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Air, Climate, and Energy

STRATEGIC RESEARCH ACTION PLAN
FISCAL YEARS 2023-2026

Office of Research and Development
Air, Climate, and Energy Research Program

Air, Climate, and Energy (ACE)

STRATEGIC RESEARCH ACTION PLAN

Fiscal Years 2023–2026

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List of Acronyms

ACE	Air, Climate, and Energy
A-E	Air and Energy
CAA	Clean Air Act
CDC	Centers for Disease Control
CMAQ	Community-Multiscale Air Quality Model
CO	Carbon monoxide
CSS	Chemical Safety for Sustainability
DOE	Department of Energy
DOI	Department of Interior
EA	Environmental Assessments
ECOS	Environmental Council of States
EIS	Environmental Impact Statements
EISA	Energy Independence and Security Act
EPA	U.S. Environmental Protection Agency
ERIS	Environmental Research Institute of the States
EtO	Ethylene oxide
FEM	Federal Equivalent Method
FRM	Federal Reference Method
FY	Fiscal year
GCRA	Global Change Research Act
GHG	Greenhouse gas
HAPs	Hazardous air pollutants
HERA	Health and Environmental Risk Assessment
HSRP	Homeland Security Research Program
MACT	Maximum achievable control technology
NAAQS	National ambient air quality standards
NASA	National Aeronautics and Space Administration
NEI	National Emissions Inventory
NEPA	National Environmental Policy Act

NGO	Non-governmental organization
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
NOAA	National Oceanic and Atmospheric Administration
O_3	Ozone
OAR	Office of Air and Radiation
OECA	Office of Enforcement and Compliance Assurance
OLEM	Office of Land and Emergency Management
ORD	Office of Research and Development
OTAQ	Office of Transportation and Air Quality
OW	Office of Water
Pb	Lead
PFAS	Per-and Polyfluoroalkyl Substances
PM	Particulate matter
PO	Program Office
PRST	Program and regional offices, states, Tribes
RO	Regional Office
SHC	Sustainable and Healthy Communities
SIP	State Implementation Plan
SO_2	Sulfur dioxide
SOA	Secondary organic aerosol
SSWR	Safe and Sustainable Water Resources
StRAP	Strategic Research Action Plan
TDEP	Total Deposition
TSC	Tribal Science Council
UNFCCC	United Nations Framework Convention on Climate Change
USFS	U.S. Forest Service
USGCRP	U.S. Global Change Research Program
VOCs	Volatile organic compounds

Definitions

Office of Research and Development (ORD): Scientific research arm of EPA that conducts leading-edge research to inform Agency decisions and support partner needs, including state, Tribal, and community partners.

National Research Program (NRP): ORD's overall research effort is organized around six integrated and transdisciplinary national programs and closely aligned with the Agency's strategic goals and cross-Agency strategies. ORD is a matrixed organization with research direction coming from its six NRPs, each being guided by a Strategic Research Action Plan that identifies the most pressing environmental and public health research needs with input from many internal and external partners and stakeholders.

Strategic Research Action Plan (StRAP): A description of the overarching direction of ORD's research in a specified timeframe and under a specific research program. Each of ORD's NRPs is guided by a StRAP to structure and coordinate research activities. A StRAP includes a description of identified environmental and public health challenges, research priorities, and ORD's approach to meeting the challenges.

Topic: Overarching research focus under a NRP that encompasses Research Areas, Outputs, and Products.

Research Area: Science area or body of research and expertise assembled to address partner needs in the protection of human health and the environment. It encompasses problem statements, which are delineated through Outputs. Research Areas are nested under Topics and are composed of Outputs, which are composed of Products.

Output: A statement of the results to be achieved in pursuing a Research Area problem statement. It is not a tangible deliverable but encompasses Products that are deliverables. They are designed and developed to address specific partner needs that draw on the scientific knowledge and expertise represented in research areas. An Output can be expressed in many ways, such as an intended intermediate outcome, a purpose, aim, goal, or target. Outputs are composed of Products and nested within Research Areas, which are nested within Topics.

Product: A tangible scientific or technical deliverable. It addresses the research needs of ORD and ORD's partners. Products are nested within Outputs, which are nested within Research Areas, which are nested within Topics.

Partner: An EPA program office, EPA region, representative of a state, or a representative of a Tribe—often referred to as PRST.

Program, Regional, State, and Tribal (PRST) needs: A description of research needs related to human health and the environment as identified by EPA program offices, EPA regional offices, states, and/or Tribes.

Executive Summary

This *Air, Climate, and Energy (ACE) Strategic Research Action Plan, 2023–2026* (ACE StRAP) lays the foundation for research that promotes the strategic objectives of the U.S. Environmental Protection Agency (EPA) to improve air quality, address the causes and consequences of climate change, and protect public health and the environment. In addition to outlining a research framework, this StRAP also describes the overall structure and purpose of the Office of Research and Development (ORD) ACE National Research Program (NRP).

The challenges we face are interrelated and complex, from climate change, environmental injustice, and the public health and environmental impacts of air pollution to the transformations in our Nation's energy and transportation systems. Climate change is a public health crisis affecting the lives of all Americans and, as recent catastrophic wildfires, extreme heat waves, and floods demonstrate, there are real and substantial impacts to the environment and public health. As a Nation, we have made progress in improving air quality, but climate change threatens this progress, and is creating new challenges, including the growing threat of air pollution from wildfires. Climate change is also an environmental justice concern, since its effects are disproportionally felt by low-income and minority communities, who already bear an inequitable share of the air pollution health burden. Additionally, many communities, including those with environmental justice concerns, face an elevated cancer risk from exposures to air toxics as well as risks from emerging chemicals of concern. To provide the science needed to address these challenges, we will employ systems-based approaches that integrate the social and physical sciences to identify and develop solutions that consider technological, social, cultural, and economic factors and provide evidence of real-world effectiveness.

This StRAP builds on and continues the successful research conducted over several decades, with increasing emphasis on developing and evaluating science-based solutions. The ACE NRP will provide our partners—EPA program and regional offices, states, Tribes, and others—with the knowledge and tools to consider potential benefits and consequences of actions, and to make more informed decisions. ACE will expand the development and evaluation of science-based interventions that are accessible to individuals and communities and that directly reduce their public health and environmental impacts. We will continue to advance research on air quality measurement and improve capabilities in understanding and modeling the impacts of a changing climate, with an increased focus on the spatial and temporal resolution needed for decision-making at community scales. We will continue to investigate how humans and ecosystems are exposed to pollutants, taking into account many determining factors, including concentrations of air pollutants, climatic conditions, and social, cultural, behavioral, and lifestage factors. We will engage in forward-looking research to lay the groundwork for responding to future challenges.

Research activities are organized broadly around two topics: (1) *understanding climate change and air pollution impacts*, and (2) *responding to those impacts and preparing for the future*. Within these topics, the research areas are then designed to promote systems approaches to science activities that address the key priority needs identified by program, regional, state, and Tribal partners. This approach recognizes that addressing the increasing risks posed by climate change and reducing the disproportionate burdens faced by low-income and minority communities requires effective air quality risk management with consideration of criteria and other toxic air pollutants, indoor air quality,

wildfires, and the transformation of the Nation's energy and transportation systems. ACE will continue to engage with EPA and external partners to identify specific deliverables and, through this collaborative approach, we will ensure that the innovative work of our scientists and engineers informs the needs of the Agency, states, and Tribes.

Introduction

Air pollution in the United States has declined dramatically over the past 50 years, resulting in tremendous savings of lives and resources.[1] These achievements were made possible by developing and applying high-quality, timely, and relevant scientific and technical knowledge. However, more progress is needed, and this is being made more challenging by climate change.

Ambient air pollution has significant adverse consequences on human health and the environment. These include asthma, cancer, visibility impairment, and other respiratory and cardiovascular effects that can lead to disease and death in humans, as well as deposition of air pollutants that can harm ecosystems and surface waters. It is estimated that in 2020, almost 30 percent of people in the United States resided in counties that still do not meet the National Ambient Air Quality Standards (NAAQS) for at least one of the six criteria air pollutants (ozone, particulate matter, sulfur dioxide, nitrogen dioxide, carbon monoxide, and lead), even as emissions of these pollutants have been reduced by more than 77 percent over the past 50 years[2]. Toxic compounds continue to be emitted into the air at levels that pose health risks to millions. The most recent data for 2014 show that approximately nine million people in the United States lived in census tracts with cancer risks exceeding 50 in a million.[3] The public and environmental management community are growing increasingly concerned about other toxic compounds, such as per- and polyfluoroalkyl substances (PFAS) and ethylene oxide (EtO), which have higher concentrations and sources in communities with environmental justice concerns.

Greenhouse gas (GHG) emissions are changing the climate, causing harm to public health, ecosystems, and infrastructure, and climate change is exacerbating many other environmental and social challenges.[4] In the absence of additional emissions reductions, climate change is likely to worsen air quality in many locations while posing additional health risks due to more extreme temperatures and precipitation, and the resulting fires, floods, and drought, shifts in infectious diseases, increases in aeroallergens, and other impacts. As our Nation moves to a more decarbonized energy and transportation system, air pollutant emissions will be changing in magnitude, composition, and location, further complicating our understanding of the measures needed to improve air quality and address carbon pollution now and into the future.

We recognize that underlying health, demographic, and socioeconomic factors can cause populations within low-income communities, communities of color, and immigrant communities—as well as Indigenous peoples, children, pregnant women, older adults, vulnerable occupational groups, persons with disabilities, and persons with preexisting or chronic conditions—to be disproportionately affected

[1] See EPA reports on Benefits and Costs of the Clean Air Act, epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act

[2] See Our Nation's Air Status and Trends, gispub.epa.gov/air/trendsreport/2021/#summary

[3] See National Air Toxics Assessment, https://www.epa.gov/national-air-toxics-assessment

[4] See Fourth National Climate Assessment, nca2018.globalchange.gov

by pollution and climate change. Many of the factors that contribute to inequitable environmental burdens have long-standing societal roots, including systemic racism and discriminatory practices such as redlining, which is a discriminatory practice of refusing to provide financial services to people in neighborhoods with more minorities. Whether the stressors are chemical (e.g., criteria and air toxics) or non-chemical (e.g., extreme temperatures, noise, social factors), the total burden of these stressors and their interactions can impact the health, well-being, and quality of life of individuals, families, and communities. Our research will help strengthen the scientific foundation for assessing these cumulative impacts and support potential individual and Agency actions to alleviate them.

We also recognize that many pathways through which climate change affects public health cross environmental media and intersect with EPA's core mission of ensuring clean air and water, healthy ecosystems, and resilient communities.

To assist the Agency in meeting its goals and objectives, the ACE Research Program developed this Strategic Research Action Plan (StRAP) for fiscal years 2023–2026 (FY23-26). The ACE StRAP is one of six of the following research plans for each of the NRPs in EPA's Office of Research and Development (ORD):

- Air, Climate, and Energy (ACE)
- Chemical Safety for Sustainability (CSS)
- Health and Environmental Risk Assessment (HERA)
- Homeland Security (HS)
- Safe and Sustainable Water Resources (SSWR)
- Sustainable and Healthy Communities (SHC)

The StRAPs outline four-year research strategies to deliver the research necessary to support EPA's overall mission to protect human health and the environment. The StRAPs are designed to guide an ambitious research portfolio that delivers the science and engineering solutions the Agency needs to meet its goals now and into the future. They also inform our partners and the public of the program's strategic direction over the next four years. The ACE StRAP FY23-26 builds upon the previous StRAP FY19-22, and where appropriate, continues research efforts to address longer-term strategic research objectives that can bridge between the four-year research planning cycles.

The strategic directions and Research Areas (RAs) identified in each StRAP serve as planning guides for ORD's research Centers to design specific research products to address the needs of EPA program and regional offices, states, Tribes, and external partners. Partner engagement is an essential part of the StRAP development process to identify research needs to be addressed.

Solutions-Driven Research

ORD is committed to producing research results that address real-world problems, inform implementation of environmental regulations, and help EPA partners make timely decisions based on sound science. This commitment includes exploring ways to improve research processes through the application of a solutions-driven research (SDR) framework. SDR is a specific research approach that emphasizes partner engagement and integration of tasks to develop research that is directly along the path to a solution or decision. Solutions-driven research emphasizes the following:

- Planned partner engagement throughout the research process, starting with problem formulation and informing all elements of research planning, implementation, dissemination, and evaluation.
- A focus on solutions-oriented research Outputs identified in collaboration with partners.
- Coordination, communication, and collaboration both among ORD researchers and between researchers and partners to develop integrated research that multiplies value to partners.
- Cooperation with partners to apply research results to develop solutions that are feasible, appropriate, meaningful, and effective.

ORD is applying principles of SDR broadly across its six NRPs. ORD will also monitor how we engage with our partners and how we design and conduct our research to ensure that it informs solutions for our partners' most pressing environmental problems. By doing this, we are engaging in translational science, which will continually improve and increase the value of our research for our partners. Our emphasis on translating science is exemplified by the Outputs listed in this StRAP—they provide solutions to problems identified by our partners.

Examples of Solutions-Driven Research (SDR) Projects in the ACE Research Program

Wildfire ASPIRE: Researchers are partnering with the Missoula City-County Health Department in Montana, University of Montana, and the Hoopa Valley Tribe in California, in the Wildfire Advancing Science Partnerships for Indoor Reductions of Smoke Exposures (ASPIRE) Study. The objectives of the study are to compare indoor and outdoor fine particulate matter ($PM_{2.5}$) concentrations and develop strategies such as use of portable air cleaners and HEPA filters for reducing indoor exposures during wildland fire smoke events.

Blue Carbon and Coastal Resilience: This collaborative SDR across ORD, OW, Region 3, the Chesapeake Bay Program Office, and coastal communities in the Chesapeake Bay region aims to restore, conserve, and monitor wetlands, tidal marshes, and sea grasses to help mitigate climate change by promoting long-term carbon sequestration and to empower communities with knowledge and tools to build resilience to future flooding, storm surge, coastline erosion, and habitat degradation.

Program Vision

The ACE Research Program will provide scientific and technical information critical to

- improve air quality,
- reduce the impacts of air pollutants and GHG on human health and ecosystems,
- reduce environmental and health inequities, and
- respond to impacts of climate change and transformations of the energy and transportation infrastructure.

The ACE Research Program primarily responds to issues addressed in the Clean Air Act (CAA), as revised, with additional responsibilities under the Energy Independence and Security Act (EISA) of 2007, the

Global Change Research Act (GCRA) of 1990, the Federal Water Pollution Control Act (FWPCA), and the National Environmental Policy Act (NEPA). In addition, Executive Order 14008 "Tackling the Climate Crisis at Home and Abroad" calls on federal agencies to "implement a Government-wide approach that reduces climate pollution in every sector of the economy; increases resilience to the impacts of climate change; protects public health; conserves our lands, waters, and biodiversity; delivers environmental justice; and spurs well-paying union jobs and economic growth, especially through innovation, commercialization, and deployment of clean energy technologies and infrastructure." The policy context for the ACE Research Program closely follows the legislative context of these statutes and Executive Order 14008. The Program provides scientific and technical information to support efforts by EPA program and regional partners, state and local agencies, and Tribes to develop and implement policies required under these statutes and meet the goals of E.O. 14008. These policies and actions include review and implementation of the NAAQS, policies and regulations that address GHG emissions and adaptation to climate change, development and review of ambient and source emission measurement methods, evaluations of emission control technologies, assessment of hazardous air pollutant health risks after application of maximum achievable control technology (MACT) standards, and development of Environmental Impact Statements (EIS) and Environmental Assessments (EA).

Strategic Direction

Relationship to EPA and ORD Strategic Plans

The FY 2023-2026 EPA Strategic Plan is designed to implement the Administrator's priorities for the next four years. This Strategic Plan identifies four cross-cutting strategies and seven strategic goals with related objectives, describing how the Agency will work toward its mission to protect human health and the environment.

ORD will develop its own Strategic Plan to respond to and build upon the FY 2023-2026 EPA Strategic Plan. ORD's Strategic Plan will align with the StRAPs for ORD's six research programs, which outline specific research activities that address objectives of the Agency's Strategic Plan.

ACE research activities will align with the strategic goals and cross-cutting strategies in the Agency's Strategic Plan. ORD's overall research program, including that of ACE, will be guided by Cross-Agency Strategy 1, **Ensure Scientific Integrity and Science-Based Decision Making**, to ensure that Agency partners are supported in meeting their programmatic goals. ACE research, in particular, will also support Strategy 2, **Consider the Health of Children at All Life Stages and Other Vulnerable Populations**; and Strategy 4, **Strengthen Tribal, State, and Local Partnerships and Enhance Engagement**. ACE will integrate efforts with other ORD research programs, with EPA program and regional office partners, and with external partners to implement a research portfolio that is aligned with the Agency's strategic goals and cross-cutting strategies. ACE will assist EPA's program and regional offices, as well as states and Tribes, in addressing the Administrator's priorities related to environmental justice, cumulative impacts, and climate change.

