.org/10.1080/10962247.2020.1802365>
108. Afrin, S. and F. Garcia-Menendez, 2021: Potential impacts of prescribed fire smoke on public health and socially vulnerable populations in a southeastern U.S. state. *Science of The Total Environment*, **794**, 148712. <https://doi.org/10.1016/j.scitotenv.2021.148712>

109. NWCG, 2020: NWCG Smoke Management Guide for Prescribed Fire. PMS 420-3, NFES 001279, Peterson, J., P. Lahm, M. Fitch, M. George, D. Haddow, M. Melvin, J. Hyde, and E. Eberhardt, Eds. National Wildfire Coordinating Group. <https://www.nwcg.gov/sites/default/files/publications/pms420-3.pdf>
110. EPA, 2021: Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S. EPA/600/R-21/197. U.S. Environmental Protection Agency, Washington, DC. <https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=352824>
111. Hill, L.A., J. Jaeger, and A. Smith, 2022: Can Prescribed Fires Mitigate Health Harm? A Review of Air Quality and Public Health Implications of Wildfire and Prescribed Fire. American Lung Association and PSE Healthy Energy. https://www.lung.org/getmedia/fd7ff728-56d9-4b33-82eb-abd06f01bc3b/pse_wildfire-and-prescribed-fire-brief_final.pdf
112. Chen, J., K. Anderson, R. Pavlovic, M.D. Moran, P. Englefield, D.K. Thompson, R. Munoz-Alpizar, and H. Landry, 2019: The FireWork v2.0 air quality forecast system with biomass burning emissions from the Canadian Forest Fire Emissions Prediction System v2.03. *Geoscientific Model Development*, **12** (7), 3283–3310. <https://doi.org/10.5194/gmd-12-3283-2019>
113. June, N., J. Vaughan, Y. Lee, and B.K. Lamb, 2021: Operational bias correction for PM_{2.5} using the AIRPACT air quality forecast system in the Pacific Northwest. *Journal of the Air & Waste Management Association*, **71** (4), 515–527. <https://doi.org/10.1080/10962247.2020.1856216>
114. Lee, P., J. McQueen, I. Stajner, J. Huang, L. Pan, D. Tong, H. Kim, Y. Tang, S. Kondragunta, M. Ruminski, S. Lu, E. Rogers, R. Saylor, P. Shafran, H.-C. Huang, J. Gorline, S. Upadhyay, and R. Artz, 2017: NAQFC developmental forecast guidance for fine particulate matter (PM_{2.5}). *Weather and Forecasting*, **32** (1), 343–360. <https://doi.org/10.1175/waf-d-15-0163.1>
115. O'Neill, S., P. Xian, J. Flemming, M. Cope, A. Baklanov, N. Larkin, J. Vaughan, D. Tong, R. Howard, R. Stull, D. Davignon, R. Ahmadov, M. Odman, J. Innis, M. Azzi, C. Gan, R. Pavlovic, B.N. Chew, J. Reid, and A. MacNeil, 2022: Profiles of Operational and Research Forecasting of Smoke and Air Quality Around the World. ESS Open Archive. <https://doi.org/10.1002/essoar.10512975.1>
116. Xian, P., J.S. Reid, E.J. Hyer, C.R. Sampson, J.I. Rubin, M. Ades, N. Asencio, S. Basart, A. Benedetti, P.S. Bhattacharjee, M.E. Brooks, P.R. Colarco, A.M. da Silva, T.F. Eck, J. Guth, O. Jorba, R. Kouznetsov, Z. Kipling, M. Sofiev, C. Perez Garcia-Pando, Y. Pradhan, T. Tanaka, J. Wang, D.L. Westphal, K. Yumimoto, and J. Zhang, 2019: Current state of the global operational aerosol multi-model ensemble: An update from the International Cooperative for Aerosol Prediction (ICAP). *Quarterly Journal of the Royal Meteorological Society*, **145** (S1), 176–209. <https://doi.org/10.1002/qj.3497>
117. EPA, 2021: Wildfire Smoke: A Guide for Public Health Officials. EPA-452/R-21-901. U.S. Environmental Protection Agency. https://www.airnow.gov/sites/default/files/2021-09/wildfire-smoke-guide_0.pdf
118. Barn, P.K., C.T. Elliott, R.W. Allen, T. Kosatsky, K. Rideout, and S.B. Henderson, 2016: Portable air cleaners should be at the forefront of the public health response to landscape fire smoke. *Environmental Health*, **15** (1), 116. <https://doi.org/10.1186/s12940-016-0198-9>
119. Davison, G., K.K. Barkjohn, G.S.W. Hagler, A.L. Holder, S. Coefield, C. Noonan, and B. Hassett-Sipple, 2021: Creating clean air spaces during wildland fire smoke episodes: Web Summit summary. *Frontiers in Public Health*, **9**, 508971. <https://doi.org/10.3389/fpubh.2021.508971>
120. Fisk, W.J. and W.R. Chan, 2017: Health benefits and costs of filtration interventions that reduce indoor exposure to PM_{2.5} during wildfires. *Indoor Air*, **27** (1), 191–204. <https://doi.org/10.1111/ina.12285>
121. Rappold, A.G., N.L. Fann, J. Crooks, J. Huang, W.E. Cascio, R.B. Devlin, and D. Diaz-Sanchez, 2014: Forecast-based interventions can reduce the health and economic burden of wildfires. *Environmental Science & Technology*, **48** (18), 10571–10579. <https://doi.org/10.1021/es5012725>
122. Lahm, P. and N.K. Larkin, 2020: The interagency wildland fire air quality response program. *The Magazine for Environmental Managers*, **24**, 9–15.
123. John D. Dingell Jr. Conservation, Management, and Recreation Act. 116th Congress, Pub. L. No. 116–119, 133 Stat. 580–839, March 12, 2019. <https://www.congress.gov/bill/116th-congress/senate-bill/47/text>

124. Rappold, A.G., M.C. Hano, S. Prince, L. Wei, S.M. Huang, C. Baghdikian, B. Stearns, X. Gao, S. Hoshiko, W.E. Cascio, D. Diaz-Sanchez, and B. Hubbell, 2019: Smoke sense initiative leverages citizen science to address the growing wildfire-related public health problem. *GeoHealth*, **3** (12), 443–457. <https://doi.org/10.1029/2019gh000199>
125. Burke, M., S. Heft-Neal, J. Li, A. Driscoll, P. Baylis, M. Stigler, J.A. Weill, J.A. Burney, J. Wen, M.L. Childs, and C.F. Gould, 2022: Exposures and behavioural responses to wildfire smoke. *Nature Human Behaviour*, **6** (10), 1351–1361. <https://doi.org/10.1038/s41562-022-01396-6>
126. Rice, M.B., S.B. Henderson, A.A. Lambert, K.R. Cromar, J.A. Hall, W.E. Cascio, P.G. Smith, B.J. Marsh, S. Coefield, J.R. Balmes, A. Kamal, M.I. Gilmour, C. Carlsten, K.M. Navarro, G.W. Collman, A. Rappold, M.D. Miller, S.L. Stone, and D.L. Costa, 2021: Respiratory impacts of wildland fire smoke: Future challenges and policy opportunities. An official American Thoracic Society workshop report. *Annals of the American Thoracic Society*, **18** (6), 921–930. <https://doi.org/10.1513/annalsats.202102-148st>
127. EPA, 2022: AirNow Fire and Smoke Map. U.S. Environmental Protection Agency. <https://fire.airnow.gov/>
128. Bullard, R.D., P. Mohai, R. Saha, and B. Wright, 2008: Toxic wastes and race at twenty: Why race still matters after all of these years. *Environmental Law*, **38** (2), 371–411. <http://www.jstor.org/stable/43267204>
129. Di, Q., Y. Wang, A. Zanobetti, Y. Wang, P. Koutrakis, C. Choirat, F. Dominici, and J.D. Schwartz, 2017: Air pollution and mortality in the Medicare population. *New England Journal of Medicine*, **376** (26), 2513–2522. <https://doi.org/10.1056/nejmoa1702747>
130. Hajat, A., C. Hsia, and M.S. O'Neill, 2015: Socioeconomic disparities and air pollution exposure: A global review. *Current Environmental Health Reports*, **2** (4), 440–450. <https://doi.org/10.1007/s40572-015-0069-5>
131. Wilson, S.M., H. Fraser-Rahim, E. Williams, H. Zhang, L. Rice, E. Svendsen, and W. Abara, 2012: Assessment of the distribution of toxic release inventory facilities in metropolitan Charleston: An environmental justice case study. *American Journal of Public Health*, **102** (10), 1974–1980. <https://doi.org/10.2105/ajph.2012.300700>
132. Ard, K., 2015: Trends in exposure to industrial air toxins for different racial and socioeconomic groups: A spatial and temporal examination of environmental inequality in the U.S. from 1995 to 2004. *Social Science Research*, **53**, 375–390. <https://doi.org/10.1016/j.ssresearch.2015.06.019>
133. Castillo, M.D., P.L. Kinney, V. Southerland, C.A. Arno, K. Crawford, A. van Donkelaar, M. Hammer, R.V. Martin, and S.C. Anenberg, 2021: Estimating intra-urban inequities in PM_{2.5}-attributable health impacts: A case study for Washington, DC. *GeoHealth*, **5** (11), e2021GH000431. <https://doi.org/10.1029/2021gh000431>
134. Clark, L.P., D.B. Millet, and J.D. Marshall, 2017: Changes in transportation-related air pollution exposures by race-ethnicity and socioeconomic status: Outdoor nitrogen dioxide in the United States in 2000 and 2010. *Environmental Health Perspectives*, **125** (9), 097012. <https://doi.org/10.1289/ehp959>
135. Colmer, J., I. Hardman, J. Shimshack, and J. Voorheis, 2020: Disparities in PM_{2.5} air pollution in the United States. *Science*, **369** (6503), 575–578. <https://doi.org/10.1126/science.aaz9353>
136. Kravitz-Wirtz, N., K. Crowder, A. Hajat, and V. Sass, 2016: The long-term dynamics of racial/ethnic inequality in neighborhood air pollution exposure, 1990–2009. *Du Bois Review: Social Science Research on Race*, **13** (2), 237–259. <https://doi.org/10.1017/s1742058x16000205>
137. Liu, J., L.P. Clark, M.J. Bechle, A. Hajat, S.Y. Kim, A.L. Robinson, L. Sheppard, A.A. Szpiro, and J.D. Marshall, 2021: Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environmental Health Perspectives*, **129** (12), 127005. <https://doi.org/10.1289/ehp8584>
138. Demetillo, M.A.G., C. Harkins, B.C. McDonald, P.S. Chodrow, K. Sun, and S.E. Pusede, 2021: Space-based observational constraints on NO₂ air pollution inequality from diesel traffic in major US cities. *Geophysical Research Letters*, **48** (17), e2021GL094333. <https://doi.org/10.1029/2021gl094333>
139. Tessum, C.W., J.S. Apte, A.L. Goodkind, N.Z. Muller, K.A. Mullins, D.A. Paoletta, S. Polasky, N.P. Springer, S.K. Thakrar, J.D. Marshall, and J.D. Hill, 2019: Inequity in consumption of goods and services adds to racial-ethnic disparities in air pollution exposure. *Proceedings of the National Academy of Sciences of the United States of America*, **116** (13), 6001–6006. <https://doi.org/10.1073/pnas.1818859116>
140. Johnson Gaither, C., S. Afrin, F. Garcia-Menendez, M.T. Odman, R. Huang, S. Goodrick, and A. Ricardo da Silva, 2019: African American exposure to prescribed fire smoke in Georgia, USA. *International Journal of Environmental Research and Public Health*, **16** (17), 3079. <https://doi.org/10.3390/ijerph16173079>

141. Mirabelli, M.C., S. Wing, S.W. Marshall, and T.C. Wilcosky, 2006: Race, poverty, and potential exposure of middle-school students to air emissions from confined swine feeding operations. *Environmental Health Perspectives*, **114** (4), 591–596. <https://doi.org/10.1289/ehp.8586>
142. Ogneva-Himmelberger, Y., L. Huang, and H. Xin, 2015: CALPUFF and CAFOs: Air pollution modeling and environmental justice analysis in the North Carolina hog industry. *ISPRS International Journal of Geo-Information*, **4** (1), 150–171. <https://doi.org/10.3390/ijgi4010150>
143. Son, J.-Y., M.L. Miranda, and M.L. Bell, 2021: Exposure to concentrated animal feeding operations (CAFOs) and risk of mortality in North Carolina, USA. *Science of The Total Environment*, **799**, 149407. <https://doi.org/10.1016/j.scitotenv.2021.149407>
144. Wing, S., D. Cole, and G. Grant, 2000: Environmental injustice in North Carolina's hog industry. *Environmental Health Perspectives*, **108** (3), 225–231. <https://doi.org/10.1289/ehp.00108225>
145. Wing, S. and S. Wolf, 2000: Intensive livestock operations, health, and quality of life among eastern North Carolina residents. *Environmental Health Perspectives*, **108** (3), 233–238. <https://doi.org/10.1289/ehp.00108233>
146. Thind, M.P.S., C.W. Tessum, I.L. Azevedo, and J.D. Marshall, 2019: Fine particulate air pollution from electricity generation in the US: Health impacts by race, income, and geography. *Environmental Science & Technology*, **53** (23), 14010–14019. <https://doi.org/10.1021/acs.est.9b02527>
147. Emanuel, R.E., M.A. Caretta, L. Rivers III, and P. Vasudevan, 2021: Natural gas gathering and transmission pipelines and social vulnerability in the United States. *GeoHealth*, **5** (6), e2021GH000442. <https://doi.org/10.1029/2021gh000442>
148. González, D.J.X., C.M. Morton, L.A.L. Hill, D.R. Michanowicz, R.J. Rossi, S.B.C. Shonkoff, J.A. Casey, and R. Morello-Frosch, 2023: Temporal trends of racial and socioeconomic disparities in population exposures to upstream oil and gas development in California. *GeoHealth*, **7** (3), e2022GH000690. <https://doi.org/10.1029/2022gh000690>
149. Bryant, B. and P. Mohai, 2019: *Race And The Incidence Of Environmental Hazards: A Time For Discourse*, 1st ed. Routledge, New York, 251 pp. <https://doi.org/10.4324/9780429303661>
150. Lane, H.M., R. Morello-Frosch, J.D. Marshall, and J.S. Apte, 2022: Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environmental Science & Technology Letters*, **9** (4), 345–350. <https://doi.org/10.1021/acs.estlett.1c01012>
151. Morello-Frosch, R. and R. Lopez, 2006: The riskscape and the color line: Examining the role of segregation in environmental health disparities. *Environmental Research*, **102** (2), 181–196. <https://doi.org/10.1016/j.envres.2006.05.007>
152. Wilson, S.M., 2009: An ecologic framework to study and address environmental justice and community health issues. *Environmental Justice*, **2** (1), 15–24. <https://doi.org/10.1089/env.2008.0515>
153. Bell, M.L., A. Zanobetti, and F. Dominici, 2013: Evidence on vulnerability and susceptibility to health risks associated with short-term exposure to particulate matter: A systematic review and meta-analysis. *American Journal of Epidemiology*, **178** (6), 865–876. <https://doi.org/10.1093/aje/kwt090>
154. Josey, K.P., S.W. Delaney, X. Wu, R.C. Nethery, P. DeSouza, D. Braun, and F. Dominici, 2023: Air pollution and mortality at the intersection of race and social class. *New England Journal of Medicine*, **388** (15), 1396–1404. <https://doi.org/10.1056/nejmsa2300523>
155. EPA, 2021: Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts. EPA 430-R-21-003. U.S. Environmental Protection Agency. <https://www.epa.gov/cira/social-vulnerability-report>
156. Morello-Frosch, R. and O.K. Obasogie, 2023: The climate gap and the color line—Racial health inequities and climate change. *New England Journal of Medicine*, **388** (10), 943–949. <https://doi.org/10.1056/nejmsb2213250>
157. Anenberg, S.C., S. Haines, E. Wang, N. Nassikas, and P.L. Kinney, 2020: Synergistic health effects of air pollution, temperature, and pollen exposure: A systematic review of epidemiological evidence. *Environmental Health*, **19** (1), 130. <https://doi.org/10.1186/s12940-020-00681-z>
158. Lee, W., H.M. Choi, D. Kim, Y. Honda, Y.-L. Leon Guo, and H. Kim, 2019: Synergic effect between high temperature and air pollution on mortality in Northeast Asia. *Environmental Research*, **178**, 108735. <https://doi.org/10.1016/j.envres.2019.108735>