ACE research has a focus on supporting the Clean Air Act and its Amendments, as well as Goal 4 of the Agency's Strategic Plan, to **Ensure Clean and Healthy Air for All Communities.** Research conducted by ACE will provide science-based methods and evidence to support achieving this goal while working collaboratively with EPA's Office of Air and Radiation (OAR), EPA Regions, and states and Tribes. With

research activities to both understand air pollution and climate change impacts and also take action to address these challenges, ACE supports Objective 4.1: **Improve Air Quality and Reduce Localized Pollution and Health Impacts** and Objective 4.2: **Reduce Exposure to Radiation and Improve Indoor Air**.

Efforts throughout the ACE Program will further support Goal 1 to **Tackle the Climate Crisis** and Goal 2 to **Take Decisive Action to Advance Environmental Justice and Civil Rights**, with particular consideration of Executive Orders (E.O.s) 13985: Advancing Racial Equity and Support for Underserved Communities Through the Federal Government and 14008: Tackling the Climate Crisis at Home and Abroad.

Changes from FY19-FY22 StRAP

The FY19-FY22 Air and Energy (A-E) StRAP was structured around three topic areas: Science for Air Quality Decisions, Extreme Events and Emerging Risks, and Next Generation Methods to Improve Public Health and the Environment. The FY23-FY26 ACE StRAP has been restructured to emphasize the Administration's priorities of tackling the climate crisis and increasing environmental justice, while continuing to focus on specific challenges that are of growing importance to the Agency and states (e.g., wildfires, PFAS, EtO). The new structure also provides a framework to support forward-looking research so that ACE can provide the scientific and technical knowledge and methods to inform future policies and actions.

ACE will employ a SDR framework to address interrelated environmental challenges. Through integrated, interdisciplinary research areas, we will characterize problems and develop solutions that consider technical, social, and economic dimensions. This approach recognizes the need to develop a better understanding of, and responses to, the unprecedented, global-scale risks posed by climate change, the disproportionate burdens faced by low-income and minority communities, and the intersection of these challenges with air quality risk management. The magnitude and pace of the anticipated transformations in energy and transportation are likewise unprecedented and addressing them will require interdisciplinary approaches and partnerships. ACE will continue to focus on developing the science and evaluating solutions to inform decision-making by EPA programs, states, Tribes, and local agencies. In addition, ACE will expand the development and evaluation of science-based interventions that can be applied at multiple levels—by individuals, communities, organizations, and governments—to decrease adverse public health and environmental impacts.

The ACE FY23-26 program will focus on the following six interrelated public health and environmental challenges:

***Criteria and Toxic Air Pollution*:** The Nation has made substantial progress in improving air quality and reducing criteria air pollutants regulated through the NAAQS, but almost 30 percent of the U.S. population still live in areas that do not meet the national standards. In addition, air toxics, those designated as hazardous air pollutants (HAPs) and other contaminants identified as emerging concerns, such as PFAS, cause cancer and other effects in humans and can impact ecosystems. While many regional sources of air pollution are controlled through existing regulations, more research is needed to understand cumulative risks from living in complex exposure environments including areas surrounding ports, railyards, or industrial complexes, urban near-road communities, and rural communities near agricultural operations. In these cases, remaining local sources of emissions are contributing a greater fraction to population exposures for both criteria pollutants and air toxics.

Climate Change: Climate change impacts are already being felt in communities across the country. Extreme weather events and changes in seasonal rainfall and temperatures driven by climate change are adversely affecting people, communities, and ecosystems through worsened air and water quality and related health impacts. The damage to infrastructure, ecosystems, and social systems—all of which provide essential benefits to communities—is expected to continue and worsen. With shifts in ecosystems come potential expansions in the range of disease vectors and the spread of invasive species. The likelihood of damaging disruptions will increase and will exacerbate existing challenges posed by aging infrastructure, already-stressed ecosystems, and economic and social inequality. Impacts will not be equally distributed; those who are already vulnerable have lower capacity to prepare for and cope with extreme weather and climate-related events and are likely to experience greater impacts in the future. A more equitable future means prioritizing adaptation actions for these most vulnerable populations. Immediate, transformative change is needed in sectors and activities emitting climate forcers (GHGs and other substances in the atmosphere that force or push the climate towards being warmer or cooler), along with investments to identify effective technologies and strategies for adapting and becoming more resilient to the effects of climate change.

Environmental and Climate Injustice: While significant reductions in regional sources of air pollution have led to improvements in air quality, those benefits have not always been equitably distributed. For instance, many of the locations with poorer air quality three decades ago still face relatively poor air quality today. Historically racist practices such as redlining, which was used to deny loans and opportunities to minorities, siting of heavily polluting facilities, and systemic social inequities have led to a much higher health burden among minority and low-income groups relative to more affluent, white communities. As previously noted, the impacts from climate change (e.g., extreme weather conditions such as flooding) will disproportionally affect overburdened communities. Reducing and removing these inequities requires consideration of long-standing economic, social, and environmental practices and the participation of those most affected.

Transformation of Energy and Transportation Systems: Energy and transportation systems are rapidly transforming. To avoid the worst impacts of climate change, the United States (as well as other nations) will, within a scant few decades, need to completely restructure its energy system to decrease emissions of GHGs to approach zero. Other drivers for energy system change are economic factors, innovation in alternative energy sources, and energy consumption (energy hungry vs. energy efficient technology) choices. Furthermore, modes of transportation used for personal and business travel, long-range transport of goods, and local delivery of goods and services are transforming. Because energy and transportation are two of the largest contributors to emissions of both climate forcers and air pollution, they affect the Nation's ability to meet and maintain air quality standards, reduce exposures to toxic air pollutants, and reduce GHGs.

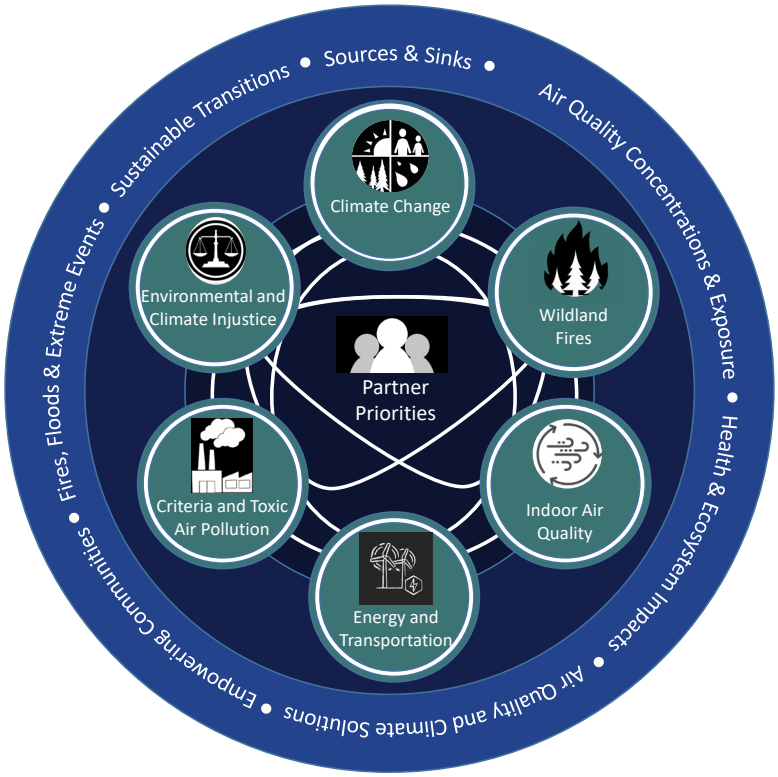

Figure 1. The Air, Climate, and Energy research program is designed to address the multiple connections that exist across the key priority challenges faced by partners.

Wildland Fires: Smoke from wildland fires impacts human health by contributing to ambient particulate matter and ozone, both near fires and extending far downwind of them. Smoke also contains other criteria pollutants and air toxics, especially when fires occur in the wildland urban interface (WUI), where additional toxics such as benzene and formaldehyde can be released when structures and vehicles are burned. Wildland fires also impact ecosystems, abruptly and adversely changing watersheds by disturbing soils, removing canopy cover, and increasing erosion and runoff of nutrients, metals, and other contaminants to water bodies. Water bodies can also be contaminated with deposited ash from wildfires as well as nitrogen and other pollutants deposited from transported smoke.

***Indoor Air Quality*:** Because Americans spend the vast majority of their time indoors in homes, schools, offices or other buildings, the impact of indoor air quality on human health and exposure is important. Building design, indoor appliances, air conditioners, ventilation, use of indoor cleaning products and other sources of emissions can greatly affect indoor exposures to air pollution. Exposures to pollutants such as radon and mold occur primarily indoors, and the recent COVID-19 pandemic highlighted the importance of indoor air quality in maintaining a safe and healthy environment. Indoor exposures can be impacted by the built environment, which is itself impacted by adaptation to climate change and transformations in energy systems, including increases in energy efficiency.

The above challenges are interconnected and create a complex landscape on which to develop effective solutions for reducing air pollution and climate impacts. The complexity of problems, coupled with an increasingly urgent need for information and understanding, requires adapting our approaches to research. These changes begin with a continued commitment to close engagement with those who use

the research, starting from problem formulation through translation and delivery of the results. Research solutions should be designed to consider people, equity, and justice as well as physical measures such as changes in emissions or air quality. These challenges require that research addressing air quality, climate change, and energy is well coordinated across disciplines and includes activities that both address immediate needs and anticipate future challenges.

Partner Engagement

Development of ORD's StRAPs has been informed by ongoing and extensive engagement with EPA program and regional offices and external (non-EPA) partners. ORD's partner engagement during strategic research planning ensures a collaborative, transparent, and highly coordinated research portfolio that delivers the data and information that Agency program and regional offices need, and provides resources that help states, Tribes, local communities, and other partners. ORD relies on partner engagement as an essential component throughout the research cycle and especially during problem formulation to identify partner research needs and develop the research Outputs outlined in the StRAPs.

The ACE Research Program engages partners at different levels and stages throughout the research cycle to identify and discuss their research needs. Building from engagement during StRAP FY19-22 planning and implementation, engagement methods for the ACE StRAP FY23-26 included the following:

- Recurring dialogues and meetings with EPA program and regional offices.
- Listening sessions with external partners, including state, Tribal, and local partners.
- Engagement meetings with non-governmental organizations (e.g., National Association of Clean Air Agencies, Association of Air Pollution Control Agencies).
- Workshops with ORD staff and EPA program and regional offices.
- Participation in organizational meetings with EPA regions and states (e.g., Environmental Council of the States and ERIS) and Tribes (e.g., Tribal Science Council, National Tribal Air Association).
- Collaboration with other federal agencies including the National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Forest Service, Centers for Disease Control and Prevention, Department of Health and Human Services, Department of Defense, U.S. Geological Survey, and Department of Energy.

The ACE Research Program will continue to engage with our EPA partners and state, Tribal, and local organizations as we implement the research program outlined in the StRAP, support our research products after they are delivered, and evaluate the usefulness and effectiveness of our research in helping solve environmental and public health problems.

Research Topics and Research Areas

The ACE program is organized around two topics—understanding climate change and air pollution impacts and responding to those impacts and preparing for the future—with integrated, interdisciplinary research areas. The program is designed to promote systems-based science activities to address the key priority challenges identified by program, regional, state, and Tribal partners. These challenges include climate change; environmental and climate injustice; public health and environmental impacts of criteria air pollutants and air toxics (including emerging contaminants, such as

PFAS); wildland fires; indoor air pollution; and transformations of the Nation's energy and transportation systems.

The overall structure of the ACE program is provided in Table 1, with the following sections providing additional information about each topic and research area. Descriptions of research areas broadly describe the research needs addressed by each Output.[5] Appendix 1 provides a complete list of Output titles, numbers, and which partner research needs are addressed by each. Appendix 2 describes, in more detail, the program, regional, state, and Tribal (PRST) needs summarized in the body of the ACE Research Program. Appendix 3 provides short descriptions of the Outputs. The full portfolio of research areas is designed to promote systems approaches to solutions-driven research. In the following discussions, linkages between goals of research areas are identified to highlight the systems design of the program.

Table 1. Overview of Air, Climate, and Energy Research Program Structure

Topic	Research Areas
1. Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems	#1: Sources and Sinks of Air Pollution and Climate Forcers
	#2: Air Quality Concentrations and Exposure Characterization – Measurements
	#3: Air Quality Concentrations and Exposure Characterization – Models
	#4: Health Impacts of Air Pollution and Climate Change
	#5: Ecosystem Impacts of Air Pollution and Climate Change
2. Responding to Risks and Impacts and Preparing for the Future	#6: Scientific Support for Climate Change and Air Quality Policy Solutions
	#7: Empowering Communities and Individuals to Improve Public and Ecosystem Health
	#8: Responses to Risks of Fires, Floods, and Other Extreme Events
	#9: Transitions to a Sustainable Future

Topic 1: Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems

EPA must continue advancing the scientific understanding of sources and emissions of air and climate pollution, atmospheric processes and concentrations of air pollutants, human and ecosystem exposure to air pollution and climate-related stressors, and their associated effects. These advances are needed to inform decisions and solutions that achieve and sustain healthy air quality for all Americans, address the causes and consequences of climate change, and promote greater equity in environmental protection.

Research under Topic 1 will address the source-to-impacts continuum, recognizing that climate change affects all elements of it. Concerns with environmental injustice have also led to a focus on proximity of

[5] In order to facilitate linking the body of the document with descriptions in the appendices, Output numbers are included as ACE.X.Y, where X identifies the Research Area and Y identifies the Output number.

low-income and minority populations to polluting sources, and disparate exposures to environmental contaminants and climate-related stressors, and increased burden of impacts. The scope of Topic 1 is illustrated by Figure 2.

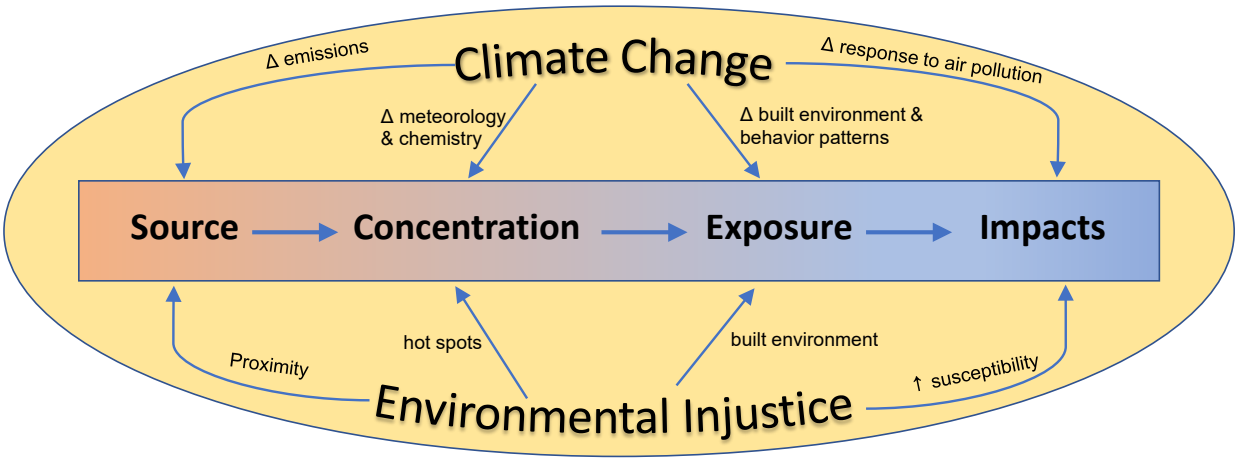

Figure 2. This figure illustrates some examples of how climate change and environmental justice issues impact multiple parts of the source-to-impacts continuum. Climate change has direct impacts on human health and ecosystems. Climate change also affects emissions and ambient concentrations of air pollution, and how humans and ecosystems respond to air pollution. Environmental injustice results from proximity to sources, higher air pollution concentrations in vulnerable communities, different exposure pathways, and potentially greater susceptibility to health and ecological impacts for some people and groups.

Problem Statement

Climate change poses an unprecedented, global-scale risk to the health and well-being of current and future populations of Americans, creating unique challenges and amplifying existing challenges of attaining clean air goals, improving water quality, and ensuring protections against exposures to hazardous waste. Air pollution continues to adversely affect human health and the environment, especially in communities with environmental justice concerns. Expanding our knowledge of the sources of air pollutants, how pollutants are transported through the environment, and how people and ecosystems are exposed and impacted will lead to more effective and targeted air quality management solutions. As environmental conditions are affected by climate change, air pollution transport and exposures will also be affected. Research is needed to further understand factors all along the source-to-impacts continuum now and into the future. Improved understanding of the causes and consequences of disparities in exposures and impacts of air pollution and climate change is also needed to reduce inequities and address environmental injustice.

The effects of a changing climate on air and water quality are characterized by complex synergies between human and natural systems as well as social and economic factors. For example, the impacts of wildland fires on human health, ecosystems, and air quality may be affected by smoke exposures, which materials are burning and how, individual susceptibility and vulnerability, and the duration and level of exposure, which are partly determined by social, cultural, behavioral, economic, and lifestage factors. Climate change will also lead to environmental problems that go beyond those we are facing now or have faced in the past. This requires research that looks ahead to anticipate and prepare for new challenges.

Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems contains five Research Areas (RAs) that will include the following:

- Measure emissions of criteria and toxic air pollution and climate forcers from a wide variety of stationary, mobile, area, and fugitive sources with and without emissions control technologies to reduce emissions data gaps.
- Characterize biogenic and anthropogenic sinks for air pollutants and climate forcers.
- Improve and expand methods and technologies for measuring near-source and ambient air quality concentrations for criteria pollutants, air toxics, and emerging air contaminants.
- Improve understanding of dry and wet deposition of air pollutants including emerging contaminants such as PFAS.
- Advance the science of air pollution dynamics and chemistry to improve the assessment of related health and ecological effects and to support the management of air pollution problems across different scales of time and space.
- Address key uncertainties and data gaps to inform future reviews of the NAAQS and inform air toxics policies.
- Expand our understanding of the biological, environmental, social, behavioral, and economic characteristics that put populations, lifestages, and ecosystems at increased risk of effects from exposure to air pollutants and the impacts of a changing climate.
- Improve characterization of the multipollutant exposures, effects, and integrated impacts of climate change on health, air and water quality, and ecosystems.

Research Area 1: Sources and Sinks of Air Pollution and Climate Forcers

The first component of the source-to-impacts continuum is characterizing the nature of sources of emissions of air pollutants and climate forcers (GHGs and particles), as well as natural and manmade sinks for air pollution. This requires understanding emissions from current sources as well as consideration of how sources and their emissions are likely to change in the future due to regulations, patterns of economic growth, and technological advancements. Reaching net-zero carbon emissions will require additional understanding of how natural and manmade sinks can remove and store carbon. An accurate representation of the air pollution mixture requires methods that include spatial and temporal emissions information throughout the year, season, and day and during periods of abrupt changes in activity, such as the recent COVID-19 pandemic.

RA 1 includes work to accomplish the following:

- Develop and evaluate measurement methods to characterize sources of emissions of air pollutants and climate forcers including criteria pollutants, air toxics, and emerging contaminants of concern (e.g., PFAS, EtO), and nitrogen species.
- Characterize and compare the chemistry and bioactivity of emissions from fugitive, area, point, and mobile sources, including natural and manmade sources such as biomass burning, the oil and gas industry, vehicles, indoor and agricultural activities, and other novel and emerging sources.
- Characterize natural and manmade sinks or deposition rates for air pollutants and climate forcers, such as PFAS, nitrogen species, CO_2, and others.

- Develop well-characterized information on emissions composition for various sources and conditions for use in development of emissions inventories, health studies, and the broader research community.

EPA partners, state and local agencies, and Tribes have a strong need for this research, especially for high-priority sectors and broad source categories (e.g., industrial operations; oil and gas facilities and refineries; landfills; on- and off-road mobile sources; wildland fires; agricultural sources; and indoor sources, such as residential heating and cooking) and pollutants (criteria pollutants and their precursors, air toxics and contaminants of emerging concern, such as EtO and PFAS), as well as emissions of GHGs and other climate forcers. Improved source emissions data are critical for reducing uncertainties in national emissions inventories and informing the development, implementation, and enforcement of regulations. Source measurement methods are needed for improved characterization of source emissions, especially in communities with environmental justice concerns, as these will provide critical information to help inform programs that empower citizens and local governments to seek reductions in air pollution emissions and reduce exposures and health impacts.

Within this RA, the ACE Research Program is characterizing point, fugitive, area, and mobile sources of air pollution and climate forcers (Outputs ACE.1.1, 1.2, 1.3). Activity includes focused effort to understand wildland fire emissions (Output ACE.1.4) and to understand the potential effectiveness of natural and anthropogenic systems for carbon sequestration (Output ACE.1.5). Researchers will also continue the foundational research needed to develop emissions inventories (Output ACE.1.6) and continue measurements on EtO and PFAS (Output ACE.1.7).

Research Area 2: Air Quality Concentrations and Exposure Characterization – Measurements

The second element of the source-to-impacts continuum is characterization of concentrations of pollutants in the atmosphere and environment and how much humans and ecosystems are exposed to them through inhalation and deposition, respectively. This RA will study ambient concentrations and exposure to pollutants with a variety of measurement methods investigating pollutant concentrations and the factors impacting exposure, such as time-activity patterns of individuals and their social, cultural, economic, and behavioral information.

This RA includes work to measure near-source and ambient concentrations and deposition for criteria pollutants, air toxics, and GHGs, and for air-pollution species emerging as contaminants of concern such as PFAS. Methods developed and used by the ACE Research Program include the use of state-of-the-art instruments, portable sensors, integrated sensor networks, and other advanced next-generations systems that provide near real-time, continuous data to evaluate near-source concentrations and to detect and measure pollutants in ambient air.

Measurements are also a critical element in informing and validating air pollution models and models of human exposure (RA ACE.3). These models require an increased understanding of photochemical processing and atmospheric transformation of pollutant emissions, and of the factors impacting human exposure described earlier.

RA 2 includes work to accomplish the following:

- Develop and evaluate measurement methods and approaches to characterize near-source, ambient, and indoor air concentrations of criteria pollutants and their precursors, air toxics, and climate forcers, as well as emerging air contaminants of concern, using ground-based, aerial, mobile, and remote instruments.
- Develop and evaluate measurement methods to characterize human and ecosystem exposures to chemical and non-chemical stressors to inform understanding of health and ecosystem impacts.
- Investigate photochemical processing and atmospheric transformation of pollutant emissions to inform model development and health outcomes research.
- Improve characterization of individual and population exposures using measurements and information on time-activity patterns, and other social, cultural, and economic determinants that affect exposures.

The ACE Program measurement research plays a critical role in supporting the setting and implementation of the NAAQS. EPA partners, state and local agencies, and Tribes rely on ACE research on Federal Reference Methods (FRMs) and Federal Equivalent Methods (FEMs); these methods are used to inform NAAQS attainment/nonattainment decisions as well as a wide range of analyses requiring ambient measurements. OAR and multiple EPA regional offices have expressed growing concerns about the potential for atmospheric exposures to air toxics, as well as emerging contaminants such as PFAS and EtO and the need for ambient measurement methods and data to understand the sources, fate, and transport of these chemicals. Additionally, EPA partners and PRSTs have expressed the need for ORD support to understand the performance of, and the quality of data produced by, lower-cost sensor technologies. OAR places a very high priority on ACE research and support for understanding sensor technology performance in determining concentrations near-sources, and in ambient and indoor air. Understanding community and ecosystem exposure to deposited pollutants also requires deposition measurements and modeling.

In addition to the fundamental research on reference methods to support NAAQS (Output ACE.2.1), research includes development and evaluation of state-of-the-science methods for measuring air toxics including EtO, PFAS, GHGs, and ultrafine particles (Outputs ACE.2.2 and ACE.2.6), as well as less traditional methods using sensors and personal, mobile, and remote sensing devices (Output ACE.2.3). Research efforts with measurements made in the field and laboratory chambers provide data and understanding to inform and support air quality model development and evaluation (Output ACE.2.4). Personal and community level measurements will be studied to understand and model exposures to air pollution (Output ACE.2.5).

Research Area 3: Air Quality Concentrations and Exposure Characterization – Modeling

Air quality concentrations, deposition, and exposure characterization are informed through development and application of models that represent chemical transport, dispersion, and exposure. Research in this area will focus on development, evaluation, and application of air quality models across a range of geographic scales from local (neighborhood scale) to urban, regional, and global, with a particular emphasis on finer temporal and spatial scales to provide information for communities with environmental justice concerns. RAs 2 and 3 are tightly connected as measurements and models work together to provide a holistic characterization of air quality and deposition that, when combined with information on time-activity patterns, improves understanding of individual and population-level exposures to air pollution.

Higher resolution models will also inform research in health studies (RA ACE.4), decision-support tools (RA ACE.6), development of intervention strategies (RA ACE.7), and responses to smoke from wildland fires (RA ACE.8). This research will also provide improved characterization of exposures of ecosystems to both ambient concentrations and deposition, which will provide opportunities to increase understanding of ecosystem impacts (RA ACE.5).

RA 3 includes work to accomplish the following:

- Conduct air quality modeling activities, such as model development and evaluation across a range of geographic scales including local dispersion scale, fine- or community-scale, and regional to global scales.
- Enhance the capabilities and application of air quality models to provide air pollution concentrations at finer temporal and spatial scales to address a wide range of toxic air pollutants and better characterize air pollution at the neighborhood level.
- Investigate and implement model updates and improvements, including methods for data fusion, updates to chemical and physical mechanisms, and representation of changing meteorology.
- Improve individual and population level exposure estimates through data fusion, modeling of time/activity patterns, consideration of indoor environments, and more detailed studies of multipollutant exposures (e.g., ozone, PM, air toxics, or total photochemical oxidants) and exceptional events (e.g., wildfires).

EPA regions, as well as state and local agencies and Tribes, often use air quality models in the permit review process to estimate air pollutant concentrations at ground-level receptors surrounding particular sources. ACE researchers will continue to work closely with EPA's OAR to develop and refine near-field, air dispersion models, such as AERMOD[6], to assess local-scale impacts from a variety of source types and situations. EPA program and regional office partners, as well as states, local agencies, and Tribes, have also expressed a strong interest in use of these models to better understand air pollutant exposures in near-road and other near-source environments—including complex roadway configurations with noise and vegetative roadside barriers, elevated roadways and bridges, and depressed roadways—especially as local and cumulative air pollutant exposures are needed to evaluate community concerns, particularly in overburdened communities.

Regional air quality models, such as the Community Multiscale Air Quality (CMAQ) modeling system[7], inform understanding of air pollution across a larger area and are an important tool for developing air quality management strategies, exploring the estimated short- and long-term impacts of different policy and regulatory options, and investigating the impacts of climate change and future changes in energy and transportation systems. The ACE research strategy is to continue working with programs and regions, states, and Tribes to maintain CMAQ as the state-of-the-science air quality model and expand capabilities and applications of CMAQ to address climate change and environmental justice priorities.

New modeling methods are needed for data fusion tools that bring together the information from multiple measurement platforms. Evaluation of these data fusion approaches is also needed at multiple temporal and spatial scales. Partners also desire models that are capable of investigating issues across a

[6] Learn more about AERMOD at epa.gov/scram/aermod-modeling-system-development.
[7] Learn more about CMAQ at epa.gov/cmaq.

range of spatial scales from hemispherical scale modeling to modeling indoor spaces, improving human exposure models, such as HEM[8], and even consideration of aerosols and viruses.

Work within this research area includes both development and evaluation of strictly physical dispersion models for understanding near-source concentrations and exposures (Output ACE.3.1) and the more complex hemispheric, regional, and community scale chemical transport models (Output ACE.3.2). To provide greater spatial and temporal understanding of the atmospheric mixture, researchers are investigating methods for combining data from multiple measurement sources and models (Output ACE.3.3). Research will also be undertaken to better understand the links between atmospheric concentrations and health (RA ACE.4) and ecosystem (RA ACE.5) impacts, through models of exposure to air pollution (Output ACE.3.4).

Research Area 4: Human Health Impacts of Air Pollution and Climate Change

Exposure to air pollution and climate stressors has numerous health impacts on human populations. The overall strategic objective of RA 4 is to improve and expand understanding of the types and magnitudes of human health impacts, with an emphasis on those occurring in overburdened communities. Information is needed at the regional and community levels on the impacts to public health resulting from not only air pollution, but also excess heat and humidity, increased aeroallergens, infectious disease vectors, water-borne and enteric diseases, and stress associated with extreme weather events. Understanding the expanded range of health impacts will require increased partnership, collaboration, and coordination with other institutions, including state and Tribal health departments, the Department of Health and Human Services (HHS) and other federal agencies, and interagency coordinating groups (e.g., the U.S. Global Change Research Program, or USGCRP). Consideration of how air pollution and climate change impacts vulnerable groups such as communities with environmental justice concerns, elderly, and children, will be expanded to consider the linkages between past and current exposures to air pollution and previous respiratory illnesses such as COVID-19.

Additional research is needed to expand understanding of health effects associated with exposures to short-term peaks in air pollution, such as those related to wildfires, traffic-related sources, or other episodic events, as well as improving our understanding of health effects associated with seasonal-length exposures, such as those related to wintertime wood-burning emissions. Research is needed to better understand subclinical health effects and how a combination of social, environmental, climate, and pollution stressors interact. These factors are also important as communities assess how best to adapt to climate-change-induced extreme weather events that are expected to occur with increasing frequency.

RA 4 includes work to accomplish the following:

- Explore criteria and toxic air pollution and climate health impacts (e.g., thermal stress) within different lifestages and populations, including overburdened groups; assess vulnerabilities to air pollution resulting from chronic illnesses and sequelae from respiratory viruses such as SARS-CoV-2; improve understanding of social determinants of air pollution and climate health

[8] Learn more about the Human Exposure Model (HEM) at epa.gov/fera/risk-assessment-and-modeling-human-exposure-model-hem.

impacts; and investigate differences in air pollution impacts resulting from different exposure time-activity patterns.

- Explore linkages between animal and human biomarkers for different adverse outcome pathways and specific human individual and population health outcomes that can be quantified for use in climate and air pollution risk and benefits assessments, including for air toxics.
- Investigate interactions between acute and chronic air pollution exposures on susceptibility to, and exacerbation of, air pollution health effects and illnesses caused by respiratory viruses such as SARS-CoV-2.
- Investigate cumulative impacts and the interactions between air pollution and climate-change-related stressors (e.g., heat, aeroallergens) that affect human health.
- Investigate health effects from exposures to smoke from wildland fires, including differential effects of smoke from prescribed and unplanned wildfires; and of smoke from fires that burn structures and hazardous waste sites.

Emissions of criteria air pollutants have declined significantly over recent decades as a result of implementation of the CAA by EPA, state and local agencies, and Tribes.[9] To inform future NAAQS reviews, research is needed to increase understanding of whether adverse effects continue to be observed at concentrations below current standard levels; of how air pollution impacts are affected by lifestages, climate conditions, and other environmental stressors that may arise; and of how uncertainties in health impacts may vary with pollutant concentration.

This research area will address targeted studies of the impacts of air pollution on human health (Output ACE.4.1) and studies considering the combined impact of climate change, air pollution, and other stressors (Output ACE.4.2). Additional effort will focus on the impacts of fires, floods, and other extreme events that are increasing in frequency (Output ACE.4.3). Information on longer-term health impacts will inform decisions on air pollution and climate mitigation and adaptation and resilience actions (Outputs ACE.4.4 and ACE.4.5).

Research Area 5: Ecosystem Impacts of Air Pollution and Climate Change

Climate change has already impacted ecosystems and the services they provide, and those impacts will become more widespread and severe as the climate continues to change in the coming decades. Impacts to ecosystems are more severely felt by vulnerable people and communities, such as those in rural communities and especially Tribes, for whom ecosystems provide a livelihood and cultural identity. An improved understanding of the impacts of changing mean and extreme precipitation and temperature patterns on forested and coastal ecosystems is needed to inform decisions to increase the resilience of these ecosystems as well as to preserve critical and culturally important ecosystems and ecosystem services. Air pollution also continues to contribute to adverse impacts on ecosystems, especially due to deposition of reduced nitrogen species which, in some locations, exceeds critical loads. Expanded understanding is needed to inform critical loads for a wider range of aquatic and terrestrial species.

The interconnections of ecosystem and human health are recognized as important to better understand how air pollution and climate change jointly affect ecosystems and public health and well-being.

[9] See *Our Nation's Air*, summarizing the United States air quality status and trends through 2020.

Ecosystems play a critical role in sequestering carbon. Disruptions to ecosystems can result in emissions of sequestered carbon or changes to the carbon carrying capacity of the ecosystems. Improved understanding of the sensitivity of ecosystem carbon storage to air pollution and climate change is needed to develop improved carbon inventories.

RA 5 includes work to accomplish the following:

- Assess air pollution impacts on ecosystem functions and their vulnerability attributable to changes in climate, energy production, and infrastructure.
- Evaluate ecosystem-mediated effects on human health in response to climate change and air pollution, including flooding and wildland fires.
- Investigate impacts on ecosystem resilience and capacity to sequester carbon from changes in air pollution, critical loads, temperature and precipitation patterns, wildland fires, and other consequences of climate and global change.

EPA partners are interested in ecosystem impacts that may inform the secondary (welfare-based) standards in the NAAQS reviews. Additional information on critical loads of deposition of pollutants to ecosystems are needed to support impact assessments and the evaluation of environmental management strategies. EPA regional offices need information on the impacts to ecosystems from wildfires, floods, droughts, and changes in mean and extreme weather patterns, including impacts to ecosystems important to Tribal culture and sustenance.

Work in RA 5 will improve characterization of the ecological impacts of air pollution through atmospheric exposures and deposition (Output ACE.5.1) in a changing climate, which may include extreme weather events (Output ACE.5.2). Research will evaluate how ecosystem management practices impact human health (Output ACE.5.3), as well as ecosystem responses to carbon sequestration, air pollution, and climate events (Outputs ACE.5.4 and ACE.5.5).

Topic 2: Responding to Risks and Impacts and Preparing for the Future

The improved understanding of the sources and impacts of air pollutants and climate forcers developed by research under Topic 1 will expand opportunities in Topic 2 to develop and evaluate strategies and approaches to reduce air pollution, exposure, and health and ecosystem impacts. EPA must conduct and apply scientific research to identify and evaluate evidence-based strategies that inform decisions and actions at scales of governance from local to international. This research can then inform efforts to reduce emissions of air pollutants and climate forcers, decrease exposures to and health impacts from air pollution, adapt and build resilience to climate change, and transition to more sustainable energy, transportation, and building sectors.

Many of the challenges posed by a changing climate, such as increased wildfires, will be difficult to address with regulations. Likewise, the current regulatory structure presents challenges for addressing cumulative impacts from the combination of criteria and toxic air pollutants, climate change impacts, and other non-chemical stressors, including social determinants of health. Consequently, EPA must also identify and evaluate science-based interventions to reduce pollutant exposures to individuals and communities. These interventions complement policies to reduce emissions, and require expanded consideration of social, cultural, behavioral, and economic factors in their design and implementation.

Research is also needed on scenarios to reach a decarbonized future in the energy, transportation, and building sectors. Ideally, this transition should bring benefits that are shared by all and not contribute to existing inequalities, create new inequalities, or lead to disproportionate impacts, including in those communities impacted by the shift away from fossil energy sources.

The action-oriented research under Topic 2 will address responses to air pollution and climate change risks in four areas that span decision types, levels of governance, and decision timeframes.

Problem Statement

Climate change and environmental injustice are "wicked" problems defined not only by their environmental characteristics, but also by the uncertain and changing nature of the problem, the role that society plays in exacerbating or alleviating the problem, and by the inextricable linkages to the energy, transportation, and building sectors that drive our economy. Specifically, problems include attaining air quality standards in complex urban environments and under a changing climate, responding to extreme events resulting from climate change, addressing risks of exposure and health impacts in vulnerable populations, and addressing the potential impacts on human health and the environment resulting from transformations of the energy, transportation, and building sectors. Addressing these problems requires systems approaches to recognize the linkages and to identify and evaluate integrated social-environmental strategies and solutions. Characterizing the specific and system-wide risks associated with climate change to inform effective response options is therefore a critical charge for EPA science.

Responding to Risks and Impacts and Preparing for the Future contains four RAs that will include the following:

- Evaluate control technologies and identify best practices for more efficient and effective integrated and sustainable pollution reduction and prevention solutions, considering relevant social, behavioral, and economic factors, and impacts on communities with environmental justice concerns.
- Provide EPA partners, states, Tribes, and others with scientifically robust, user-friendly information based on state-of-the-science measurement technologies and modeling methods to support implementation of air quality and climate change regulations and policies.
- Deliver information and methods to inform decisions by states, Tribes, communities, and individuals to prepare for, and adapt to, climate change and emerging and future risks of air pollution, recognizing the social, behavioral, and economic factors that may hinder the ability of communities and individuals to prepare and implement adaptation strategies for changes in climate.
- Inform approaches to adapt and build resilience to the increase in extreme events resulting from climate change, including extreme precipitation, heat, and humidity, wildland and wildland-urban interface fires, and major storms such as hurricanes.
- Identify and evaluate interventions to reduce air pollution exposures and associated public health impacts, especially in communities with environmental justice and equity concerns.
- Pursue and evaluate innovations in monitoring and sensors to inform interventions to reduce air pollution-related risks associated with various sources.

- Identify and quantify the public health and environmental benefits of reducing GHG emissions and sustainably reshaping our energy system, while ensuring that these benefits are distributed equitably and improve the lives of all Americans.
- Develop methods and obtain data to conduct life-cycle analyses of alternative pollution reduction strategies and potential transitions in energy sources.

Research Area 6: Science-based Support for Solutions to Climate Change and Air Quality Management Challenges

Climate change threatens air and water quality and the health of people, ecosystems, and communities. Managing these trends will involve applying and adapting the Agency's regulatory and other environmental management mechanisms to ensure their continued effectiveness in an environment with higher temperatures, more frequent and more severe heavy rainfall events, longer and deeper droughts, larger and more widespread wildfires over longer seasons, rising seas, and melting permafrost. Effective air quality management, including reducing climate forcers, requires decisions at multiple governance levels, guided by relevant federal and state statutes and local planning objectives. The key challenges related to air quality and climate change are in many cases linked to the same emissions sources, and those sources are often connected through the economy. Multipollutant and multisectoral solutions are needed with consideration of both positive and negative impacts on ecosystems and public health. Research is needed to connect and improve a variety of models to characterize the cumulative effects of pollutants across media, including carbon storage.

At the same time, complex NAAQS nonattainment areas provide unique challenges for air quality managers. Information is needed to improve the characterization of criteria pollutants in such areas (e.g., ground-level ozone photochemical formation in near-shore environments). In addition, urban areas present broad challenges for reducing concentrations of both criteria and toxic air pollution.

RA 6 includes work to accomplish the following:

- Develop, evaluate, and apply data, models, and tools to identify and evaluate strategies for reducing emissions of air pollution and climate forcers, including multipollutant and multisector approaches.
- Quantify public health and ecosystem service benefits and co-benefits of air quality management and climate change response actions, as well as mitigation and adaptation strategies.
- Develop data, models, scientific knowledge, and tools to inform climate policies, regulations, and decisions from local to state, federal, and international organizations.

EPA partners and state, local, and Tribal air quality managers need reliable information to inform decisions on cost-effective and efficient ways for improving air quality and mitigating emissions of climate forcers at national, regional, and local scales. As climate change impacts air and water quality, a critical need is advancement of approaches to evaluate the public health and environmental consequences of mitigation and adaptation options. This includes the need to develop approaches that can identify multipollutant/multisector scenarios and strategies that maximize the climate, air quality, and water quality benefits of climate protection. The ACE Research Program will continue to develop, evaluate, and apply methods and models to support air quality management programs. This work includes enhancing capabilities to conduct multipollutant air quality assessments in specific place-based

studies using local, regional, national, and global scales, and further developing multimedia and multi-stressor models to address complex environmental issues.[10]

Work in RA 6 includes efforts to investigate specific locations where environmental managers are struggling to understand the causes of persistent air quality problems (Output ACE.6.1). Research also investigates methods to quantify the value of addressing both improving air quality and decreasing climate forcers, while considering overlaps and synergies in costs and benefits (Output ACE.6.2). Beyond evaluating benefits, tools are developed and used to evaluate multipollutant control strategies that extend across multiple sectors (Output ACE.6.3).

Research Area 7: Empowering Communities and Individuals to Improve Public and Ecosystem Health

Many of the challenges facing overburdened communities are long-standing and systemic, and are the causes of multiple environmental, economic, and social stressors in those communities. Individuals and local communities want information on how they can respond to air pollution, the changing climate, and other environmental stressors with individual and coordinated actions in addition to government policies. Providing this information democratizes science and enables choices and actions to respond to specific experiences. Research is needed that translates the results of health studies to inform public health and well-being practices, improve strategies for communities to take actions to increase public awareness of air pollution-related exposures and risks, and support decisions to reduce adverse public health and environmental effects. Research is also needed to understand and incorporate traditional Tribal and cultural knowledge into the study of air pollution and climate change. This broadened focus will address ways to lower exposure or mitigate biological responses at individual, community, or ecosystem levels, and ultimately evaluate whether such interventions have benefits as measured by indicators of health, well-being, and economics.

RA 7 includes work to accomplish the following:

- Develop and evaluate the effectiveness of strategies that individuals and communities can use to reduce exposure and public health impacts of air pollution including technologies, risk communication and management approaches, community preparedness, and infrastructure, with particular consideration of communities with environmental justice concerns.
- Evaluate effectiveness of individual and community level health protective interventions such as facemasks or portable air cleaners to reduce health effects associated with air pollutant exposures.
- Develop and evaluate strategies to reduce ecosystem impacts of air pollution, including land use management strategies, use of green infrastructure, green spaces, and other nature-based solutions and best practices.
- Engage individuals and groups in developing science-based solutions to specific air-quality related problems at the individual and community levels, with a focus on improving communication, accessibility, and usability of data and information for individuals with less technical expertise.

[10] Multipollutant air quality assessments may include consideration of simple and complex mixtures of particles, criteria pollutant gases, and selected HAPs.

EPA partners need information on how to interpret, communicate, and use sensor data generated by EPA, as well as data generated by other agencies, and community and citizen scientists. Information is needed to identify and evaluate solutions that incorporate community perspectives and enable individual and community level actions that can be revised as new information becomes available. Agency interest is particularly focused on information to inform questions about which interventions and policies have improved or worsened existing disparities.

Efforts in this research area are directed at enabling interventions to mitigate risks and impacts from emissions of criteria pollutants, air toxics, and emerging chemicals of concern—working through individuals and community groups (Output ACE.7.1). Research projects work to improve the accessibility of data and information (Output ACE.7.3) and the environmental health literacy needed to make decisions on the basis of data (Output ACE.7.4). Research to better understand the linkages of individuals with their local environment and air pollution may also inform future actions (Outputs ACE.7.6 and ACE.7.7).[11]

Research Area 8: Responding to Risks of Fires, Floods, and Other Extreme Events

As the pace of climate change has accelerated, its impacts are being felt throughout the United States through historic droughts, extreme high heat, flooding, and increased intensity and size of wildfires. These extreme events directly impact human and ecosystem health, and adversely impact air and water quality by decreasing air quality over wider areas and mobilizing nutrients and contaminants into water systems. Responding to these events requires knowledge about the vulnerability of critical ecosystems and species, along with approaches to communicate risks of exposure to smoke from wildland fires and help communities to prepare for wildland fire smoke events. As climate change impacts worsen, the frequency and magnitude of extreme precipitation events, temperatures, droughts, and wildfires continue to move outside the range of impacts experienced in the past.

Research is needed to prepare for and respond to current risks and impacts, as well as to support decisions to address anticipated increases in these risks as climate change worsens. This will require improvements in the ability to evaluate the resilience of communities to extreme events in a changing climate, such as wildfire, floods, heat waves, drought, and permafrost melt, especially for vulnerable and underserved communities already experiencing environmental injustice. Enhancing risk management decisions to lessen impacts will also require development and evaluation of adaptation measures. Research will also be needed to develop evidence-based approaches that can increase resilience by enabling communities to prepare for expected changes in future conditions, and to more quickly and completely recover from disasters.

RA 8 includes work to accomplish the following:

- Improve ability to evaluate the resilience of communities, especially communities with environmental justice concerns, to extreme events such as wildland fires, floods, drought, and permafrost thaw.
- Develop and assess interventions to reduce adverse ecosystem, water quality, and health risks from wildland fires (e.g., acute and chronic exposure to smoke), and compound and cascading disasters.
- Develop evidence-based approaches that can increase community resilience to extreme events.
- Address exposures to contaminants following climate-related events, such as mold resulting from flooding.

[11] Content of Outputs ACE.7.1 and ACE.7.5 were combined into others and these have been removed.

EPA partners need information to better quantify and map environmental impacts to socially vulnerable populations in the United States, and to inform environmental management and city planning while accounting for projected impacts of climate change—including sea level rise, storm surges, and increased intense precipitation events. Information is needed on how responses to wildland fires can be made more effective by accounting for composition (RA ACE.1) and effects (RA ACE.4, RA ACE.5) of smoke from uncontrolled wildland fires and those that occur at the wildland-urban interface. Research from RA ACE.4 and RA ACE.5 on the human and ecosystem health impacts of wildland fire, droughts, and floods will be used to evaluate interventions, vulnerability, and susceptibility to such extreme events.

Work in this RA includes focused efforts to respond to fires, floods, and other extreme events. Research includes development of information and tools to reduce the impacts of fires on air quality, as well as water and ecosystems (Outputs ACE.8.1 and ACE.8.2). Research will investigate increases in water flows due to extreme precipitation or ice, snow, or permafrost thaw, and ways to develop detailed information that can be used in community planning and preparation (Outputs ACE.8.3 and ACE.8.4). Research using real data and an understanding of earth systems will provide methods to identify areas most vulnerable to the impacts of these extremes, offering guidance on how and where to prioritize actions (Output ACE.8.5).

Research Area 9: Transitions to a Sustainable Future

Climate change requires transformational responses that will challenge EPA's mission in ways that transcend policy or regulatory precedents. Research is needed to understand how the changing climate will impact existing systems and structures, and what changes accompany the transition to decarbonize the energy, transportation, and building sectors. Multipollutant, multisector decarbonization strategies will have implications for air and water quality, waste management, and chemical exposures. Research is needed to characterize new or expanded waste streams associated with electric vehicles, solar, wind, and other renewable energy sources. Shifts from carbon-based to renewable fuels may also lead to legacy infrastructure issues; for example, thousands of abandoned oil and natural gas wells continue to emit methane and other air pollutants.

Research is needed to identify and evaluate urban- and regional-scale infrastructure changes that can support multiple layers of resilience and environmental protection. Addressing environmental and climate justice will require partnering with vulnerable and underserved communities to create evidence-based solutions and improve the sustainability of their communities.

Strategies to combat climate change are not limited to emissions controls, and research is needed to identify and evaluate approaches for removing and storing carbon; for example, "blue carbon" approaches can store carbon in coastal and marine ecosystems.

RA 9 includes work to accomplish the following:

- Identify and evaluate technology and behavior transitions within the energy system (including resource extraction, electric utilities, building, transportation, and industrial sectors) induced by impacts resulting from climate change and responses to mitigate and adapt to those impacts.
- Investigate and develop information on broad economy, community, societal, and sectoral transformations that result from the changing climate and mitigation and adaptation choices.

- Improve understanding of the health and environmental consequences of future energy and climate scenarios, including multi-pollutant, multi-sectoral approaches for mitigation options and responses.
- Examine the technical capabilities and limitations, environmental consequences, and costs and benefits of nature-based solutions to reduce net emissions and remove atmospheric concentrations of GHGs at meaningful scales.
- Evaluate the environmental impacts of biofuel production and use, including those driven by land use change associated with biofuel feedstock production, to inform development of the required triennial Report to Congress describing current and likely future environmental impacts of the Renewable Fuel Standard. [12]

EPA partners need information on how broad policies and management strategies will impact emissions from multiple sectors and the associated air quality. Data are needed for spatially explicit projections of population and land use. OAR, states, and Tribes need detailed projections of potential future air pollutant and climate forcer emissions to analyze strategies for attaining NAAQS and meeting goals for reductions in climate forcers. Investigations will be necessary on how new energy producing and transportation technologies will impact overall emissions, the environment, and public health. A key research area is identifying and quantifying the public health and environmental benefits of reducing GHG emissions and sustainably reshaping our energy system, while ensuring that these benefits are distributed equitably and improve the lives of all Americans.

Work within this RA addresses the development and use of models for predicting how the energy and transportation systems operate and evolve, the potential for cross-sectoral changes, and the associated implications for environmental impacts and benefits (Output ACE.9.1). Information in these models is extended to inform decision-making needed during a transition to a low-carbon energy and transportation system (Output ACE.9.2) and a net-zero electricity system (Output ACE.9.3). Other research focuses on how the natural environment can help reduce climate change (Output ACE.9.4) and how research and tools can support the increase climate considerations in environmental management decisions (Output ACE.9.5). New and creative methods to increase understanding of how adaptation to a changing climate and extreme events will inform decision-making at many levels (Output ACE.9.6). Finally, research is extended to understand impacts on the environment and natural resources associated with the Renewable Fuel Standards (Output ACE.9.7).

Implementing the Strategic Research Action Plan

In collaboration with EPA program, regional, state, and Tribal partners, ORD scientists and engineers design specific research products responsive to the Outputs outlined in the StRAPs. During the implementation of the previous FY19-22 StRAPs, ORD piloted a successful process in which Research Area Coordination Teams (RACTs), made up of ORD scientists and engineers, EPA program and regional staff, and state members, collaborated to determine the individual research products responding to each Output. ORD is continuing this process for the FY23-26 StRAPs.

Each Output in the StRAPs is reviewed by a RACT, which develops goals and objectives for the Output and establishes criteria for the work needed to accomplish it. ORD researchers propose research

[12] *Biofuels and the Environment: The Second Triennial Report to Congress* was completed in June 2018 (cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=341491).

products, which the RACT reviews and refines to ensure products will meet the goals and objectives of the Output and reflect the timing and specific needs of EPA program and regional, state, and Tribal partners. RACT members serve as liaisons to their programs or organizations, which ensures that ORD's partners are able to provide input into the proposed research products. Products developed to address the Outputs may take the form of assessments, reports, tools, methods, journal articles, or other deliverables.

Throughout implementation of the StRAPs, ORD's researchers develop and deliver products. Research to deliver StRAP products is implemented by staff scientists and engineers at research laboratories and facilities in twelve locations across the country, which collectively comprise ORD's four Centers and four Offices. EPA staff are joined in this endeavor by a network of collaborators and partners within and external to EPA. In addition to the extensive intramural research program outlined in the StRAPs, ORD's research portfolio includes extramural research programs that complement or add special focus areas to the overarching program.