159. McDonald, R.I., T. Biswas, C. Sachar, I. Housman, T.M. Boucher, D. Balk, D. Nowak, E. Spotswood, C.K. Stanley, and S. Leyk, 2021: The tree cover and temperature disparity in US urbanized areas: Quantifying the association with income across 5,723 communities. *PLoS ONE*, **16** (4), e0249715. <https://doi.org/10.1371/journal.pone.0249715>
160. O'Neill, M.S., A. Zanobetti, and J. Schwartz, 2005: Disparities by race in heat-related mortality in four US cities: The role of air conditioning prevalence. *Journal of Urban Health*, **82** (2), 191–197. <https://doi.org/10.1093/jurban/jti043>
161. Romitti, Y., I. Sue Wing, K.R. Spangler, and G.A. Wellenius, 2022: Inequality in the availability of residential air conditioning across 115 US metropolitan areas. *PNAS Nexus*, **1** (4), 210. <https://doi.org/10.1093/pnasnexus/pgac210>
162. Shrestha, P.M., J.L. Humphrey, E.J. Carlton, J.L. Adgate, K.E. Barton, E.D. Root, and S.L. Miller, 2019: Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons. *International Journal of Environmental Research and Public Health*, **16** (19), 3535. <https://doi.org/10.3390/ijerph16193535>
163. Dressel, I.M., M.A.G. Demetillo, L.M. Judd, S.J. Janz, K.P. Fields, K. Sun, A.M. Fiore, B.C. McDonald, and S.E. Pusede, 2022: Daily satellite observations of nitrogen dioxide air pollution inequality in New York City, New York and Newark, New Jersey: Evaluation and application. *Environmental Science & Technology*, **56** (22), 15298–15311. <https://doi.org/10.1021/acs.est.2c02828>
164. Anenberg, S.C., D.K. Henze, V. Tinney, P.L. Kinney, W. Raich, N. Fann, C.S. Malley, H. Roman, L. Lamsal, B. Duncan, R.V. Martin, A. van Donkelaar, M. Brauer, R. Doherty, J.E. Jonson, Y. Davila, K. Sudo, and J.C.I. Kuylenstierna, 2018: Estimates of the global burden of ambient PM_{2.5}, ozone, and NO₂ on asthma incidence and emergency room visits. *Environmental Health Perspectives*, **126** (10), 107004. <https://doi.org/10.1289/ehp3766>
165. Wu, J., C. Ren, R.J. Delfino, J. Chung, M. Wilhelm, and B. Ritz, 2009: Association between local traffic-generated air pollution and preeclampsia and preterm delivery in the South Coast Air Basin of California. *Environmental Health Perspectives*, **117** (11), 1773–1779. <https://doi.org/10.1289/ehp.0800334>
166. Chan, N.W. and J.W. Morrow, 2019: Unintended consequences of cap-and-trade? Evidence from the Regional Greenhouse Gas Initiative. *Energy Economics*, **80**, 411–422. <https://doi.org/10.1016/j.eneco.2019.01.007>
167. Hernandez-Cortes, D. and K. Meng, 2020: Do Environmental Markets Cause Environmental Injustice? Evidence from California's Carbon Market. Working Paper 27205. National Bureau of Economic Research, Cambridge, MA. <https://doi.org/10.3386/w27205>
168. Cushing, L., D. Blaustein-Rejto, M. Wander, M. Pastor, J. Sadd, A. Zhu, and R. Morello-Frosch, 2018: Carbon trading, co-pollutants, and environmental equity: Evidence from California's cap-and-trade program (2011–2015). *PLoS Medicine*, **15** (7), e1002604. <https://doi.org/10.1371/journal.pmed.1002604>
169. Wang, Y., J.S. Apte, J.D. Hill, C.E. Ivey, R.F. Patterson, A.L. Robinson, C.W. Tessum, and J.D. Marshall, 2022: Location-specific strategies for eliminating US national racial-ethnic PM_{2.5} exposure inequality. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (44), e2205548119. <https://doi.org/10.1073/pnas.2205548119>
170. Hsiang, S., P. Oliva, and R. Walker, 2019: The distribution of environmental damages. *Review of Environmental Economics and Policy*, **13** (1), 83–103. <https://doi.org/10.1093/reep/rey024>
171. Ku, A., D.M. Kammen, and S. Castellanos, 2021: A quantitative, equitable framework for urban transportation electrification: Oakland, California as a mobility model of climate justice. *Sustainable Cities and Society*, **74**, 103179. <https://doi.org/10.1016/j.scs.2021.103179>
172. Al-Fadhli, F.M., Y. Kimura, E.C. McDonald-Buller, and D.T. Allen, 2012: Impact of flare destruction efficiency and products of incomplete combustion on ozone formation in Houston, Texas. *Industrial & Engineering Chemistry Research*, **51** (39), 12663–12673. <https://doi.org/10.1021/ie201400z>
173. Johnson, G.S., S.C. Washington, D.W. King, and J.M. Gomez, 2014: Air quality and health issues along Houston's ship channel: An exploratory environmental justice analysis of a vulnerable community (Pleasantville). *Race, Gender & Class*, **21** (3/4), 273–303. <http://www.jstor.org/stable/43496996>
174. Olaguer, E.P., M.H. Erickson, A. Wijesinghe, and B.S. Neish, 2016: Source attribution and quantification of benzene event emissions in a Houston ship channel community based on real-time mobile monitoring of ambient air. *Journal of the Air & Waste Management Association*, **66** (2), 164–172. <https://doi.org/10.1080/10962247.2015.1081652>
175. Chakraborty, J., T.W. Collins, S.E. Grineski, M.C. Montgomery, and M. Hernandez, 2014: Comparing disproportionate exposure to acute and chronic pollution risks: A case study in Houston, Texas: Acute and chronic pollution risks in Houston. *Risk Analysis*, **34** (11), 2005–2020. <https://doi.org/10.1111/risa.12224>

176. Collins, T.W., S.E. Grineski, J. Chakraborty, M.C. Montgomery, and M. Hernandez, 2015: Downscaling environmental justice analysis: Determinants of household-level hazardous air pollutant exposure in Greater Houston. *Annals of the Association of American Geographers*, **105** (4), 684–703. <https://doi.org/10.1080/00045608.2015.1050754>
177. Demetillo, M.A.G., A. Navarro, K.K. Knowles, K.P. Fields, J.A. Geddes, C.R. Nowlan, S.J. Janz, L.M. Judd, J. Al-Saadi, K. Sun, B.C. McDonald, G.S. Diskin, and S.E. Pusede, 2020: Observing nitrogen dioxide air pollution inequality using high-spatial-resolution remote sensing measurements in Houston, Texas. *Environmental Science & Technology*, **54** (16), 9882–9895. <https://doi.org/10.1021/acs.est.0c01864>
178. Lam, Y., R. Sivasubramanian, M. Guerrero, J. Parras, and A. Parras, 2021: Toxic Air Pollution in the Houston Ship Channel: Disparities Show Urgent Need for Environmental Justice. Natural Resources Defense Council, 8 pp. <https://www.nrdc.org/sites/default/files/air-pollution-houston-ship-channel-ib.pdf>
179. Linder, S.H., D. Marko, and K. Sexton, 2008: Cumulative cancer risk from air pollution in Houston: Disparities in risk burden and social disadvantage. *Environmental Science & Technology*, **42** (12), 4312–4322. <https://doi.org/10.1021/es072042u>
180. Loustaunau, M.G. and J. Chakraborty, 2019: Vehicular air pollution in Houston, Texas: An intra-categorical analysis of environmental injustice. *International Journal of Environmental Research and Public Health*, **16** (16), 2968. <https://doi.org/10.3390/ijerph16162968>
181. Flores, A.B., T.W. Collins, S.E. Grineski, and J. Chakraborty, 2020: Disparities in health effects and access to health care among Houston area residents after Hurricane Harvey. *Public Health Reports*, **135** (4), 511–523. <https://doi.org/10.1177/0033354920930133>
182. Misuri, A., V. Casson Moreno, N. Quddus, and V. Cozzani, 2019: Lessons learnt from the impact of Hurricane Harvey on the chemical and process industry. *Reliability Engineering & System Safety*, **190**, 106521. <https://doi.org/10.1016/j.ress.2019.106521>
183. Thomas, K.A., J.R. Elliott, and S. Chavez, 2018: Community perceptions of industrial risks before and after a toxic flood: The case of Houston and Hurricane Harvey. *Sociological Spectrum*, **38** (6), 371–386. <https://doi.org/10.1080/02732173.2018.1532367>
184. Reed, S.D., T.A. Lee, and D.C. McCrory, 2004: The economic burden of allergic rhinitis. *PharmacoEconomics*, **22** (6), 345–361. <https://doi.org/10.2165/00019053-200422060-00002>
185. Choi, Y.-J., K.S. Lee, and J.-W. Oh, 2021: The impact of climate change on pollen season and allergic sensitization to pollens. *Immunology and Allergy Clinics of North America*, **41** (1), 97–109. <https://doi.org/10.1016/j.iac.2020.09.004>
186. Gilles, S., C. Blume, M. Wimmer, A. Damialis, L. Meulenbroek, M. Gökkaya, C. Bergougnan, S. Eisenbart, N. Sundell, M. Lindh, L.M. Andersson, Å. Dahl, A. Chaker, F. Kolek, S. Wagner, A.U. Neumann, C.A. Akdis, J. Garssen, J. Westin, B. Van't Land, D.E. Davies, and C. Traidl-Hoffmann, 2020: Pollen exposure weakens innate defense against respiratory viruses. *Allergy*, **75** (3), 576–587. <https://doi.org/10.1111/all.14047>
187. Seth, D. and L. Bielory, 2021: Allergenic pollen season variations in the past two decades under changing climate in the United States. *Immunology and Allergy Clinics of North America*, **41** (1), 17–31. <https://doi.org/10.1016/j.iac.2020.09.006>
188. Berger, M., M. Bastl, J. Bouchal, L. Dirr, and U. Berger, 2021: The influence of air pollution on pollen allergy sufferers. *Allergologie Select*, **5**, 345–348. <https://doi.org/10.5414/alx02284e>
189. Gleason, J.A., L. Bielory, and J.A. Fagliano, 2014: Associations between ozone, PM_{2.5}, and four pollen types on emergency department pediatric asthma events during the warm season in New Jersey: A case-crossover study. *Environmental Research*, **132**, 421–429. <https://doi.org/10.1016/j.envres.2014.03.035>
190. Ochkur, S., K. Iijima, J. Gibson, J. Miech, J. Molar, M. Fraser, E. Jacobsen, B. Wright, H. Kita, P. Herckes, and M. Rank, 2022: Ozone and nitrogen oxide enhance the immunogenicity of ragweed pollen. *Journal of Allergy and Clinical Immunology*, **149** (2), AB29. <https://doi.org/10.1016/j.jaci.2021.12.130>
191. Damialis, A., S. Gilles, M. Sofiev, V. Sofieva, F. Kolek, et al., 2021: Higher airborne pollen concentrations correlated with increased SARS-CoV-2 infection rates, as evidenced from 31 countries across the globe. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (12), e2019034118. <https://doi.org/10.1073/pnas.2019034118>