Cross-Cutting Research Priorities

For priorities that cut across their programs, ORD's six NRPs will work together to integrate efforts, provide a research portfolio aligned around the Agency's goals, and assist all of EPA's program and regional offices, as well as states and Tribes. Where appropriate, the NRPs will combine efforts to conduct research that advances the science and informs public and ecosystem health decisions and community efforts on the following cross-cutting priorities (Appendix 4):

- Environmental Justice
- Climate Change
- Cumulative Impacts
- Community Resiliency
- Children's Environmental Health
- Contaminants of Immediate and Emerging Concern

EPA program and regional offices and external (non-EPA) partners and stakeholders will also be engaged for these integrated efforts. Long-term, innovative, and multi-disciplinary research is needed to make progress on these complex issues to support a sustainable pathway towards equitable distribution of social, economic, health, and environmental benefits.

Conclusion

Climate change, the public health and environmental impacts of air pollution, environmental injustices, and the transformations occurring in our Nation's energy and transportation systems are complex and interrelated challenges. While we have had significant improvements to air quality over the past decades, air pollution issues persist at the local level. In the absence of additional emission reductions, climate change is likely to exacerbate existing air quality concerns as well as pose additional health risks due to temperature and precipitation extremes. Because of underlying health, demographic, and socioeconomic factors, climate change will disproportionally affect vulnerable populations and overburdened communities, who already bear an inequitable share of the air pollution burden. Climate change scenarios are compelling our Nation to move toward a decarbonization of the energy,

transportation, and building sectors. This transition will require looking at air-quality risk management in a comprehensive way, so that the transition brings benefits that can be shared by all and not worsen existing inequalities or create new inequalities.

The ACE program will respond to these complex challenges by building on past successful research and emphasizing the development and evaluation of science-based solutions, including interventions that can be adopted by individuals, communities, and governments. By working with our partners—EPA program and regional offices, states, Tribes, and others who use our research—we can help develop the knowledge and tools needed to make more informed decisions that consider potential benefits and consequences. In our research, we will continue to recognize that human and ecosystem exposure to pollution is affected by many factors, including the concentrations of air pollutants and climatic conditions, as well as social, cultural, and behavioral factors. Forward-looking research will also help lay the foundation to respond to the challenges of the future.

This research plan is guided by two broad topics: understanding climate change and air pollution impacts and responding to those impacts and preparing for the future. These topics further EPA's core mission of ensuring clean air and water, healthy ecosystems, and resilient communities. The research guided by this plan will be developed through engagement with our partners so that the innovative work of our scientists and engineers continues to inform the needs of EPA and our partners.

Appendix 1: Summary of Proposed Outputs Mapped to Program, Regional, State, and Tribal (PRST) Needs

The following table lists the proposed ACE Research Program Outputs organized by topic and mapped to PRST needs. It should be noted that the Outputs might change as new scientific findings emerge and are also contingent on budget appropriations. See Appendix 2 for more detailed descriptions of the PRST needs and Appendix 3 for detailed descriptions of the Outputs.

Research Area	Output	PRST Need(s)
Topic 1: Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems		
ACE.1 Sources and Sinks of Air Pollution and Climate Forcers	ACE.1.1 Characterization of point source air pollution and climate forcers	• Agricultural emissions • Emissions from other industrial sectors • Emissions of air toxics and contaminants of emerging concern • Emissions of criteria pollutants and precursors • Emissions of GHG and climate forcers • Residential heating and cooking emissions • Source measurement
	ACE.1.2 Characterization and mitigation of fugitive and area source air pollution and climate forcers	• Agricultural emissions • Emissions from other industrial sectors • Emissions of air toxics and contaminants of emerging concern • Emissions of criteria pollutants and precursors • Emissions of GHG and climate forcers • Indoor air quality • Residential heating and cooking emissions • Source measurement
	ACE.1.3 Characterization of mobile source emissions of air pollution and climate forcers	• Emissions of criteria pollutants and precursors • Emissions of GHG and climate forcers • Emissions of mobile and transportation sources • Source measurement

Research Area	Output	PRST Need(s)
Topic 1: Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems		
ACE.1 Sources and Sinks of Air Pollution and Climate Forcers	ACE.1.4 Characterization of wildland fire emissions	• Emissions of air toxics and contaminants of emerging concern • Emissions of criteria pollutants and precursors • Emissions of GHG and climate forcers • Impacts of fire and smoke • Source measurement
	ACE.1.5 Anthropogenic and natural systems for carbon sequestration	• Atmospheric deposition and critical loads assessment • Emissions of criteria pollutants and precursors • Emissions of GHG and climate forcers • Source measurement
	ACE.1.6 Development and Verification of Emissions Inventories	• Agricultural emissions • Emissions from other industrial sectors • Emissions inventory development and methods • Emissions of air toxics and contaminants of emerging concern • Emissions of criteria pollutants and precursors • Indoor air quality • Residential heating and cooking emissions
	ACE.1.7 Characterization of EtO and PFAS source air pollution	• Contaminants of immediate (PFAS, EtO) and emerging concern • Emissions from other industrial sectors • Source measurement
ACE.2 Air Quality Concentrations and Exposure Characterization: Measurements	ACE.2.1 Reference and Equivalents methods to support NAAQS	• Ambient measurement and modeling
	ACE.2.2 Methods for measuring air toxics and ultrafine particles for exposure characterization	• Ambient measurement and modeling • Indoor air quality • Sensors
	ACE.2.3 Characterization of sensors and other non-regulatory measurements for stationary, personal, and mobile monitoring	• Ambient measurement and modeling • Indoor air quality • Sensors

Research Area	Output	PRST Need(s)
Topic 1: Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems		
ACE.2 Air Quality Concentrations and Exposure Characterization: Measurements	ACE.2.4 Methods and characterizations to inform air pollution dynamics and support model development	• Ambient measurement and modeling • Sensors
	ACE.2.5 Methods to measure personal and community level exposures to air pollution	• Ambient measurement and modeling • Atmospheric deposition and critical loads assessment • Indoor air quality • Regional to hemispherical scale modeling • Sensors • Human health and environmental impacts
	ACE.2.6 Methods for measuring and characterizing EtO and PFAS	• Ambient measurement and modeling • Contaminants of immediate (PFAS, EtO) and emerging concern
ACE.3 Air Quality Concentrations and Exposure Characterization: Models	ACE.3.1 Modeling of near-source concentrations and exposures	• Ambient measurement and modeling • Data fusion tools and evaluation • Indoor air quality • Near-field modeling • Place-based studies • SARS-CoV-2 and other respiratory viruses
	ACE.3.2 Global, regional, and community scale chemical transport modeling (development and evaluation)	• Ambient measurement and modeling • Atmospheric chemistry and chemical mechanism • Data fusion tools and evaluation • Place-based studies • Regional to hemispherical scale modeling
	ACE.3.3 Fusion of data from multiple models and measurement sources	• Ambient measurement and modeling • Data fusion tools and evaluation • Near-field modeling • Place-based studies • Regional to hemispherical scale modeling
	ACE.3.4 Modeling exposure to air pollution	• Ambient measurement and modeling • Data fusion tools and evaluation • Indoor air quality • Near-field modeling • Regional to hemispherical scale modeling

Research Area	Output	PRST Need(s)
Topic 1: Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems		
ACE.4 Health Impacts of Air Pollution and Climate Change	ACE.4.1 Impacts of air pollution on human health	• Human health and environmental impacts of air pollution • Impacts of fire and smoke • Indoor air quality • SARS-CoV-2 and other respiratory viruses • Valuation of health impacts
	ACE.4.2 Climate change, air pollution, and cumulative impacts on human health	• Human health and environmental impacts of air pollution • Human health and environmental impacts of climate change • Impacts of fire and smoke • Indoor air quality • SARS-CoV-2 and other respiratory viruses
	ACE.4.3 Impacts of climate change-related extreme events on human health	• Human health and environmental impacts of climate change • Impacts of fire and smoke • Indoor air quality
	ACE.4.4 Longer-term impacts of climate change on human health and damage functions	• Human health and environmental impacts of air pollution • Human health and environmental impacts of climate change • Valuation of health impacts
ACE.5 Ecosystem Impacts of Air Pollution and Climate Change	ACE.5.1 Air pollution impacts on ecosystems under a changing climate	• Human health and environmental impacts • Valuation of health impacts
	ACE.5.2 Ecosystem impacts of a changing climate	• Atmospheric deposition and critical loads assessment • Ecosystem health impacts • Floods and drought • Impacts of fire and smoke
	ACE.5.3 Ecosystem-mediated effects on human health and wellbeing	• Ecosystem health impacts • Human health and environmental impacts
	ACE.5.4 Effects on ecosystem carbon sequestration and storage	• Atmospheric deposition and critical loads assessment • Ecosystem health impacts
	ACE.5.5 Ecosystem recovery from pollution and climate-related disturbances	• Atmospheric deposition and critical loads assessment • Ecosystem health impacts • Floods and drought • Impacts of fire and smoke

Research Area	Output	PRST Need(s)
Topic 2: Responding to Risks and Impacts and Preparing for the Future		
ACE.6 Scientific Support for Climate Change and Air Quality Policy Solutions	ACE.6.1 Locations with persistent air quality problems	• Multipollutant/multisector control strategies • Place-based studies • Regional to hemispherical scale modeling
	ACE.6.2 Quantifying benefits of reducing air pollution and emissions of climate forcers	• Regional to hemispherical scale modeling • Valuation of health impacts
	ACE.6.3 Multipollutant/ Multisector control strategy evaluations	• Ecosystem health impacts • Multipollutant/multisector control strategies • Human health and environmental impacts • Regional to hemispherical scale modeling
ACE.7 Empowering Communities and Individuals to Improve Public and Ecosystem Health	ACE.7.1 Interventions to reduce risks and impacts from emissions of criteria pollutants, air toxics, and emerging chemicals of concern	• Human health and environmental impacts • Indoor air quality • SARS-CoV-2 and other respiratory viruses
	ACE.7.3 Accessible and usable data and information	• Data fusion tools and evaluation
	ACE.7.4 Building environmental health literacy to inform health decision-making	• Human health and environmental impacts
	ACE.7.6 Community and Individual Strategies for Green Spaces and the Built Environment to Reduce Exposures to Air Pollution	• Human health and environmental impacts
	ACE.7.7 Community-based approaches to reduce ecosystem impacts of air pollution	• Ecosystem health impacts
ACE.8 Responding to Risks of Fires, Floods, and Other Extreme Events	ACE.8.1 Interventions to reduce exposures and risks from wildland fire smoke	• Impacts of wildfire
	ACE.8.2 Strategies to reduce adverse ecosystem and water quality effects from wildland fires	• Floods and drought • Impacts of wildfire

Research Area	Output	PRST Need(s)
Topic 2: Responding to Risks and Impacts and Preparing for the Future		
ACE.8 Responding to Risks of Fires, Floods, and Other Extreme Events	ACE.8.3 Resilience to floods and drought	• Data fusion tools and evaluation • Ecosystem health impacts • Floods and drought
	ACE.8.4 Methods to inform resilience decisions	• Data fusion tools and evaluation • Floods and drought
	ACE.8.5 Evaluating susceptibility, vulnerability, resilience, and adaptation measures	• Data fusion tools and evaluation • Ecosystem health impacts
ACE.9 Transitions to a Sustainable Future	ACE.9.1 Models for energy system transformation	• Data fusion tools and evaluation • Energy and transportation system changes
	ACE.9.2 Environmental impacts of transitions in the energy, transportation, and building sectors	• Energy and transportation system changes • Floods and drought
	ACE.9.3 Assessment of implications for EPA of achieving net-zero electricity generation	• Energy and transportation system changes
	ACE.9.4 Nature-based solutions to reducing climate change	• Ecosystem health impacts • Floods and drought
	ACE.9.5 Regional capacity building for sustainable transitions	• Data fusion tools and evaluation • Floods and drought
	ACE.9.6 Building capacity for community energy and climate change decision-making	• Data fusion tools and evaluation • Floods and drought
	ACE.9.7 Biofuels Report to Congress	• Fourth Biofuels Report to Congress

Appendix 2: Descriptions of Program, Regional, State, and Tribal (PRST) Needs

The following describe, in more detail, the PRST needs summarized in the body of the ACE Research Program StRAP for each Research Area and as listed in Appendix 1.

- **Agricultural emissions** – Multiple aspects of emissions from the agricultural sector need development including emissions estimates for fertilizer application, agricultural emissions estimate models (EEMs) for compliance, emissions estimates for pesticide drift and agricultural burning, and agricultural livestock spatial surrogate updates using satellite data.
- **Ambient measurement and monitoring** – Research efforts are needed to support the ambient air quality monitoring networks for NAAQS and air toxics, including products that support the modernization and increased resiliency of these networks. This need includes the ongoing review of applications for designation as Federal Reference and Equivalent Methods (FRMs and FEMs) for ambient air monitoring, development of traceable calibration methods for direct nitrogen dioxide (NO_2) analyzers, and measurements of ozone precursors (NO_2, VOCs) to understand linkages between emissions, transport, and ozone exceedances. Development and evaluation are needed for methods to measure concentrations of air toxics (formaldehyde and other carbonyls, polycyclic aromatic hydrocarbons, and passive method for VOCs) as well as PFAS and EtO.
- **Atmospheric chemistry and chemical mechanism** – Research is needed to understand the chemical reactions occurring as pollutants and precursors age and transform in the atmosphere. Work is needed to identify which species are important precursors and the details of reactions critical for representing the current atmospheric conditions in air quality models. Additional investigation is needed to understand how atmospheric chemistry may differ under extreme conditions, such as those found in wildfire plumes and near household combustion appliances and energy sources.
- **Atmospheric deposition and critical loads assessment** – Continue support for improved total **deposition** data used for program and regulatory accountability, reduce uncertainties in deposition budgets, and improve ecological/critical loads assessments is needed to assess impacts from climate change and extreme events on deposition. This includes long-term flux measurements, model development, understanding air-surface exchange, and the assessment and modeling of **critical loads** to be used in local to regional assessments that incorporate how changes in air quality and climate change will impact ecosystems, vegetation, and biota.
- **Contaminants of immediate (PFAS, EtO) and emerging concern** – Contaminants of immediate (e.g., PFAS, EtO) and emerging (e.g., ultrafine particles, cobalt, and others) concern include chemical substances that may cause ecological or human health impacts and are either long-term or new contaminants of increased priority. Work is needed to understand potential background concentrations, sources of emissions, emissions from incineration and destruction, the potential impact of operating conditions on these emissions, and inhalation toxicity. Further investigation is needed to advance methods to support the prioritization, monitoring, and management of these potential risks. A workshop is also needed to improve understanding of

key research questions related to **ultrafine particulate matter** and to prioritize research related to emissions, air quality, indoor and outdoor exposure, and public health risks.

- **Data fusion tools and evaluation** – Tools are needed to develop and evaluate ensemble/data fusion methods that combine regulatory monitoring data and low-cost sensor measurements with chemical transport models, dispersion models, and satellite data. Research is also needed to evaluate applications of ensemble/data fusion methods for exposure assessment, air pollution epidemiology, regulatory analysis, and risk communication.
- **Ecosystem health impacts** – Research is needed to improve characterization of how air pollution under a changing climate affects ecosystem functioning and resilience, determine factors that control ecosystem vulnerability and resilience to climate change, and evaluate how land management techniques other than prescribed burning affect ecosystem services and risk of future wildland fires. Work is also needed to identify impacts resulting from changes in air and water temperature, sea level rise, weather patterns, permafrost melt, and the loss of carbon and other GHG from ecosystems adversely affected by climate change. Research is needed to understand climate impacts to traditional Tribal foods, culturally important species and resources, and wetlands.
- **Emissions from other industrial sectors** – Other priority topics include understanding emissions from commercial lumber treatment and other production facilities.
- **Emissions inventory development and methods** – Data, methods, and techniques are needed to include additional **temporal and spatial distribution** for emissions information, maintaining up-to-date source profile information in the **SPECIATE** database, and methods to analyze data from satellite photos/images that may offer ways to better quantify the high spatiotemporal resolution of mobile source counts (e.g., cars, trucks, locomotives, farming tractors, etc.).
- **Emissions of air toxics** – Research is needed for measurement of air toxics from sources as well as in near-field and ambient environments. Species of interest include formaldehyde, mercury, hydrogen sulfide and other odorous gases.
- **Emissions of criteria pollutants and precursors** – Improvements are needed in the emissions inventories of **precursors for organic aerosols**, including volatile organic compounds, and especially those from volatile chemical products (VCPs). As improved chemical mechanisms are developed for use in air quality models, emissions of additional volatile species are a high priority in order to improve model performance. Following research suggesting that air quality models underestimate **ammonia**, work is needed for direct measurements of ammonia emissions from fertilizer, livestock waste and fires, along with sensitivity analysis and investigation of the impacts on air quality.
- **Emissions of GHGs and climate forcers** – In order to update emissions inventories and fill key gaps, work is needed to collect data and conduct analyses to estimate emissions of methane, and other climate forcers such as black carbon, from ecosystems, **reservoirs** (water impoundments), the **oil and gas sector** (including from onshore production tanks and equipment leaks, methane leaks at appliances, power plants and natural gas vehicles, and the impact of plugged and un-used wells), and improving estimates for other sectors in the GHG

Inventory. Improved data needed from waste management within the U.S. includes **landfills** and waste incineration and other sectors in the GHG Inventory.