192. Idroze, N.S., C.J. Lodge, B. Erbas, J.A. Douglass, D.S. Bui, and S.C. Dharmage, 2022: A review of the respiratory health burden attributable to short-term exposure to pollen. *International Journal of Environmental Research and Public Health*, **19** (12), 7541. <https://doi.org/10.3390/ijerph19127541>
193. Dbouk, T. and D. Drikakis, 2021: On pollen and airborne virus transmission. *Physics of Fluids*, **33** (6), 063313. <https://doi.org/10.1063/5.0055845>
194. Anderegg, W.R.L., J.T. Abatzoglou, L.D.L. Anderegg, L. Bielory, P.L. Kinney, and L. Ziska, 2021: Anthropogenic climate change is worsening North American pollen seasons. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (7), e2013284118. <https://doi.org/10.1073/pnas.2013284118>
195. Choi, Y.J., H.R. Oh, J.W. Oh, K.R. Kim, M.J. Kim, B.J. Kim, and W.G. Baek, 2018: Chamber and field studies demonstrate differential Amb a 1 contents in common ragweed depending on CO₂ levels. *Allergy, Asthma & Immunology Research*, **10** (3), 278–282. <https://doi.org/10.4168/aair.2018.10.3.278>
196. Ziska, L.H. and K.L. Ebi, 2021: Ch. 7. Climate change, carbon dioxide, and public health: The plant biology perspective. In: *Global Climate Change and Human Health: From Science to Practice*, 2nd ed. Lemery, J., K. Knowlton, and C. Sorensen, Eds. Wiley. <https://www.wiley.com/en-au/Global+Climate+Change+and+Human+Health:+From+Science+to+Practice,+2nd+Edition-p-9781119667957>
197. Ziska, L.H., J. Yang, M.B. Tomecek, and P.J. Beggs, 2016: Cultivar-specific changes in peanut yield, biomass, and allergenicity in response to elevated atmospheric carbon dioxide concentration. *Crop Science*, **56** (5), 2766–2774. <https://doi.org/10.2135/cropsci2015.12.0741>
198. Manangan, A., C. Brown, S. Saha, J. Bell, J. Hess, C. Uejio, S. Fineman, and P. Schramm, 2021: Long-term pollen trends and associations between pollen phenology and seasonal climate in Atlanta, Georgia (1992–2018). *Annals of Allergy, Asthma & Immunology*, **127** (4), 471–480. <https://doi.org/10.1016/j.anai.2021.07.012>
199. Paudel, B., T. Chu, M. Chen, V. Sampath, M. Prunicki, and K.C. Nadeau, 2021: Increased duration of pollen and mold exposure are linked to climate change. *Scientific Reports*, **11** (1), 12816. <https://doi.org/10.1038/s41598-021-92178-z>
200. Zhang, Y., L. Bielory, Z. Mi, T. Cai, A. Robock, and P. Georgopoulos, 2015: Allergenic pollen season variations in the past two decades under changing climate in the United States. *Global change biology*, **21** (4), 1581–1589. <https://doi.org/10.1111/gcb.12755>
201. Ziska, L.H., L. Makra, S.K. Harry, N. Bruffaerts, M. Hendrickx, F. Coates, A. Saarto, M. Thibaudon, G. Oliver, A. Damialis, A. Charalampopoulos, D. Vokou, S. Heidmarsson, E. Gudjohnsen, M. Bonini, J.-W. Oh, K. Sullivan, L. Ford, G.D. Brooks, D. Myszkowska, E. Severova, R. Gehrig, G.D. Ramón, P.J. Beggs, K. Knowlton, and A.R. Crimmins, 2019: Temperature-related changes in airborne allergenic pollen abundance and seasonality across the Northern Hemisphere: A retrospective data analysis. *The Lancet Planetary Health*, **3** (3), e124–e131. [https://doi.org/10.1016/s2542-5196\(19\)30015-4](https://doi.org/10.1016/s2542-5196(19)30015-4)
202. Ziska, L., K. Knowlton, C. Rogers, D. Dalan, N. Tierney, M.A. Elder, W. Filley, J. Shropshire, L.B. Ford, C. Hedberg, P. Fleetwood, K.T. Hovanky, T. Kavanaugh, G. Fulford, R.F. Vrtis, J.A. Patz, J. Portnoy, F. Coates, L. Bielory, and D. Frenz, 2011: Recent warming by latitude associated with increased length of ragweed pollen season in central North America. *Proceedings of the National Academy of Sciences of the United States of America*, **108** (10), 4248–4251. <https://doi.org/10.1073/pnas.1014107108>
203. Damialis, A., C. Traidl-Hoffmann, and R. Treudler, 2019: Ch. 3. Climate change and pollen allergies. In: *Biodiversity and Health in the Face of Climate Change*. Marselle, M.R., J. Stadler, H. Korn, K.N. Irvine, and A. Bonn, Eds. Springer, Cham, Switzerland, 47–66. https://doi.org/10.1007/978-3-030-02318-8_3
204. Cai, T. 2019: Modeling Impacts of Climate Change on Air Quality and Associated Human Exposures. Doctor of Philosophy in Environmental Sciences, Rutgers, The State University of New Jersey. <https://doi.org/10.7282/t3-c6hd-ns81>
205. Cai, T., Y. Zhang, X. Ren, L. Bielory, Z. Mi, C.G. Nolte, Y. Gao, L.R. Leung, and P.G. Georgopoulos, 2019: Development of a semi-mechanistic allergenic pollen emission model. *Science of The Total Environment*, **653**, 947–957. <https://doi.org/10.1016/j.scitotenv.2018.10.243>
206. Cai, T., X. Ren, Z. Mi, L. Bielory, and P.G. Georgopoulos, 2019: Modeling impacts of climate change on population co-exposures to ozone and allergenic pollen across different regions of the United States. In: *APHA's 2019 Annual Meeting and Expo*. 2–6 November 2019. American Public Health Association. <https://apha.confex.com/apha/2019/meetingapp.cgi/Paper/447910>

207. Zhang, Y., L. Bielory, T. Cai, Z. Mi, and P. Georgopoulos, 2015: Predicting onset and duration of airborne allergenic pollen season in the United States. *Atmospheric Environment*, **103**, 297–306. <https://doi.org/10.1016/j.atmosenv.2014.12.019>
208. Zhang, Y. and A.L. Steiner, 2022: Projected climate-driven changes in pollen emission season length and magnitude over the continental United States. *Nature Communications*, **13** (1), 1234. <https://doi.org/10.1038/s41467-022-28764-0>
209. D'Amato, G., H.J. Chong-Neto, O.P. Monge Ortega, C. Vitale, I. Ansotegui, N. Rosario, T. Haahtela, C. Galan, R. Pawankar, M. Murrieta-Aguttes, L. Cecchi, C. Bergmann, E. Ridolo, G. Ramon, S. Gonzalez Diaz, M. D'Amato, and I. Annesi-Maesano, 2020: The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens. *Allergy*, **75** (9), 2219–2228. <https://doi.org/10.1111/all.14476>
210. Ren, X., T. Cai, Z. Mi, L. Bielory, C.G. Nolte, and P.G. Georgopoulos, 2022: Modeling past and future spatiotemporal distributions of airborne allergenic pollen across the contiguous United States. *Frontiers in Allergy*, **3**, 959594. <https://doi.org/10.3389/falgy.2022.959594>
211. Chivato, T., E. Valovirta, R. Dahl, J.d. Monchy, A.B. Thomsen, S. Palkonen, and L. Jacobsen, 2012: Allergy, living and learning: Diagnosis and treatment of allergic respiratory diseases in Europe. *Journal of Investigational Allergology & Clinical Immunology*, **22** (3), 168–179. <https://pubmed.ncbi.nlm.nih.gov/22697006/>
212. Hesse, L., J.N.G. Oude Elberink, A.J.M. van Oosterhout, and M.C. Nawijn, 2022: Allergen immunotherapy for allergic airway diseases: Use lessons from the past to design a brighter future. *Pharmacology & Therapeutics*, **237**, 108115. <https://doi.org/10.1016/j.pharmthera.2022.108115>
213. Linares, C., G.S. Martinez, V. Kendrovski, and J. Diaz, 2020: A new integrative perspective on early warning systems for health in the context of climate change. *Environmental Research*, **187**, 109623. <https://doi.org/10.1016/j.envres.2020.109623>
214. Wikstén, J., S. Toppila-Salmi, and M. Mäkelä, 2018: Primary prevention of airway allergy. *Current Treatment Options in Allergy*, **5** (4), 347–355. <https://doi.org/10.1007/s40521-018-0190-4>
215. EPA, 2023: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. EPA 430–R-23–002. U.S. Environmental Protection Agency. <https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021>
216. Thakrar, S.K., S. Balasubramanian, P.J. Adams, I.M.L. Azevedo, N.Z. Muller, S.N. Pandis, S. Polasky, C.A. Pope, A.L. Robinson, J.S. Apte, C.W. Tessum, J.D. Marshall, and J.D. Hill, 2020: Reducing mortality from air pollution in the United States by targeting specific emission sources. *Environmental Science & Technology Letters*, **7** (9), 639–645. <https://doi.org/10.1021/acs.estlett.0c00424>
217. EPA, 2011: The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report. U.S. Environmental Protection Agency, Office of Air and Radiation, 34 pp. <https://www.epa.gov/sites/default/files/2015-07/documents/summaryreport.pdf>
218. Hubbell, B.J., R.V. Crume, D.M. Evarts, and J.M. Cohen, 2010: Policy monitor: Regulation and progress under the 1990 Clean Air Act amendments. *Review of Environmental Economics and Policy*, **4** (1), 122–138. <https://doi.org/10.1093/reep/rep019>
219. Feng, K., S.J. Davis, L. Sun, and K. Hubacek, 2015: Drivers of the US CO₂ emissions 1997–2013. *Nature Communications*, **6** (1), 7714. <https://doi.org/10.1038/ncomms8714>
220. Lamb, W.F., T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J.G.J. Olivier, D. Wiedenhofer, G. Mattioli, A.A. Khourdajie, J. House, S. Pachauri, M. Figuerola, Y. Saheb, R. Slade, K. Hubacek, L. Sun, S.K. Ribeiro, S. Khennas, S. de la Rue du Can, L. Chapungu, S.J. Davis, I. Bashmakov, H. Dai, S. Dhakal, X. Tan, Y. Geng, B. Gu, and J. Minx, 2021: A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*, **16** (7), 073005. <https://doi.org/10.1088/1748-9326/abee4e>
221. IPCC, 2022: Summary for policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, and J. Malley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA. <https://doi.org/10.1017/9781009157926.001>