- **Emissions of mobile and transportation sources** – Improved physical and chemical characterization of both onroad and nonroad **mobile source** exhaust and evaporative emissions is needed for both onroad and nonroad engines with the latest technology. Research is needed to understand the impacts of emissions programs not just on direct pollutant emissions, but on precursor compounds that react in the atmosphere to form pollutants. Data are also needed on composition of emissions from **brake and tire wear**. Improved inventories and understanding of impacts from higher volume transportation methods such as locomotive engines, railyards, ocean-going vessels, and **aircraft** are also critical research needs.
- **Energy and transportation system changes** – As the nation transitions to greater production and use of electric and autonomous vehicles, much critical research is needed. This includes continued work on energy systems models such as GCAM, TIMES, and GLIMPSE; and developing linkages between the process-oriented projections in global economic models and the emissions sectors, which are inputs for photochemical air quality models. More work would be useful to provide spatially explicit projections of population and land use for the U.S. and Tribal nations, and additional demographic details for environmental justice analysis and explicit linkages to macroeconomic drivers such as economic output and employment. Research is needed to understand impacts of low-carbon energy sources and renewable energies and the overall evolution of the energy grid economics and operations. Research is also needed on impacts to traditional and cultural resources of energy transitions, especially considering disadvantaged communities and communities that produce fossil fuels; and on how changing energy sources/energy systems can exacerbate local extinctions and cultural issues.
- **Exposure, interventions, and community actions** – Research is needed on the effectiveness of interventions to reduce smoke and $PM_{2.5}$ exposures such as face masks, indoor air cleaners, different HVAC setups, clean air shelters, DIY box fans, HEPA filters etc. Research is also needed on the benefits of using clean energy and other exposure mitigation strategies such as vegetative barriers, and on approaches to increase environmental health literacy in health care providers.
- **Fourth biofuels Report to Congress** – The third Biofuels Report to Congress will identify research needs that will have to be addressed for the fourth report. Additional research is needed for more attribution work, including attribution between the biodiesel/renewable diesel production and production of soybeans or other oilseed crops. A cross-media analysis related to impacts of land use change on environmental endpoints (other than climate change) is also needed.
- **Floods and drought** – Greater availability of information is needed on the potential health and environmental impacts of extreme precipitation events and permafrost melt at the community level, particularly for frontline communities with environmental justice concerns that have often experienced disproportionate impacts. More information is also needed to identify and evaluate different methods for computing "typical" rainfall conditions and solutions that incorporate community perspectives, such as identification of areas or neighborhoods and populations most at risk from street flooding of combined sewage and sewer backups, mold, sea level rise,

permafrost melt, storm surges, and increased intense precipitation events. This work should provide public health decision-makers the information needed for development of policy, guidance, and actions to minimize risks.

- **Human health and environmental impacts research from air pollution** – To support efforts to protect public health and inform NAAQS reviews, core air pollution health research is needed (e.g., any new O_3 chamber studies, or use of electronic health records to evaluate linkage between AQ and health impacts). Additionally, work is needed to evaluate health benefits of using HVAC filtration/ air cleaners to reduce indoor exposures (and mitigate exposure disparities) to $PM_{2.5}$, including PM from wildfires (e.g., cardiovascular, respiratory, maternal & birth outcomes, neurological) with a focus on reducing exposure disparities. Research efforts should elucidate the interactions between air pollution and transmission and severity of respiratory viruses such as SARS-CoV-2, and the potential for populations who have contracted such viruses to have increased vulnerability to air pollution or other environmental stressors. Further understanding is needed on the linkages between air pollution health effects and exposure to chemical and non-chemical flood-related contaminants, changes in built environments, and shifting disease vectors due to climatic conditions.
- **Human health and environmental impacts from climate change** – Research is needed to understand the environmental and human health impacts of the changing climate. This includes advancing research on the interaction between air quality, climate change, and resulting health impacts (both nationally and on vulnerable populations); and translating the physical impacts of climate change into monetized estimates of their effects on economic and human systems (in particular for impacts related to storms, flooding, agriculture, and heat). For example, in some areas the length of the pollen season is extending, and exposures to indoor air pollution may change with more extreme temperatures. Climatic shifts may also lead to changes in built environments or shifting disease vectors. Research is needed to understand climate impacts to traditional Tribal foods and culturally important species and resources, utilizing traditional and indigenous knowledge, and addressing inequitable burdens of adaptation costs borne by Tribes.
- **Impacts of fire and smoke** – Understanding the emissions of both wildfire and prescribed fire is needed to determine potential health impacts and inform public health decision making during associated smoke events. Research is also needed for a holistic understanding of wildfire impacts on air, human physical and mental health, ecosystems, and water quality.
- **Indoor air quality** – Research is needed to understand indoor exposures to pollutants of indoor and outdoor origin; to understand fuel consumption and emissions of a range of pollutants from stoves and ranges (including various fuels and electric); and to develop and test low-cost, low-noise mitigation options for stove and range hoods. Additional effort is needed to evaluate alternatives to sub-slab depressurization radon mitigation techniques that can reduce residential radon risks reliably for low-income and Tribal communities. Research is also needed to understand the health benefits (e.g., cardiovascular, respiratory, maternal & birth outcomes, neurological) of reducing indoor exposure to $PM_{2.5}$ from various sources with filtration/air cleaners; to understand disparities in exposure to indoor pollutants and assess mitigation options, including consideration of indoor conditions and indoor activities (e.g., cooking, cleaning); and finally, to evaluate whether and how new, lower-cost air sensors could be used to

guide consumers and inform decision making related to indoor pollutant sources and actions during extreme events, such as wildfire smoke events.

- **Multipollutant/multisector control strategies** – Research is needed to understand which sectors and source types can benefit from multipollutant control approaches and which combinations of criteria pollutants, GHGs, and/or air toxics could be combined to holistically identify and evaluate the public health and environmental impacts of policies and programs. Research and tools are needed to inform transportation planning; while tools, guidance, and training are needed to support decisions at different levels of governance. Further discussions clarify this research need.
- **Near-field modeling** – Research to continue evaluation and enhancement of the EPA's preferred near-field dispersion model, the AERMOD Modeling System, is crucial to inform our Federal and state/local/Tribal regulatory permitting and toxics programs. Model development priorities include improving representation of building downwash from a variety of structures, roadway features such as barriers (solid and vegetative), depressed roadways, and updated treatment of NO_2 chemistry.
- **Place-based studies** – Air quality studies and modeling in support of core regulatory work are needed, especially in challenging areas such as the San Joaquin Valley, South Coast air basins, Long Island Sound, Fairbanks, AK, and other nonattainment zones. Further support for field studies and modeling improvements will be essential for efficient and effective air quality planning in those areas for development of SIPs and responses to the regional haze rule.
- **Regional to global scale modeling** – Regional to hemispheric air quality modeling tools need continuous development and evaluation. Keeping CMAQ up to date is critical to inform EPA's air quality modeling for national rules and risk/benefit assessments, as well as for modeling demonstrations needed for NAAQS implementation by state/local/Tribal air agencies. Model development priorities include improvements to chemical/physical mechanisms, tools for source attribution and source sensitivity, and updates that improve functionality, runtime, and ease-of-use. Work is needed to simulate concentrations of emerging pollutants of interest such as PFAS and using models to understand regional and local air quality issues.
- **Residential heating and cooking emissions** – Improved emissions factors for residential wood combustion are needed including the current test methods and in-use conditions with information categorized by appliance type, wood type, and moisture content of wood. Standards are also needed for measurements of emissions from cookstoves, including black carbon emissions. Research is needed to compare emissions of various stove technologies including biomass pellet-fueled cookstoves, and stoves that capture carbon through char production in environments ranging from residential to industrial (e.g., large stoves used in schools, hospitals, churches) so that a unified understanding fuel efficiency and emissions exists.
- **SARS-CoV-2 and other respiratory viruses** – Critical work is needed to evaluate recent advanced ventilation and filtration approaches, portable air cleaners, and other emerging technologies for home/ school/ office/ commercial buildings (e.g., vertical displacement, dedicated outdoor air systems, monitoring and control systems/automated HVAC systems) that can reduce exposure to SARS-CoV-2, indoor PM, and other indoor pollutants.

- **Sensors** – Research is needed on the development, performance, and testing of low-cost sensors with defined quality objectives/indicators, and protocols for criteria pollutants and air toxics. Applications and evaluation of new, lower-cost air sensors for consumer use, particularly in residential environments and in community-based data capturing efforts, are needed along with additional research on how to interpret, communicate, and use sensor data generated by EPA as well by other agencies and citizen scientists.
- **Source measurement** – Research is needed to support a variety of point, fugitive and near source measurement and monitoring techniques including those for 1) EtO and PFAS (speciated and surrogate); 2) real-time, continuous analyzers for additional Tier 1 air toxics compounds; and 3) primary PM. Methods are needed for continuous and cost-effective measurements, in-facility monitoring and mitigation of fugitive emissions criteria, air toxics and GHG compounds, near source emissions measurements and monitoring methods such as UAVs, fence line deployed measurements, and small resolution satellite data. Additionally, work is needed for on-going support for reference material (e.g., gas cylinders and generators) for accuracy and bias of compliance measurements.
- **Valuation of health impacts** – Before undertaking any effort to regulate air pollution, EPA is required to assess all costs and benefits of available regulatory alternatives. Estimating the economic impacts of any regulatory action to reduce air pollution is an extremely complex exercise that requires a multi-dimensional understanding of air pollution exposure, the human health or ecosystem response that results from that exposure, and the economic value of those impacts. Updating our methods for estimating the dollar value of air pollution effects will ensure future Regulatory Impact Analyses are able to properly evaluate the comparison between control strategy costs and benefits. Work is needed to understand whether costs and valuations vary across regions of the country, community and ethnic groups, and Tribes.

Appendix 3: Output Descriptions

The following describe, in more detail, the ACE Research Program Outputs listed in Appendix 1. Outputs are planned under each Topic and respective Research Area (RA). It should be noted that the Outputs might change as new scientific findings emerge and are also contingent on budget appropriations.

Topic 1: Understanding Air Pollution and Climate Change and Their Impacts on Human Health and Ecosystems

RA ACE.1: Sources and Sinks of Air Pollution and Climate Forcers

Output ACE.1.1: Characterization of point source air pollution and climate forcers

Sampling and physical and chemical characterization of point source emissions are needed to develop effective regulatory strategies that improve air quality and public health. This Output aims to 1) develop and improve methods and techniques that measure and characterize the properties of pollutant emissions from point sources of interest; 2) improve the knowledge and understanding of point source emissions; 3) provide air quality model input and support development of national inventories for criteria pollutants, air toxics, and climate forcers; and 4) address measurement needs for the array of complex source conditions that occur when sampling emissions.

Output ACE.1.2: Characterization and mitigation of fugitive and area source air pollution and climate forcers

Detailed information on levels and composition of emissions from fugitive and area sources at refineries, chemical plants, oil and gas production sites, and other industrial/commercial operations is needed to develop effective strategies to improve air quality and reduce climate forcing pollutants. This Output aims to 1) provide methods and measurements for the physical and chemical properties of air pollution emissions with complex temporal and spatial patterns, and 2) reduce uncertainty in emissions from fugitive and area sources.

Output ACE.1.3: Characterization of mobile source emissions of air pollution and climate forcers

Better understanding and improved characterization of emissions of air pollutants and climate forcers from mobile sources is needed to inform regulatory actions. In addition, methods of mitigating these impacts to improve public health are critical including improved vehicle technologies, cleaner fuels, and use of urban-built and green infrastructure. This Output aims to 1) improve understanding of the properties of emissions (including from brake and tire wear) from new light-duty and heavy-duty vehicle technologies and fuels and non-road equipment; 2) increase understanding of emissions changes from evolution of the composition of the vehicle fleet and mobility patterns; 3) increase understanding of the role of high-emitting vehicles, including in communities with environmental justice concerns; and 4) increase understanding of the emissions reductions associated with emissions control technologies

Output ACE.1.4: Characterization of wildland fire emissions

Improved characterization of emissions from wildland fires, including wildfires and prescribed fires, is needed to better understand the relative contributions of wildland fires to local and regional air quality trends and air toxics exposures. This Output aims to 1) improve understanding of properties of

emissions from wildland and agricultural fires across a variety of burn types, fuels, combustion conditions, and meteorological scenarios; and 2) improve understanding of emission speciation (organic and inorganic) from wildland fires including the burning of residential and commercial structures, vehicles, and other built infrastructure during wildfire events.

Output ACE.1.5: Anthropogenic and natural systems for carbon sequestration

Detailed understanding of how much carbon is taken up and stored by a variety of natural systems is needed to develop effective plans that meet climate mitigation goals. Accurate methods for determining the amount of carbon stored by man-made systems over different time horizons is also needed, taking into account uncertainties and potential impacts of future climate change. This Output aims to 1) improve understanding of different types of ecosystems and water bodies that act as sinks for carbon and other air pollutants and develop methods for measuring carbon storage capacity; and 2) improve understanding of the carbon storage capacity of man-made or managed systems.

Output ACE.1.6: Development and Verification of Emissions Inventories

Improved inventories and ambient measurements are needed in research and modeling to support regulatory and non-regulatory approaches to meet air quality standards, understand health impacts, reduce exposures, and mitigate emissions of climate forcers, as well as assess the frequency and level of exposure impacting overburdened communities and other vulnerable populations. This Output aims to 1) develop information and models to incorporate spatial and temporal emissions information throughout the year, season, and day, and during periods of abrupt changes in activity; 2) update speciated emissions profiles, including details of volatile chemical products (VCPs), semi-volatiles and speciated PM; and 3) improve temporal/spatial information to support model-ready emissions inventories.

Output ACE.1.7: Characterization of source emissions of EtO and PFAS

Detailed information on emissions and composition is needed to develop effective strategies for reducing levels of ethylene oxide (EtO) and PFAS—emerging pollutants of concern, particularly in communities with environmental justice considerations that are impacted by nearby pollution sources. This Output aims to 1) identify potential EtO and PFAS sources; 2) develop and improve measurement technologies, measurement methods, and reference materials; 3) provide information on control technology options and the effectiveness of new and existing control strategies; and 4) characterize atmospheric fate and transport of EtO and PFAS compounds.

RA ACE.2: Air Quality Concentrations and Exposure Characterization: Measurements

Output ACE.2.1: Reference and Equivalents methods to support NAAQS

Accurate and unbiased regulatory monitoring is needed to support implementation of the NAAQS and to understand concentrations of pollutants of concern. This Output aims to 1) develop and evaluate new measurement methods for accuracy and bias operating in a variety of conditions, and evaluate the quality, durability, reliability, and accuracy of these instruments in the field; 2) develop calibration methods to ensure quality of measurements; and 3) provide designations for FRM and FEM applications and modifications to method designations.

Output ACE.2.2: Methods for measuring air toxics and ultrafine particles for exposure characterization

New and expanded methods are needed to measure air toxics and ultrafine particles in ambient air to address growing concerns about outdoor and indoor exposures to these pollutants, especially in communities with environmental justice concerns. This Output aims to 1) develop improved methods for measurement of air toxics and ultrafine particles in indoor and outdoor ambient air, including continuous measurement approaches; 2) improve approaches for using air toxics and ultrafine particle measurement data in exposure characterization, especially in communities with environmental justice concerns; and 3) develop and evaluate methods for characterizing deposition of air toxics to water and soil.

Output ACE.2.3: Characterization of sensors and other non-regulatory measurements for stationary, personal, and mobile monitoring

Smaller, more portable, mobile, and personal monitoring methods are needed to improve spatial resolution to increase understanding of community scale air quality. This Output aims to 1) develop and assess capabilities of new sensors and measurement packages measuring criteria pollutants, air toxics, and climate forcers in multiple geographic settings and conditions; 2) develop performance standards and testing protocols for additional air pollutants other than PM2.5 and ozone; 3) develop air sensor data quality and QA targets for non-regulatory applications including remote sensing validations; and 4) catalog resources, guidance, and best practices for sensor use and data cleaning and correction.

Output ACE.2.4: Methods and characterizations to inform air pollution dynamics and support model development

Data on ambient concentrations and field-scale or laboratory measurements of important processes, such as deposition, are needed to develop and evaluate models and ensure high quality, reliable estimates of air pollution impacts from actions that change air pollutant emissions, formation, transformations, or sinks. This Output aims to 1) develop remote sensing techniques and algorithms for trace gases, aerosols, and meteorological variables; 2) collect concentration and emissions measurements needed to evaluate chemical mechanisms that underlie chemical transport models; 3) conduct controlled environmental chamber experiments and field studies to improve understanding of photochemical aging of pollution and other chemical processes for inclusion in chemical transport models; 4) conduct controlled experiments and field studies to improve understanding of pollutant deposition; and (5) improve understanding of pollutant dispersion in complex environments and terrains.