222. Ou, Y., W. Shi, S.J. Smith, C.M. Ledna, J.J. West, C.G. Nolte, and D.H. Loughlin, 2018: Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution. *Applied Energy*, **216**, 482–493. <https://doi.org/10.1016/j.apenergy.2018.02.122>
223. Roth, M.B., P.J. Adams, P. Jaramillo, and N.Z. Muller, 2022: Policy spillovers, technological lock-in, and efficiency gains from regional pollution taxes in the U.S. *Energy and Climate Change*, **3**, 100077. <https://doi.org/10.1016/j.egycc.2022.100077>
224. Vasilakos, P.N., H. Shen, Q. Mehdi, P. Wilcoxon, C. Driscoll, K. Fallon, D. Burtraw, M. Domeshek, and A.G. Russell, 2022: Us clean energy futures—Air quality benefits of zero carbon energy policies. *Atmosphere*, **13** (9), 1401. <https://doi.org/10.3390/atmos13091401>
225. Mailloux, N.A., D.W. Abel, T. Holloway, and J.A. Patz, 2022: Nationwide and regional PM_{2.5}-related air quality health benefits from the removal of energy-related emissions in the United States. *GeoHealth*, **6** (5), e2022GH000603. <https://doi.org/10.1029/2022gh000603>
226. Markandya, A., J. Sampedro, S.J. Smith, R. Van Dingenen, C. Pizarro-Irizar, I. Arto, and M. González-Eguino, 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: A modelling study. *The Lancet Planetary Health*, **2** (3), e126–e133. [https://doi.org/10.1016/s2542-5196\(18\)30029-9](https://doi.org/10.1016/s2542-5196(18)30029-9)
227. Nemet, G.F., T. Holloway, and P. Meier, 2010: Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters*, **5** (1), 014007. <https://doi.org/10.1088/1748-9326/5/1/014007>
228. Shindell, D., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8** (4), 291–295. <https://doi.org/10.1038/s41558-018-0108-y>
229. Vandyck, T., K. Keramidas, A. Kitous, J.V. Spadaro, R. Van Dingenen, M. Holland, and B. Saveyn, 2018: Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nature Communications*, **9** (1), 4939. <https://doi.org/10.1038/s41467-018-06885-9>
230. West, J.J., S.J. Smith, R.A. Silva, V. Naik, Y. Zhang, Z. Adelman, M.M. Fry, S. Anenberg, L.W. Horowitz, and J.-F. Lamarque, 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3** (10), 885–889. <https://doi.org/10.1038/nclimate2009>
231. Gallagher, C.L. and T. Holloway, 2020: Integrating air quality and public health benefits in U.S. decarbonization strategies. *Frontiers in Public Health*, **8**, 563358. <https://doi.org/10.3389/fpubh.2020.563358>
232. Bell, M.L., D.L. Davis, L.A. Cifuentes, A.J. Krupnick, R.D. Morgenstern, and G.D. Thurston, 2008: Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environmental Health*, **7** (1), 41. <https://doi.org/10.1186/1476-069x-7-41>
233. Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the health-related costs of 10 climate-sensitive U.S. events during 2012. *GeoHealth*, **3** (9), 245–265. <https://doi.org/10.1029/2019gh000202>
234. Tomlin, A.S., 2021: Air quality and climate impacts of biomass use as an energy source: A review. *Energy & Fuels*, **35** (18), 14213–14240. <https://doi.org/10.1021/acs.energyfuels.1c01523>
235. Zhang, Y., S.J. Smith, J.H. Bowden, Z. Adelman, and J.J. West, 2017: Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050. *Environmental Research Letters*, **12** (11), 114033. <https://doi.org/10.1088/1748-9326/aa8f76>
236. Mewes, C. and C. Unger, 2021: Learning by doing: Co-benefits drive national plans for climate and air quality governance. *Atmosphere*, **12** (9), 1184. <https://doi.org/10.3390/atmos12091184>
237. Adan, O.C.G. and R.A. Samson, Eds., 2011: *Fundamentals of Mold Growth in Indoor Environments and Strategies for Healthy Living*. 1st ed., Springer. <https://doi.org/10.3920/978-90-8686-722-6>
238. Ortiz, M., L. Itard, and P.M. Bluyssen, 2020: Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. *Energy and Buildings*, **221**, 110102. <https://doi.org/10.1016/j.enbuild.2020.110102>

239. Shindell, D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, 2012: Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, **335** (6065), 183–189. <https://doi.org/10.1126/science.1210026>
240. Szopa, S., V. Naik, B. Adhikary, P. Artaxo, T. Berntsen, W.D. Collins, S. Fuzzi, L. Gallardo, A. Kiendler-Scharr, Z. Klimont, H. Liao, N. Unger, and P. Zanis, 2021: Ch. 6. Short-lived climate forcers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 817–922. <https://doi.org/10.1017/9781009157896.008>
241. West, J.J. and A.M. Fiore, 2005: Management of tropospheric ozone by reducing methane emissions. *Environmental Science & Technology*, **39** (13), 4685–4691. <https://doi.org/10.1021/es048629f>
242. IWG, 2021: Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide—Interim Estimates under Executive Order 13990. U.S. Government, Interagency Working Group on Social Cost of Greenhouse Gases. https://www.whitehouse.gov/wp-content/uploads/2021/02/technicalsupportdocument_socialcostofcarbonmethanenitrousoxide.pdf
243. Shindell, D.T., J.S. Fuglestad, and W.J. Collins, 2017: The social cost of methane: Theory and applications. *Faraday Discussions*, **200**, 429–451. <https://doi.org/10.1039/c7fd00009j>
244. UNEP and Climate and Clean Air Coalition, 2021: Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. United Nations Environment Programme, Nairobi, Kenya. <https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions>
245. Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the ozone-related health benefits of methane emission controls. *Environmental and Resource Economics*, **66** (1), 45–63. <https://doi.org/10.1007/s10640-015-9937-6>
246. Fry, M.M., V. Naik, J.J. West, M.D. Schwarzkopf, A.M. Fiore, W.J. Collins, F.J. Dentener, D.T. Shindell, C. Atherton, D. Bergmann, B.N. Duncan, P. Hess, I.A. MacKenzie, E. Marmer, M.G. Schultz, S. Szopa, O. Wild, and G. Zeng, 2012: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing. *Journal of Geophysical Research: Atmospheres*, **117** (D7). <https://doi.org/10.1029/2011jd017134>
247. IPCC, 2021: Summary for policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–32. <https://doi.org/10.1017/9781009157896.001>
248. Dvorak, M.T., K.C. Armour, D.M.W. Frierson, C. Proistosescu, M.B. Baker, and C.J. Smith, 2022: Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming. *Nature Climate Change*, **12** (6), 547–552. <https://doi.org/10.1038/s41558-022-01372-y>
249. Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams, D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950–2050 changes in US anthropogenic aerosols—Part 2: Climate response. *Atmospheric Chemistry and Physics*, **12** (7), 3349–3362. <https://doi.org/10.5194/acp-12-3349-2012>
250. Westervelt, D.M., A.M. Fiore, C.B. Baublitz, and G. Correa, 2021: Impact of regional Northern Hemisphere mid-latitude anthropogenic sulfur dioxide emissions on local and remote tropospheric oxidants. *Atmospheric Chemistry and Physics*, **21** (9), 6799–6810. <https://doi.org/10.5194/acp-21-6799-2021>
251. Zheng, Y., S.J. Davis, G.G. Persad, and K. Caldeira, 2020: Climate effects of aerosols reduce economic inequality. *Nature Climate Change*, **10** (3), 220–224. <https://doi.org/10.1038/s41558-020-0699-y>
252. Dreyfus, G.B., Y. Xu, D.T. Shindell, D. Zaelke, and V. Ramanathan, 2022: Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming. *Proceedings of the National Academy of Sciences of the United States of America*, **119** (22), e2123536119. <https://doi.org/10.1073/pnas.2123536119>
253. Shindell, D. and C.J. Smith, 2019: Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, **573** (7774), 408–411. <https://doi.org/10.1038/s41586-019-1554-z>

254. Domingo, N.G.G., S. Balasubramanian, S.K. Thakrar, M.A. Clark, P.J. Adams, J.D. Marshall, N.Z. Muller, S.N. Pandis, S. Polasky, A.L. Robinson, C.W. Tessum, D. Tilman, P. Tschofen, and J.D. Hill, 2021: Air quality-related health damages of food. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (20), e2013637118. <https://doi.org/10.1073/pnas.2013637118>
255. Powell, J.M., C.J.P. Gourley, C.A. Rotz, and D.M. Weaver, 2010: Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. *Environmental Science & Policy*, **13** (3), 217–228. <https://doi.org/10.1016/j.envsci.2010.03.007>
256. Robertson, G.P. and P.M. Vitousek, 2009: Nitrogen in agriculture: Balancing the cost of an essential resource. *Annual Review of Environment and Resources*, **34** (1), 97–125. <https://doi.org/10.1146/annurev.environ.032108.105046>
257. Hitaj, C., S. Rehkamp, P. Canning, and C.J. Peters, 2019: Greenhouse gas emissions in the United States food system: Current and healthy diet scenarios. *Environmental Science & Technology*, **53** (9), 5493–5503. <https://doi.org/10.1021/acs.est.8b06828>
258. Ramanathan, V. and G. Carmichael, 2008: Global and regional climate changes due to black carbon. *Nature Geoscience*, **1** (4), 221–227. <https://doi.org/10.1038/ngeo156>
259. Archibald, A.T., S.T. Turnock, P.T. Griffiths, T. Cox, R.G. Derwent, C. Knote, and M. Shin, 2020: On the changes in surface ozone over the twenty-first century: Sensitivity to changes in surface temperature and chemical mechanisms. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **378** (2183), 20190329. <https://doi.org/10.1098/rsta.2019.0329>
260. Porter, W.C. and C.L. Heald, 2019: The mechanisms and meteorological drivers of the summertime ozone–temperature relationship. *Atmospheric Chemistry and Physics*, **19** (21), 13367–13381. <https://doi.org/10.5194/acp-19-13367-2019>
261. NADP, 2022: National Atmospheric Deposition Program [Website], accessed August 7, 2023. <https://nadp.slh.wisc.edu/>
262. Anenberg, S.C., M. Bindl, M. Brauer, J.J. Castillo, S. Cavalieri, B.N. Duncan, A.M. Fiore, R. Fuller, D.L. Goldberg, D.K. Henze, J. Hess, T. Holloway, P. James, X. Jin, I. Kheirbek, P.L. Kinney, Y. Liu, A. Mohegh, J. Patz, M.P. Jimenez, A. Roy, D. Tong, K. Walker, N. Watts, and J.J. West, 2020: Using Satellites to Track Indicators of Global Air Pollution and Climate Change Impacts: Lessons Learned From a NASA-Supported Science-Stakeholder Collaborative. *GeoHealth*, **4** (7), e2020GH000270. <https://doi.org/10.1029/2020GH000270>
263. Zoogman, P., X. Liu, R.M. Suleiman, W.F. Pennington, D.E. Flittner, J.A. Al-Saadi, B.B. Hilton, D.K. Nicks, M.J. Newchurch, J.L. Carr, S.J. Janz, M.R. Andraschko, A. Arola, B.D. Baker, B.P. Canova, C. Chan Miller, R.C. Cohen, J.E. Davis, M.E. Dussault, D.P. Edwards, J. Fishman, A. Ghulam, G. González Abad, M. Grutter, J.R. Herman, J. Houck, D.J. Jacob, J. Joiner, B.J. Kerridge, J. Kim, N.A. Krotkov, L. Lamsal, C. Li, A. Lindfors, R.V. Martin, C.T. McElroy, C. McLinden, V. Natraj, D.O. Neil, C.R. Nowlan, E.J. O’Sullivan, P.I. Palmer, R.B. Pierce, M.R. Pippin, A. Saiz-Lopez, R.J.D. Spurr, J.J. Szykman, O. Torres, J.P. Veefkind, B. Veihelmann, H. Wang, J. Wang, and K. Chance, 2017: Tropospheric Emissions: Monitoring of Pollution (TEMPO). *Journal of Quantitative Spectroscopy and Radiative Transfer*, **186**, 17–39. <https://doi.org/10.1016/j.jqsrt.2016.05.008>
264. Li, Y., L.J. Mickley, P. Liu, and J.O. Kaplan, 2020: Trends and spatial shifts in lightning fires and smoke concentrations in response to 21st century climate over the national forests and parks of the western United States. *Atmospheric Chemistry and Physics*, **20** (14), 8827–8838. <https://doi.org/10.5194/acp-20-8827-2020>
265. Dosio, A., L. Mentaschi, E.M. Fischer, and K. Wyser, 2018: Extreme heat waves under 1.5°C and 2°C global warming. *Environmental Research Letters*, **13** (5), 054006. <https://doi.org/10.1088/1748-9326/aab827>
266. Porter, W.C., C.L. Heald, D. Cooley, and B. Russell, 2015: Investigating the observed sensitivities of air-quality extremes to meteorological drivers via quantile regression. *Atmospheric Chemistry and Physics*, **15** (18), 10349–10366. <https://doi.org/10.5194/acp-15-10349-2015>
267. Li, W., Y. Wang, J. Flynn, R.J. Griffin, F. Guo, and J.L. Schnell, 2022: Spatial variation of surface O₃ responses to drought over the contiguous United States during summertime: Role of precursor emissions and ozone chemistry. *Journal of Geophysical Research: Atmospheres*, **127** (1), e2021JD035607. <https://doi.org/10.1029/2021jd035607>
268. Naimark, J.G., A.M. Fiore, X. Jin, Y. Wang, E. Klovenski, and C. Braneon, 2021: Evaluating drought responses of surface ozone precursor proxies: Variations with land cover type, precipitation, and temperature. *Geophysical Research Letters*, **48** (7), e2020GL091520. <https://doi.org/10.1029/2020gl091520>