Output ACE.2.5: Methods to measure personal and community level exposures to air pollution

Improved methods are needed to characterize individual and community level exposures using measurements and information on time-activity patterns, and other social, cultural, and economic determinants. This Output aims to 1) develop innovative approaches to characterize individual and community level exposures to air pollution, 2) develop new methods for collecting continuous information on time-activity patterns, 3) characterize the relationships between non-chemical stressors and individual or community exposures to air pollution, and 4) characterize climate change related

factors that modify the relationship between ambient concentrations and individual or community exposures.

Output ACE.2.6: Methods for measuring and characterizing EtO and PFAS

Methods are needed to characterize ambient concentrations of other chemicals of emerging concern, including PFAS and EtO. This Output aims to 1) develop improved methods for measurement of EtO and PFAS in ambient and indoor air; 2) improve approaches to better characterize ambient exposure concentrations of EtO and PFAS in near-source communities, particularly those with environmental justice issues; and 3) develop and evaluate methods to gain a better understanding of chemical transport and deposition of PFAS to water and soil.

RA ACE.3: Air Quality Concentrations and Exposure Characterization: Models

Output ACE.3.1: Modeling of near-source concentrations and exposures

Near-source, high-spatial resolution model estimates of pollutant concentrations are needed to support air quality management decisions and strategies to reduce exposures in populations living near air pollution sources. This Output aims to 1) improve knowledge of how pollution disperses and moves around physical barriers such as buildings, vegetation, roadway features, or partitions within indoor spaces; and 2) improve model skill in characterizing concentration patterns of air toxics and criteria pollutants near sources and indoors.

Output ACE.3.2: Global, regional, and community scale chemical transport modeling (development and evaluation)

High spatial and temporal resolution estimates of air quality and pollution deposition across the U.S. are critical for understanding human and ecosystem exposures to criteria and toxic air pollutants to support air quality management decisions and air pollution reduction strategies. In addition, information on how global pollution and uncontrolled sources impact air quality in the U.S. is needed for development of air quality management standards and international coordination. This Output aims to 1) expand and develop CMAQ to improve functionality, runtime, and ease of use; incorporate emerging and high interest contaminants; improve species characterizations and chemical mechanisms for more complete treatment of organic species that impact secondary organic aerosol formation; and improve representation of pollutant deposition; 2) evaluate CMAQ relative to observational data and other chemical transport models; 3) improve modeling of long-range transport of pollutants; 4) increase understanding of wildfire smoke impacts on air quality; 5) improve linkages of CMAQ to global climate models and provide high-resolution global modeling capability; 6) improve model performance in areas with complex topography; and 7) explore methods to improve data sharing with partners and the modeling community, including data sharing and model application in a cloud environment.

Output ACE.3.3: Fusion of data from multiple models and measurement sources

High spatial and temporal resolution estimates of air quality characterization are needed to inform decision-making, emission reduction strategies, and exposure and health studies. Methods are needed to combine or fuse measurements from different sources with modeling inputs or results to improve the accuracy of predicted air quality concentrations across space and time. This Output aims to develop, evaluate, and apply data fusion and data assimilation algorithms and methods for agency applications, including methods for effectively incorporating data from satellites and multiple measurement platforms.

Output ACE.3.4: Modeling exposure to air pollution

Refined estimates of exposures to air pollution are needed to inform air pollution health studies and support strategies to reduce exposures to help address health disparities and environmental inequities. This Output aims to 1) increase understanding of both the levels of exposure to air pollution and the factors that affect them, 2) support more temporally- and spatially-resolved estimates of individual and population exposures, 3) integrate multiple tools and data to improve understanding of exposure to air pollution and account for joint exposures to chemical and non-chemical stressors and those associated with climate change, 4) compare exposure metrics used in epidemiology studies, and 5) improve approaches to model source contributions to exposures.

RA ACE.4: Health Impacts of Air Pollution and Climate Change

Output ACE.4.1: Impacts of air pollution on human health

Information about the impacts of air pollution on human health is critical to support development of NAAQS, and air toxics programs, as well as informing strategies to reduce the health burdens of air pollution. This Output aims to 1) improve understanding of the health impacts of criteria pollutants, air toxics, emerging contaminants, and mixtures with different composition; 2) investigate the effect of exposure duration and the possible cumulative risks or adaptive effects of previous exposures; 3) investigate potential interactions between air pollution and respiratory viruses such as SARS-CoV-2; 4) identify and characterize key reproductive factors and critical stages of development that are impacted by air pollution exposures; and 5) improve understanding how lifestyle, diet, mental health, prescriptions, and chronic diseases modify responses to air pollution.

Output ACE.4.2: Climate change, air pollution, and cumulative impacts on human health

Information is needed on how climate change related variations in temperature, humidity, and aeroallergens alter health responses to air pollution, and how cumulative exposures over a variety of spatial and temporal scales to air pollution and climate change impact public health. This Output aims to 1) evaluate the effect of changing climate conditions on biochemical effects, biomarkers, and cardiopulmonary, mental health, reproductive, and developmental risks from air pollution; 2) investigate the biological mechanisms that underlie the interactions of psychosocial stress, climate-change related stressors, air pollution exposure, and increased risk of adverse effects; 3) evaluate the interactions between chemical and non-chemical stressors in worsening the health impacts from air pollution; and 4) assess future health impacts resulting from changes in indoor and outdoor air quality associated with projected changes in climate.

Output ACE.4.3: Impacts of climate change-related extreme events on human health

Understanding impacts of climate-related extreme events on public health requires both rapid assessment techniques to assess health risks before and during events, and more forward-looking approaches to prepare for future events. This Output aims to 1) investigate health effects of smoke from wildland fires including prescribed fires and wildfires, including those resulting in burning of structures or hazardous waste sites; 2) improve understanding of health effects of extreme heat events, including both short-term and chronic effects, and effects on mental health; and 3) identify and characterize health impacts resulting from exposure to chemical and non-chemical flood-related contaminants.

Output ACE.4.4: Longer-term impacts of climate change on human health at local, regional, national, and international scales

Information on health damage functions for climate change related effects is needed to inform decision-makers at different scales of government to inform mitigation, adaptation, and resilience actions. This Output aims to 1) characterize health effects from changes in disease vectors due to shifts in ecological regimes and climatic conditions; 2) quantify mental health effects from long-term changes in temperature, humidity, precipitation, and risks of extreme events such as wildfires, floods, droughts, and storms; 3) characterize health effects from changes in built environments resulting from long-term adaptation to changing climate conditions; and 4) develop damage functions for key health effects associated with climate change, accounting for non-linearities and uncertainties.

RA ACE.5: Ecosystem Impacts of Air Pollution and Climate Change

Output ACE.5.1: Air pollution impacts on ecosystems under a changing climate

Information is needed to improve characterization of the ecological impacts of air pollution through atmospheric exposures and deposition in a changing climate. This information is needed to inform critical loads for aquatic and terrestrial ecosystems. This Output aims to 1) increase understanding of the role of deposition of nitrogen, sulfur, and toxic pollutants on ecosystem functioning and services; 2) improve and expand information on critical loads for nitrogen and sulfur; 3) increase understanding of how wildland fires affect air and water quality and ecosystem health; and 4) improve characterization of how air pollution impacts ecosystems under a changing climate.

Output ACE.5.2: Ecosystem impacts of a changing climate

Greater understanding of how climate change alone and in combination with air pollutants affects ecosystems is needed to protect ecosystem health and services. This Output aims to 1) project potential future climate-driven ecosystem impacts; 2) evaluate consequences to ecosystems undergoing particularly rapid change, such as the Arctic and Gulf Delta regions; and 3) determine factors that control ecosystem vulnerability to climate change.

Output ACE.5.3: Ecosystem-mediated effects on human health and wellbeing

Information is needed on how current and expected climate change, related extreme events, and responses to climate change will directly or indirectly impact human health through changes in ecosystem health and services. This Output aims to 1) determine the effects of climate change on ecosystem structure and functioning that directly or indirectly affects human health, 2) identify ecosystem characteristics that influence smoke toxicity during wildland and prescribed fires, 3) evaluate how different types of land management approaches impact smoke emissions, and 4) examine how climate change impacts the effectiveness of ecosystems in filtering toxic compounds from air and water.

Output ACE.5.4: Effects on ecosystem carbon sequestration and storage

Information is needed to understand how air pollution and climate change impact the carbon carrying capacity of ecosystems, to support actions to increase carbon sequestration and storage and evaluate nature-based solutions. This Output aims to 1) investigate how air pollution and climate change impact ecosystem carbon sequestration in forested ecosystems, near-shore marine ecosystems, and freshwater and estuarine aquatic ecosystems; and 2) identify which ecosystem carbon storage sources are most vulnerable or resilient to the effects of air pollution and climate change.

Output ACE.5.5: Ecosystem recovery from pollution and climate-related disturbances
Improved understanding of how ecosystems and critical services for human health and wellbeing adapt to and recover from disturbances caused by extreme events, longer term changes in temperature and precipitation patterns, and damage from air and water pollution. This Output aims to 1) investigate the relation between ecosystem recovery following disturbances and the resumption of ecosystem services; 2) evaluate the consequences to human health and wellbeing of climate change related changes in resilience to disturbances; and 3) investigate how ecosystems adapt to air pollution, disturbances and changing climate.

Topic 2: Responding to Risks and Impacts and Preparing for the Future

RA ACE.6: Scientific Support for Climate Change and Air Quality Policy Solutions

Output ACE.6.1: Locations with persistent air quality problems
Place-based studies with detailed investigations using measurements and models are needed to identify unique challenges in areas with persistent non-attainment of National Ambient Air Quality Standards and evaluate potential strategies for addressing those challenges. This Output aims to 1) improve understanding of specific air quality challenges with identification of unique physical or chemical characteristics; 2) identify and evaluate potential strategies for overcoming challenges to attainment of the NAAQS; and 3) develop tools, guidance, and training to support decision makers at different levels of government and evaluate effectiveness.

Output ACE.6.2: Quantifying benefits of reducing air pollution and emissions of climate forcers
Methods are needed to quantify the environmental and health impacts of climate change and air pollution—or conversely, the benefits of avoiding those impacts—in order to develop and evaluate potential strategies for reducing air pollution and/or climate forcer emissions. This Output aims to 1) expand approaches to quantify modeled changes in ambient concentrations and exposure to air toxics, and associated health and ecosystem impacts for criteria pollutants, air toxics, and emerging contaminants for regulatory scenarios; 2) develop and apply measurement and modeling approaches to quantify changes in ambient concentrations and exposure to air toxics, and associated health and ecosystem impacts for regulatory scenarios and benefits assessments, including traditional emissions controls, as well as novel approaches such as requirements for vegetative barriers; 3) develop, apply, and evaluate methods to quantify the predicted benefits of strategies to reduce impacts of air pollution and climate change on communities with environmental justice concerns; 4) develop approaches to quantitatively value ecosystem services and intangible assets, such as culturally important locations, flora, or fauna; and 5) develop tools, guidance and training to support decision makers at different levels of government and evaluate effectiveness.

Output ACE.6.3: Quantifying benefits of reducing air pollution and emissions of climate forcers
Information on emissions, air quality, and economic costs and impacts is needed to support development of strategies to reduce air pollution and climate forcers across multiple pollutants and interrelated sectors. This Output aims to 1) use energy system, air quality, and health and environmental impacts modeling to improve understanding of which sectors and source types can benefit from multipollutant control approaches, and which can include combinations of criteria pollutants, GHGs,

and/or air toxics; 2) develop current data comparing capital and operating costs and emission reduction performance for multipollutant and single pollutant control strategies; and (3) develop tools, guidance and training to support decision makers at different levels of government and evaluate effectiveness.

RA ACE.7: Empowering Communities and Individuals to Improve Public and Ecosystem Health

Output ACE.7.1: Interventions to reduce risks and impacts from emissions of criteria pollutants, air toxics and emerging chemicals of concern and exposure to indoor emissions

Information is needed on the types of air pollutant exposures experienced by communities, including emissions from household heating and volatile chemical products (e.g., cleaning products, personal care products); and effective interventions to reduce those exposures, especially for susceptible and vulnerable populations. This Output aims to 1) develop and evaluate applications of personal exposure data, models, and tools to inform intervention strategies for reducing exposures to air pollution and evaluate the effectiveness of those strategies; 2) develop tools and approaches to inform communities and individuals about exposures to air pollution, including indoor sources of air pollution such as home heating and volatile chemical products, and generate personalized health risk messaging and advice for reducing exposures; 3) identify and evaluate opportunities for linking personal exposure information with personal health data generated through personal health monitoring; and 4) identify and evaluate strategies to overcome social, economic, cultural, and behavioral factors that prevent or reduce use of effective exposure-reducing approaches.

Output ACE.7.2: Building environmental health literacy to inform health decision making

New approaches are needed to increase awareness and management of air pollution and climate health risks, including amongst health care professionals and their patients. This Output aims to 1) evaluate knowledge and behaviors of physicians and patients around air pollution; 2) develop individual risk metrics using personal health information; 3) design and evaluate educational interventions for physicians and their patients; 4) develop and evaluate innovative approaches to environmental literacy and evidence-based decision-making, including use of serious games, interactive simulations, tabletop scenarios, and community participatory modeling; and 5) develop serious games or similar approaches that enhance or expand citizen science efforts, including potential utilization of technologies such as low-cost sensors and mobile apps.

Output ACE.7.3: Accessible and usable data and information

New approaches and tools are needed to provide local environmental data and information to communities to enable informed local interventions for reducing air pollution exposures and health and ecological impacts. This Output aims to 1) improve the design and implementation of data systems for use by non-experts; 2) design and implement low-cost sensor data analysis and interpretation tools and approaches that can be used by communities and individuals; 3) develop and implement systems and designs to communicate changes in public data and information; and 4) develop and implement approaches to connect existing, disparate tools toward a more cohesive EPA presentation of research data.

Output ACE.7.6[13]: Community and Individual Strategies for Green Spaces and the Built Environment to Reduce Exposures to Air Pollution

Information and evidence-based strategies are needed to better understand the effects of different types of building and green space choices on exposures to both indoor and outdoor air pollution and resulting health impacts. This Output aims to 1) identify and evaluate alternative building, roads and utilities and green space designs to determine impacts on emissions of criteria pollutants, air toxics, and emerging contaminants of concern; and 2) study the joint impacts of green space, building design, and air pollution on public health.

Output ACE.7.7: Community-based approaches to reduce ecosystem impacts of air pollution

Information is needed on effective approaches that communities can take to reduce exposures of ecosystems to air pollutants and mitigate the impacts of those exposures on ecosystem services. This Output aims to 1) improve valuation of ecosystem services to provide a basis for comparing land management options; 2) evaluate impacts of zoning and land use management practices on ecosystem services, under both current and potential future climatic conditions; and 3) develop ecosystem-based filter designs for removal and sequestration of pollutants applicable at various scales, from local to regional.

RA ACE.8: Responding to Fires, Floods, and Other Extreme Events

Output ACE.8.1: Interventions to reduce exposures and risks from wildland fire smoke

Information is needed on effective strategies to reduce exposures to smoke, increase public awareness of public health impacts of smoke exposure, and reduce the health burden of smoke exposures, especially in at-risk populations. This Output aims to 1) develop and evaluate effective and accessible risk communication and exposure reduction strategies and tools that communicate air quality and health information before, during, and after fire and smoke events; 2) collect and provide information on sensor performance and interpretation during fire and smoke events; 3) apply new approach toxicology methods including high-throughput, non-targeted methods to rapidly assess risks from wildfire smoke; 4) develop and evaluate science-based community programs to increase engagement and build resilience to wildfire smoke; and 5) evaluate the health impacts of alternative land management practices, such as prescribed fires, that are intended to reduce the risks of catastrophic wildfires.

Output ACE.8.2: Strategies to reduce adverse ecosystem and water quality effects from wildland fires

Information is needed to develop effective strategies to prevent contamination of surface and drinking waters from wildland fires and build resiliency in impacted aquatic ecosystems. This Output aims to 1) improve understanding of wildland fire impacts on water quality, including the use of fire retardants and the downwind deposition of nutrients, metals, and other pollutants of interest; 2) develop tools and approaches to reduce wildfire impacts leading to contaminants in receiving waters and drinking water; 3) evaluate impacts on habitats for economically, culturally, and ecologically important fish and other aquatic life, wildlife, and plant species, and approaches for building resilience; and 4) assess the

[13] Content of Outputs ACE.7.1 and ACE.7.5 were combined into others and these have been removed.

cumulative effectiveness of prescribed fires and other management practices for reducing water quality and ecosystem impacts.

Output ACE.8.3: Resilience to floods and drought

Information is needed to inform effective strategies to reduce impacts of more frequent and greater magnitude extreme precipitation events that can adversely affect water quality, cause contaminant release, damage ecosystems, and adversely impact public health. This Output aims to 1) increase availability of information on the potential health and environmental impacts of extreme precipitation events and permafrost melt at the community level; 2) identify and evaluate solutions that incorporate community perspectives and enable individual and community-level actions; and 3) develop and evaluate methods to facilitate community-based decisions, accounting for the deep uncertainties related to climate change impacts.

Output ACE.8.4: Methods to inform resilience decisions

Finer spatial resolution information on projections of temperature and precipitation is needed to inform resilience decisions made at a local level. This Output aims to 1) develop methods and approaches to dynamically downscale global climate projection data from various sources to provide temperature, precipitation, and other key weather-related health and environmental stressors at regional and local scales, 2) expand methods to incorporate updated global climate modeling results, and 3) develop the tools and methods needed to enable these data to be used by local practitioners.

Output ACE.8.5: Evaluating susceptibility, vulnerability, resilience, and adaptation measures

Information is needed to evaluate susceptibility and vulnerability to extreme events and support development and evaluation of strategies and plans to improve adaptation and resilience. This Output aims to 1) define adaptation and resilience effectiveness metrics in relation to their importance and relevance to communities with environmental justice concerns, and their ability to account for changes over time; 2) assess current and new resilient design standards for performance and cost; 3) explore and refine quantitative measures, including valuation, and robustness to changing conditions; and 4) develop methods to evaluate impacts on equity.

RA ACE.9: Transitions to a Sustainable Future

Output ACE.9.1: Models for energy system transformation

Information is needed to inform effective strategies to reach emissions reduction goals within the six sectors (resource extraction and fuel processing, electric power, transportation, industrial, residential, and commercial) of the U.S. energy system. This Output aims to 1) evaluate cost- and environmental effectiveness of electric power, industrial, commercial, residential, and transportation sector energy-related processes and options; 2) improve understanding of energy storage options and characteristics; 3) evaluate the potential for emerging low-carbon energy technologies and zero emissions vehicles; 4) improve capabilities to incorporate energy efficiency and changes in behavior; and 5) estimate the carbon footprints of Tribal-nations, states and other regions as well as carbon intensity for major manufacturing industries, commodities and their supply chains.

Output ACE.9.2: Environmental impacts of transitions in the energy, transportation, and building sectors

Understanding of the environmental impacts, both beneficial or negative, of transitions to a low-carbon energy system under climate change is needed to inform decisions that can address these impacts and

work proactively toward beneficial and equitable outcomes. This Output aims to 1) quantify the life-cycle implications of these scenarios for domestic manufacturing activity, energy, water, emissions, and waste disposal; 2) quantify other major benefits and unintended consequences of energy system transition scenarios; and 3) evaluate the environmental justice and economic justice implications of these scenarios.

Output ACE.9.3: Assessment of implications for EPA of achieving net-zero electricity generation

Information is needed to improve understanding of how the transition to a decarbonized system of electricity generation will affect EPA's ability to maintain and improve public health and environmental quality specifically at regional and local scales. This Output aims to 1) develop an assessment of different scenarios to achieve net zero electricity generation by 2035, along with the anticipated positive and negative environmental implications of those scenarios; 2) explore more localized impacts of grid decarbonization and provide assessments on how it would impact resilience of and economic burden to communities; and 3) develop and/or identify tools to evaluate public health and environmental impacts of grid decarbonization.

Output ACE.9.4: Nature-based solutions to reducing climate change

Information is needed to support strategies that leverage a wide variety of ecosystem services to reduce emissions and atmospheric concentrations of GHGs. Additionally, information is needed on strategies that reduce risks from climate-driven extreme events and achieve near-term environmental benefits to frontline communities, ecosystems, and public health. This Output aims to 1) increase understanding of various types of nature-based solutions (NbS) and their capabilities and limits; 2) improve abilities to quantify NbS costs and benefits; 3) more fully understand and represent the dynamic processes linking NbS to human systems; 4) increase engagement with partners and stakeholders to develop scientific knowledge and implement NbS; and 5) develop and evaluate strategies to reduce ecosystem impacts of a changing climate by preserving and increasing carbon storage, maximizing mitigation and adaptation capacity, and protecting and enhancing the quality of water, soil, air, and habitats.

Output ACE.9.5: Regional capacity building for sustainable transitions

Information is needed to support GHG mitigation, climate change adaptation, and resilience decisions that account for local conditions and needs. Approaches are needed to increase access to scientific information and evidence-based strategies for states and communities to maintain and improve air and water quality in the face of climate change. This Output aims to 1) analyze current and projected climate impacts and vulnerabilities at local scales, 2) actively engage with federally supported regional climate science organizations, (3) build regional networks of climate expertise connecting experts to practitioners and both to communities, and 4) develop planning and decision frameworks for resilience-based adaptation of projects and programs.

Output ACE.9.6: Building capacity for community and individual energy and climate change decision making

New tools and innovative approaches are needed to understand and inform decision-making by individuals and communities to respond to climate change impacts and transitions to a low-carbon energy system. This Output aims to 1) develop and evaluate innovative interactive and community-engaging tools and approaches focused on energy and climate change, 2) evaluate the impact both on learning and the ability to influence behavior and community decision making, 3) assess the applicability

of serious games or other tools for engagement in climate adaptation planning for communities, and 4) apply tools such as virtual reality as a more immersive and interactive platform for visualization of climate impacts and alternative environmental futures.

Output ACE.9.7: Fourth Triennial Report to Congress on Biofuels

Information is needed to inform development of the Fourth Triennial Report to Congress on Biofuels as required by Section 204 of the Energy Independence and Security Act of 2007. This Output aims to 1) develop methods and models to support the completion of the report; and 2) assess the impacts to date and likely future effects of biofuels and the Renewable Fuel Standard (RFS) on a range of environmental and resource conservation effects, including air quality, soil quality and conservation, water quality, water availability, natural ecosystems (e.g., grasslands, forests, wetlands, aquatic habitats), invasive species, and international effects.

Appendix 4: Cross-Cutting Research Priorities

Working together on Agency priorities that cut across the six National Research Programs (NRPs), ORD will integrate efforts, provide a research portfolio aligned around the Agency's goals, and assist all of EPA's program and regional offices as well as states and Tribes. Where appropriate, the NRPs will combine efforts on the following cross-cutting priorities to conduct research that advances the science and informs public and ecosystem health decisions and community efforts. Although research efforts have been highlighted for each of these cross-cutting priorities, this does not mean that the research efforts only support that priority; the efforts may cut across priorities.

NRPs: Air, Climate, and Energy (ACE); Chemical Safety for Sustainability (CSS); Health and Environmental Risk Assessment (HERA); Homeland Security (HS); Sustainable and Healthy Communities (SHC); and Safe and Sustainable Water Resources (SSWR). The Strategic Research Action Plans for the NRPs are available on ORD's website at epa.gov/research/strategic-research-action-plans-2023-2026.

Environmental Justice

ORD's NRPs will integrate research efforts to identify, characterize, and solve environmental problems where they are most acute, in and with communities that are most at risk and least resilient. Research will strengthen the scientific foundation for actions at the Agency, state, tribal, local, and community levels to address environmental and health inequalities in vulnerable populations and communities with environmental justice and equity concerns. Coordinating research efforts will lead to a better understanding of how health disparities can arise from unequal environmental conditions, including impacts from climate change and exposures to pollution, and inequitable social and economic conditions. By working across NRPs, and through partner engagement, information, tools, and other resources will be developed that help support decision-making and empower overburdened and under-served communities to take action for revitalization.

Integrated Efforts Across National Research Programs	
ACE	Understand inequities in air pollution exposures and impacts, and impacts of climate change, accounting for social, cultural, and economic determinants that can lead to disproportionate exposures and impacts. Develop science to support effective interventions to reduce air pollution exposures and impacts, and adaptation and resilience measures to address climate impacts, including excessive heat (urban heat islands), flooding, and wildfires.
CSS	Investigate factors relevant to exposures for populations experiencing disproportionate adverse impacts from chemical exposures.
HERA	Expand the identification and consideration of information on susceptibility and differential risk in assessments, advance the evaluation of chemical mixtures and improve cumulative risk assessment practices to better characterize and assess health disparities.
HS	Assess and address community needs and vulnerabilities to ensure equitable incident management during disaster response and recovery by analyzing the community-specific cumulative impacts and the social implications of environmental cleanup; and by identifying potential interventions.
SHC	Identify risks and impacts to vulnerable communities and groups and improve the ability of communities to address cumulative impacts from contamination, climate (e.g., natural disasters and extreme events), and other stressors on health and the environment.
SSWR	Help provide clean and adequate drinking water and tools for stormwater management and urban heat island mitigation.

Climate Change

Understanding and addressing climate change impacts to human health and the environment is a critical component of ORD's research. To be effective, climate change research must be scientifically broad and systems-based. Where appropriate, the NRPs will integrate efforts to avoid duplicative efforts, fill critical gaps, and provide results that reflect the multiplicity of impacts and needs associated with climate change. Each NRP recognizes the critical need for continued communication with ORD partners to ensure that we are taking advantage of opportunities for collaboration, integration, and understanding.

Integrated Efforts Across National Research Programs	
ACE	Better understand and characterize air pollution and climate change and their individual and interrelated impacts on ecosystems and public health and identify and evaluate approaches to reduce the impacts of climate change through mitigation of climate forcing emissions, adaptation strategies, and building resilience in communities and ecosystems. Model energy, emissions, and environmental impacts of transformations in the nation's energy, transportation, and building sectors, and identify approaches to increase equitable benefits of those transformations.
CSS	Explore the use of newer analysis methods for identifying chemical contamination in environmental media after large catastrophic environmental events, such as wildland fires.
HERA	Continue development of assessments of air pollutants to inform climate policy efforts and leverage expertise, approaches, tools, and technologies in support of further climate change impact assessments.
HS	Enhance capabilities and develop new information and tools to maximize relevance and support for response and recovery from natural disasters related to climate change.
SHC	Integrated systems-approach research applicable to challenges that communities, including those with contaminated sites, face in preparing for and recovering from the impacts of natural disasters and climate change, ensuring that approaches are beneficial and equitable for the communities at risk.
SSWR	Improve resiliency of water resources and infrastructure to mitigate impacts related to climate change, including coastal acidification and hypoxia, harmful algal blooms, wildland fires, drought and water availability, stormwater flooding and combined sewer overflows, and urban heat islands.

Cumulative Impacts

Addressing the cumulative impacts of exposure to multiple chemical and non-chemical stressors is necessary for EPA to fulfill its mission to protect human health and the environment with the best available science. Cumulative Impacts refers to the total burden—positive, neutral, or negative—from chemical and non-chemical stressors and their interactions that affect the health, well-being, and quality of life of an individual, community, or population at a given point in time or over a period of time. It is the combination of these effects and any resulting environmental degradation or health effects that are the focus of ORD's cumulative impacts research. The NRPs will integrate efforts to improve understanding of cumulative impacts and develop and apply the necessary models, methods, and tools to conduct real-world assessments of cumulative impacts that result in both adverse and beneficial health and environmental effects. With this information, internal and external partners can

make informed, scientifically credible decisions to protect and promote individual, community, and environmental health.

Integrated Efforts Across National Research Programs	
ACE	Develop measurement methods and approaches to characterize ambient air quality and deposition, and human and ecosystem exposures to chemical (including criteria pollutants and air toxics) and non-chemical (including built environment, social, and climate-related) stressors, and health impacts from exposure to the combination of chemical and non-chemical stressors
CSS	Development and application of new approach methodologies to rapidly generate exposure and hazard information for chemicals, chemical mixtures, and emerging materials and technologies (including safer alternatives).
HERA	Research to advance the evaluation of chemical mixtures and improve cumulative risk assessment practices to better characterize and assess health disparities in communities with environmental justice and equity concerns.
HS	Through a focus on resilience equity, ensure that information and tools include the multitude of stressors impacting a community when used to support incident response. Research will recognize that resilience to an incident is directly impacted by the cumulative impacts of the incident and other stressors affecting a community.
SHC	Address the risks and impacts to improve the ability of communities to address cumulative impacts from contamination, climate, and other chemical and nonchemical stressors on health and the environment.
SSWR	Support human health ambient water quality criteria for chemical mixtures through research using bioassays and risk management, and assessment for exposure to groups of regulated and unregulated disinfection byproducts (DBPs) and opportunistic pathogens.

Community Resiliency

It is critical that communities have the knowledge and resources needed to prepare for and recover from adverse situations, such as natural disasters, contamination incidents, and failing infrastructure. Through combined research efforts, the NRPs will provide information and resources that support and empower communities to make science-based decisions to withstand, respond to, and recover from adverse situations.

Integrated Efforts Across National Research Programs	
ACE	Improve evaluations of climate change adaptation and mitigation measures and community resiliency to extreme events in a changing climate, such as wildfire, floods, heat waves, and drought—especially for vulnerable and disadvantaged communities experiencing environmental injustice.
CSS	Efforts relevant to chemical safety evaluations will be leveraged with other NRP activities.
HERA	Continue to expand the portfolio of assessment products to improve understanding of potential human health and environmental impacts of contamination incidents.
HS	Generate resources and tools for environmental cleanup, risk communication, outreach, building relationships, and community engagement to improve equitable community resilience for environmental contamination incidents and other disasters.
SHC	Increase resilience by reducing potential risks, promoting health, and revitalizing communities.
SSWR	Support coastal resilience by advancing monitoring, mapping, and remote sensing and by the economic valuation of coastal resources. Improve the performance, integrity, and resilience of water treatment and distribution systems through research on water infrastructure and water quality models.

Children's Environmental Health

From EPA's 2021 Policy on Children's Health, "children's environmental health refers to the effect of environmental exposure during early life: from conception, infancy, early childhood and through adolescence until 21 years of age." Environmental exposures that impact health can occur before conception, and during pregnancy, infancy, childhood, and adolescence; and include long-term effects on health, development, and risk of disease across lifestages. Much of ORD's research is relevant to communities, including susceptible and vulnerable populations. Where appropriate, the NRPs will combine efforts to conduct research that will inform public health decisions, advance our scientific understanding of early-life susceptibility to environmental stressors, and inform community efforts that create sustainable and healthy environments protective of all lifestages.

Integrated Efforts Across National Research Programs	
ACE	Explore air pollution and climate health impacts within different lifestages and populations, including overburdened groups. Assess vulnerabilities to air pollution for those with chronic illnesses and sequelae from respiratory viruses. Research social determinants of health, and air pollution impacts resulting from different exposure time-activity patterns.
CSS	Research will build the scientific foundation to predict adverse outcomes resulting from chemical exposures in various biological contexts, including early life-stage susceptibility.
HERA	Continue to evaluate health effects, over the course of a lifetime, from environmental exposure to stressors during early life (i.e., from conception to early adulthood) to inform decision-making and advance research on methods to properly characterize risks to children.
HS	Improve and develop decision-support tools and cleanup capabilities to make children less vulnerable during response to, and recovery from, contamination incidents.
SHC	Address the risks and impacts to vulnerable communities and lifestages, including underserved/overburdened communities, and improve the ability of communities to address cumulative impacts from contamination, such as site clean-ups of per- and polyfluoroalkyl substances (PFAS) and lead; climate, such as natural disasters and extreme events; and other stressors on health and the environment.
SSWR	Evaluate health effects and toxicity related to algal toxins and expanded research that will explore exposure risks for lead, DBPs, and—through quantitative microbial risk assessment models—for high priority opportunistic pathogens in drinking water (e.g., *Mycobacterium*, *Pseudomonas*, *Naegleria fowleri*).

Contaminants of Immediate and Emerging Concern

Contaminants of immediate and emerging concern (CIECs) include chemical substances that may cause ecological or human health impacts and are either new or existing contaminants of increased priority. The NRPs will work with EPA partners in the program and regional offices, along with input from Agency leadership, to identify the highest priority contaminants (broadly defined to include chemical, biological, and other

categories as appropriate), including those of immediate concern, such as PFAS and lead, that warrant further research attention.

Integrated Efforts Across National Research Programs	
ACE	Develop and evaluate measurement methods and approaches to characterize sources of air pollutants and climate forcing pollutants, such as measurement of emissions of criteria pollutant precursors and air toxics, including emerging concerns, such PFAS and EtO.
CSS	Continue to develop new approach methods for CIECs with a focus on applying these, as appropriate, for prioritization, screening, and risk assessment for decision making.
HERA	Continue and expand the portfolio of assessment products, as well as advance risk assessment models and tools, to better characterize potential human health and environmental impacts of new and existing contaminants.
HS	Predict the movement of chemical, biological, and radiological contaminants in the environment resulting from environmental contamination events and develop tools and methods for effective characterization, decontamination, and waste management.
SHC	Advance site clean-ups of PFAS and lead to protect vulnerable groups, especially children.
SSWR	Research on PFAS, including innovative drinking water and wastewater treatments, support for future drinking water regulations, the development of aquatic life criteria, management in water resources, and evaluation of land-applied biosolids; contaminants of emerging concern (CECs), lead, opportunistic pathogens, and DBPs in drinking water; cyanobacterial metabolites other than microcystin (e.g., anatoxin, saxitoxin, and nodularin); microplastics in sediments and surface water; and CECs (non-PFAS) in wastewater treatment systems and biosolids.