269. Zheng, Y., N. Unger, J.M. Tadić, R. Seco, A.B. Guenther, M.P. Barkley, M.J. Potosnak, L.T. Murray, A.M. Michalak, X. Qiu, S. Kim, T. Karl, L. Gu, and S.G. Pallardy, 2017: Drought impacts on photosynthesis, isoprene emission and atmospheric formaldehyde in a mid-latitude forest. *Atmospheric Environment*, **167**, 190–201. <https://doi.org/10.1016/j.atmosenv.2017.08.017>
270. Lin, M., L.W. Horowitz, R. Payton, A.M. Fiore, and G. Tonnesen, 2017: US surface ozone trends and extremes from 1980 to 2014: Quantifying the roles of rising Asian emissions, domestic controls, wildfires, and climate. *Atmospheric Chemistry and Physics*, **17** (4), 2943–2970. <https://doi.org/10.5194/acp-17-2943-2017>
271. Wang, Y., Y. Xie, W. Dong, Y. Ming, J. Wang, and L. Shen, 2017: Adverse effects of increasing drought on air quality via natural processes. *Atmospheric Chemistry and Physics*, **17** (20), 12827–12843. <https://doi.org/10.5194/acp-17-12827-2017>
272. Almazroui, M., M.N. Islam, F. Saeed, S. Saeed, M. Ismail, M.A. Ehsan, I. Diallo, E. O'Brien, M. Ashfaq, D. Martínez-Castro, T. Cavazos, R. Cerezo-Mota, M.K. Tippett, W.J. Gutowski, E.J. Alfaro, H.G. Hidalgo, A. Vichot-Llano, J.D. Campbell, S. Kamil, I.U. Rashid, M.B. Sylla, T. Stephenson, M. Taylor, and M. Barlow, 2021: Projected changes in temperature and precipitation over the United States, Central America, and the Caribbean in CMIP6 GCMs. *Earth Systems and Environment*, **5** (1), 1–24. <https://doi.org/10.1007/s41748-021-00199-5>
273. Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Ch. 8. Water cycle changes. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1055–1210. <https://doi.org/10.1017/9781009157896.010>
274. Johnson, C.E., W.J. Collins, D.S. Stevenson, and R.G. Derwent, 1999: Relative roles of climate and emissions changes on future tropospheric oxidant concentrations. *Journal of Geophysical Research: Atmospheres*, **104** (D15), 18631–18645. <https://doi.org/10.1029/1999jd900204>
275. Tai, A.P.K., L.J. Mickley, and D.J. Jacob, 2010: Correlations between fine particulate matter (PM_{2.5}) and meteorological variables in the United States: Implications for the sensitivity of PM_{2.5} to climate change. *Atmospheric Environment*, **44** (32), 3976–3984. <https://doi.org/10.1016/j.atmosenv.2010.06.060>
276. Doherty, R.M., O. Wild, D.T. Shindell, G. Zeng, I.A. MacKenzie, W.J. Collins, A.M. Fiore, D.S. Stevenson, F.J. Dentener, M.G. Schultz, P. Hess, R.G. Derwent, and T.J. Keating, 2013: Impacts of climate change on surface ozone and intercontinental ozone pollution: A multi-model study. *Journal of Geophysical Research: Atmospheres*, **118** (9), 3744–3763. <https://doi.org/10.1002/jgrd.50266>
277. Horton, D.E., C.B. Skinner, D. Singh, and N.S. Diffenbaugh, 2014: Occurrence and persistence of future atmospheric stagnation events. *Nature Climate Change*, **4** (8), 698–703. <https://doi.org/10.1038/nclimate2272>
278. Kalashnikov, D.A., J.L. Schnell, J.T. Abatzoglou, D.L. Swain, and D. Singh, 2022: Increasing co-occurrence of fine particulate matter and ground-level ozone extremes in the western United States. *Science Advances*, **8** (1), 9386. <https://doi.org/10.1126/sciadv.abi9386>
279. Garcia-Menendez, F., E. Monier, and N.E. Selin, 2017: The role of natural variability in projections of climate change impacts on U.S. ozone pollution. *Geophysical Research Letters*, **44** (6), 2911–2921. <https://doi.org/10.1002/2016gl071565>
280. Fiore, A.M., G.P. Milly, S.E. Hancock, L. Quiñones, J.H. Bowden, E. Helstrom, J.-F. Lamarque, J. Schnell, J.J. West, and Y. Xu, 2022: Characterizing changes in eastern U.S. pollution events in a warming world. *Journal of Geophysical Research*, **127**, e2021JD035985. <https://doi.org/10.1029/2021jd035985>
281. Fiore, A.M., J.J. West, L.W. Horowitz, V. Naik, and M.D. Schwarzkopf, 2008: Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality. *Journal of Geophysical Research: Atmospheres*, **113** (D8). <https://doi.org/10.1029/2007jd009162>
282. Barnes, E.A., A.M. Fiore, and L.W. Horowitz, 2016: Detection of trends in surface ozone in the presence of climate variability. *Journal of Geophysical Research: Atmospheres*, **121** (10), 6112–6129. <https://doi.org/10.1002/2015jd024397>
283. Shen, L. and L.J. Mickley, 2017: Effects of El Niño on summertime ozone air quality in the eastern United States. *Geophysical Research Letters*, **44** (24), 12543–12550. <https://doi.org/10.1002/2017gl076150>

284. Shen, L., L.J. Mickley, E.M. Leibensperger, and M. Li, 2017: Strong dependence of U.S. summertime air quality on the decadal variability of Atlantic sea surface temperatures. *Geophysical Research Letters*, **44** (24), 12527–12535. <https://doi.org/10.1002/2017gl075905>
285. EPA, 2019: Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2019). EPA/600/R-19/188. U.S. Environmental Protection Agency, Washington, DC. <https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534>
286. Doherty, R.M., F.M. O'Connor, and S.T. Turnock, 2022: Projections of future air quality are uncertain. But which source of uncertainty is most important? *Journal of Geophysical Research: Atmospheres*, **127** (21), e2022JD037948. <https://doi.org/10.1029/2022jd037948>
287. East, J.D., E. Monier, and F. Garcia-Menendez, 2022: Characterizing and quantifying uncertainty in projections of climate change impacts on air quality. *Environmental Research Letters*, **17** (9), 094042. <https://doi.org/10.1088/1748-9326/ac8d17>
288. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. <https://doi.org/10.1038/s41558-022-01290-z>
289. Lassman, W., B. Ford, R.W. Gan, G. Pfister, S. Magzamen, E.V. Fischer, and J.R. Pierce, 2017: Spatial and temporal estimates of population exposure to wildfire smoke during the Washington state 2012 wildfire season using blended model, satellite, and in situ data. *GeoHealth*, **1** (3), 106–121. <https://doi.org/10.1002/2017gh000049>
290. Liu, J.C., A. Wilson, L.J. Mickley, F. Dominici, K. Ebisu, Y. Wang, M.P. Sulprizio, R.D. Peng, X. Yue, J.-Y. Son, G.B. Anderson, and M.L. Bell, 2017: Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties. *Epidemiology*, **28** (1), 77–85. <https://doi.org/10.1097/ede.0000000000000556>
291. Ahmadov, R., G. Grell, E. James, I. Csiszar, M. Tsidulko, B. Pierce, S. McKeen, S. Benjamin, C. Alexander, G. Pereira, S. Freitas, and M. Goldberg, 2017: Using VIIRS fire radiative power data to simulate biomass burning emissions, plume rise and smoke transport in a real-time air quality modeling system. In: 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). Fort Worth, TX, 23–28 July 2017. IEEE. <https://doi.org/10.1109/igarss.2017.8127581>
292. Larkin, N.K., S.M. O'Neill, R. Solomon, S. Raffuse, T. Strand, D.C. Sullivan, C. Krull, M. Rorig, J. Peterson, and S.A. Ferguson, 2009: The BlueSky smoke modeling framework. *International Journal of Wildland Fire*, **18** (8), 906–920. <https://doi.org/10.1071/wf07086>
293. Odman, M.T., R. Huang, A.A. Pophale, R.D. Sakhpara, Y. Hu, A.G. Russell, and M.E. Chang, 2018: Forecasting the impacts of prescribed fires for dynamic air quality management. *Atmosphere*, **9** (6), 220. <https://doi.org/10.3390/atmos9060220>
294. Vaughan, J., B. Lamb, C. Frei, R. Wilson, C. Bowman, C. Figueroa-Kaminsky, S. Otterson, M. Boyer, C. Mass, M. Albright, J. Koenig, A. Collingwood, M. Gilroy, and N. Maykut, 2004: A numerical daily air quality forecast system for the Pacific Northwest. *Bulletin of the American Meteorological Society*, **85** (4), 549–562. <https://doi.org/10.1175/bams-85-4-549>
295. City of Ashland Oregon, 2019: Smokewise Ashland [Website]. <https://www.ashland.or.us/sectionindex.asp?sectionid=534>
296. Colville Tribes, 2022: Wildfire Smoke. The Confederated Tribes of the Colville Reservation. <https://www.cct-enr.com/smoke>
297. Missoula City-County Health Department, 2022: Wildfire Smoke [Webpage]. Missoula County, MT. <https://www.missoulacounty.us/government/health/health-department/home-environment/air-quality/wildfire-smoke>
298. State of California, 2021: Protecting Outdoor Workers Exposed to Smoke from Wildfires. State of California, Department of Industrial Relations. <https://www.dir.ca.gov/dosh/wildfire/worker-protection-from-wildfire-smoke.html>
299. California Smoke Information, 2022: California smoke information [Blog]. <http://californiasmokeinfo.blogspot.com/>
300. Idaho Smoke Information, 2022: Idaho smoke information [Blog]. <http://idsmoke.blogspot.com/>

301. Oregon DEQ, 2022: Oregon Smoke Information. Oregon Department of Environmental Quality. <https://www.oregonsmoke.org/>
302. Washington Smoke Information, 2022: Washington smoke information [Blog]. <https://wasmoke.blogspot.com/>
303. Laumbach, R.J., 2019: Clearing the air on personal interventions to reduce exposure to wildfire smoke. *Annals of the American Thoracic Society*, **16** (7), 815–818. <https://doi.org/10.1513/annalsats.201812-894ps>
304. Reisen, F., J.C. Powell, M. Dennekamp, F.H. Johnston, and A.J. Wheeler, 2019: Is remaining indoors an effective way of reducing exposure to fine particulate matter during biomass burning events? *Journal of the Air & Waste Management Association*, **69** (5), 611–622. <https://doi.org/10.1080/10962247.2019.1567623>
305. Commodore, A., S. Wilson, O. Muhammad, E. Svendsen, and J. Pearce, 2017: Community-based participatory research for the study of air pollution: A review of motivations, approaches, and outcomes. *Environmental Monitoring and Assessment*, **189** (8), 378. <https://doi.org/10.1007/s10661-017-6063-7>
306. Do, T.H., E. Tsiligianni, X. Qin, J. Hofman, V.P.L. Manna, W. Philips, and N. Deligiannis, 2020: Graph-deep-learning-based inference of fine-grained air quality from mobile IoT sensors. *IEEE Internet of Things Journal*, **7** (9), 8943–8955. <https://doi.org/10.1109/jiot.2020.2999446>
307. Ezeugoh, R.I., R. Puett, D. Payne-Sturges, R. Cruz-Cano, and S.M. Wilson, 2019: Air quality assessment of volatile organic compounds near a concrete block plant and traffic in Bladensburg, Maryland. *Environmental Justice*, **12** (6), 250–260. <https://doi.org/10.1089/env.2019.0017>
308. Ezeugoh, R.I., R. Puett, D. Payne-Sturges, R. Cruz-Cano, and S.M. Wilson, 2020: Air quality assessment of particulate matter near a concrete block plant and traffic in Bladensburg, Maryland. *Environmental Justice*, **13** (3), 75–85. <https://doi.org/10.1089/env.2020.0005>
309. Masri, S., K. Cox, L. Flores, J. Rea, and J. Wu, 2022: Community-engaged use of low-cost sensors to assess the spatial distribution of PM_{2.5} concentrations across disadvantaged communities: Results from a pilot study in Santa Ana, CA. *Atmosphere*, **13** (2), 304. <https://doi.org/10.3390/atmos13020304>
310. Pearce, J., A. Commodore, B. Neelon, R. Boaz, M. Bozigar, S. Wilson, and E. Svendsen, 2017: A novel approach for characterizing neighborhood-level trends in particulate matter using concentration and size fraction distributions: A case study in Charleston, SC. *Air Quality, Atmosphere & Health*, **10** (10), 1181–1192. <https://doi.org/10.1007/s11869-017-0503-y>
311. Wallace, L., 2022: Intercomparison of PurpleAir sensor performance over three years indoors and outdoors at a home: Bias, precision, and limit of detection using an improved algorithm for calculating PM_{2.5}. *Sensors*, **22** (7), 2755. <https://doi.org/10.3390/s22072755>
312. Kerr, G.H., D.L. Goldberg, and S.C. Anenberg, 2021: COVID-19 pandemic reveals persistent disparities in nitrogen dioxide pollution. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (30), e2022409118. <https://doi.org/10.1073/pnas.2022409118>
313. Clark, L.P., D.B. Millet, and J.D. Marshall, 2014: National patterns in environmental injustice and inequality: Outdoor NO₂ air pollution in the United States. *PLoS ONE*, **9** (4), e94431. <https://doi.org/10.1371/journal.pone.0094431>
314. Southerland, V.A., S.C. Anenberg, M. Harris, J. Apte, P. Hystad, A. van Donkelaar, R.V. Martin, M. Beyers, and A. Roy, 2021: Assessing the distribution of air pollution health risks within cities: A neighborhood-scale analysis leveraging high-resolution data sets in the Bay Area, California. *Environmental Health Perspectives*, **129** (3), 037006. <https://doi.org/10.1289/ehp7679>
315. Apte, J.S., K.P. Messier, S. Gani, M. Brauer, T.W. Kirchstetter, M.M. Lunden, J.D. Marshall, C.J. Portier, R.C.H. Vermeulen, and S.P. Hamburg, 2017: High-resolution air pollution mapping with Google street view cars: Exploiting big data. *Environmental Science & Technology*, **51** (12), 6999–7008. <https://doi.org/10.1021/acs.est.7b00891>
316. Kelly, J.T., C. Jang, B. Timin, Q. Di, J. Schwartz, Y. Liu, A. van Donkelaar, R.V. Martin, V. Berrocal, and M.L. Bell, 2021: Examining PM_{2.5} concentrations and exposure using multiple models. *Environmental Research*, **196**, 110432. <https://doi.org/10.1016/j.envres.2020.110432>
317. Nguyen, N.P. and J.D. Marshall, 2018: Impact, efficiency, inequality, and injustice of urban air pollution: Variability by emission location. *Environmental Research Letters*, **13** (2), 024002. <https://doi.org/10.1088/1748-9326/aa9cb5>

318. Chambliss, S.E., C.P.R. Pinon, K.P. Messier, B. LaFranchi, C.R. Upperman, M.M. Lunden, A.L. Robinson, J.D. Marshall, and J.S. Apte, 2021: Local- and regional-scale racial and ethnic disparities in air pollution determined by long-term mobile monitoring. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (37), e2109249118. <https://doi.org/10.1073/pnas.2109249118>
319. Morello-Frosch, R. and B.M. Jesdale, 2006: Separate and unequal: Residential segregation and estimated cancer risks associated with ambient air toxics in U.S. metropolitan areas. *Environmental Health Perspectives*, **114** (3), 386–393. <https://doi.org/10.1289/ehp.8500>
320. Piao, S., Q. Liu, A. Chen, I.A. Janssens, Y. Fu, J. Dai, L. Liu, X. Lian, M. Shen, and X. Zhu, 2019: Plant phenology and global climate change: Current progresses and challenges. *Global Change Biology*, **25** (6), 1922–1940. <https://doi.org/10.1111/gcb.14619>
321. Sapkota, A., R. Murtugudde, F.C. Curriero, C.R. Upperman, L. Ziska, and C. Jiang, 2019: Associations between alteration in plant phenology and hay fever prevalence among US adults: Implication for changing climate. *PLoS ONE*, **14** (3), e0212010. <https://doi.org/10.1371/journal.pone.0212010>
322. Stone, E.A., C.B.A. Mampage, D.D. Hughes, and L.M. Jones, 2021: Airborne sub-pollen particles from rupturing giant ragweed pollen. *Aerobiologia*, **37** (3), 625–632. <https://doi.org/10.1007/s10453-021-09702-x>
323. Tasioulis, T., K. Karatzas, A. Charalampopoulos, A. Damialis, and D. Vokou, 2022: Five ways to define a pollen season: Exploring congruence and disparity in its attributes and their long-term trends. *Aerobiologia*, **38** (1), 71–83. <https://doi.org/10.1007/s10453-021-09735-2>
324. Schramm, P.J., C.L. Brown, S. Saha, K.C. Conlon, A.P. Manangan, J.E. Bell, and J.J. Hess, 2021: A systematic review of the effects of temperature and precipitation on pollen concentrations and season timing, and implications for human health. *International Journal of Biometeorology*, **65** (10), 1615–1628. <https://doi.org/10.1007/s00484-021-02128-7>
325. Efstathiou, C., S. Isukapalli, and P. Georgopoulos, 2011: A mechanistic modeling system for estimating large-scale emissions and transport of pollen and co-allergens. *Atmospheric Environment*, **45** (13), 2260–2276. <https://doi.org/10.1016/j.atmosenv.2010.12.008>
326. Zhang, R., T. Duhl, M.T. Salam, J.M. House, R.C. Flagan, E.L. Avol, F.D. Gilliland, A. Guenther, S.H. Chung, B.K. Lamb, and T.M. VanReken, 2014: Development of a regional-scale pollen emission and transport modeling framework for investigating the impact of climate change on allergic airway disease. *Biogeosciences*, **11** (6), 1461–1478. <https://doi.org/10.5194/bg-11-1461-2014>
327. Li, W., Q. Xin, X. Zhou, Z. Zhang, and Y. Ruan, 2021: Comparisons of numerical phenology models and machine learning methods on predicting the spring onset of natural vegetation across the Northern Hemisphere. *Ecological Indicators*, **131**, 108126. <https://doi.org/10.1016/j.ecolind.2021.108126>
328. Lo, F., C.M. Bitz, and J.J. Hess, 2021: Development of a random forest model for forecasting allergenic pollen in North America. *Science of The Total Environment*, **773**, 145590. <https://doi.org/10.1016/j.scitotenv.2021.145590>
329. Schaefer, J., M. Milling, B.W. Schuller, B. Bauer, J.O. Brunner, C. Traidl-Hoffmann, and A. Damialis, 2021: Towards automatic airborne pollen monitoring: From commercial devices to operational by mitigating class-imbalance in a deep learning approach. *Science of The Total Environment*, **796**, 148932. <https://doi.org/10.1016/j.scitotenv.2021.148932>
330. Sevillano, V., K. Holt, and J.L. Aznarte, 2020: Precise automatic classification of 46 different pollen types with convolutional neural networks. *PLoS ONE*, **15** (6), e0229751. <https://doi.org/10.1371/journal.pone.0229751>
331. Holloway, T., D. Miller, S. Anenberg, M. Diao, B. Duncan, A.M. Fiore, D.K. Henze, J. Hess, P.L. Kinney, Y. Liu, J.L. Neu, S.M. O'Neill, M.T. Odman, R.B. Pierce, A.G. Russell, D. Tong, J.J. West, and M.A. Zondlo, 2021: Satellite monitoring for air quality and health. *Annual Review of Biomedical Data Science*, **4** (1), 417–447. <https://doi.org/10.1146/annurev-biodatasci-110920-093120>
332. Li, L., D. Hao, X. Li, M. Chen, Y. Zhou, D. Jurgens, G. Asrar, and A. Sapkota, 2022: Satellite-based phenology products and in-situ pollen dynamics: A comparative assessment. *Environmental Research*, **204**, 111937. <https://doi.org/10.1016/j.envres.2021.111937>
333. EPA, 2021: 2017 National Emissions Inventory: January 2021 Updated Release, Technical Support Document. EPA-454/R-21-001. U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-02/documents/nei2017_tsd_full_jan2021.pdf

334. EPA, 2022: Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf