PRELIMINARY DRAFT NOTICE: This Crosscutting Roadmap, 2016 – 2019, is a preliminary draft. It has not been formally released by the U.S. Environmental Protection Agency (EPA) and should not at this stage be construed to represent Agency policy, nor the final research program.

Climate Change Research Roadmap

Crosscutting Roadmap

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Executive Summary

Climate Change, along with Environmental Justice, Nitrogen and Co-pollutants, and Children's Environmental Health, is one of four topics having a formal roadmap that cuts across the six National Research Programs. This *Climate Change Research Roadmap* presents an overarching, integrated vision of science in the U.S. Environmental Protection Agency's (EPA) Office and Research Development (ORD) that supports the Agency in protecting human health and the environment in the face of climate change. The Roadmap places climate change science in the six National Research Programs—recent, ongoing, and planned—in the context of this vision, identifying major focus areas, opportunities for integration, and critical research gaps to inform the evolution of ORD's Strategic Research Action Plans (StRAPs). It highlights EPA's unique role within the overall Federal portfolio for climate research—in partnership with the other Federal agencies comprising the U.S. Global Change Research Program (USGCRP)—as the agency primarily responsible for protecting human health and safeguarding all aspects of the environment, air, water, natural ecosystems, and land.

"Addressing Climate Change and Improving Air Quality" is one of five strategic goals in *Fiscal Year 2014–2018, EPA Strategic Plan* because climate change directly impacts the Agency's mission to protect human health and the environment, and because EPA has a principal role in developing policies and regulations for its control. The purpose of ORD's research on climate change is to advance the understanding of its impacts on environmental media and systems by (1) supporting Agency planning and rulemaking; (2) informing the development and implementation of greenhouse gas (GHG) regulations; and (3) identifying sustainable solutions for the causes and consequences of climate change, including the environmental impacts of response strategies. Fulfilling these mandates necessitates that EPA harness the best-available science on climate change and its impacts through a research program that integrates EPA's unique strengths in the study of air quality, water quality, human health, and ecosystems with cutting-edge climate science carried out by our partner Federal agencies. Close coordination with partners and stakeholders must be a priority, so that the research most needed by EPA's Program and Regional Offices and their State and local stakeholders for supporting responses and managing climate risks can be identified, designed, and conducted.

A critical charge for EPA science is to characterize the specific and system-wide risks associated with climate change so that appropriate, informed response options can be developed. The nature of the climate change problem, however, presents significant challenges that must be overcome:

- Climate change calls into question the fundamental assumption of stationarity, which is compounded by large uncertainties associated with future climate change and its impacts.
- Climate change impacts are likely to be the result of complex interactions among climatic stressors and other, non-climatic stressors that also change over time.
- The climate change problem challenges our ability to value impacts quantitatively, in support of key tools such as benefit-cost analysis.

- Without major restructuring of our energy system, rapidly increasing global temperatures in the coming decades likely will have impacts beyond what we consider societally manageable.
- Restructuring our energy system likely will itself result in challenges for environmental health and human well-being that will need to be managed.
- Climate change is fundamentally a socioenvironmental problem, and addressing it fully and in a way that supports effective societal responses will require integrating the full range of perspectives and contributions from the social, behavioral, and economic sciences.

This Roadmap puts forward a climate research portfolio for ORD to address these issues, organized around three Science Challenges that directly respond to the needs of ORD's Program and Regional Offices.

Science Challenge 1. *Develop the knowledge base to support planning in the Program and Regional Offices to maintain water quality, air quality, the health and welfare of people and their communities, and ecosystems, in the face of non-stationarity in the climate system and uncertain future changes in key variables such as temperature, precipitation, and sea level.*

Science Challenge 2. *Inform the development, implementation, and benefits assessment of GHG control regulations through improved understanding of current and future U.S. emissions, the aggregate impacts of climate change across regions and sectors, and the mutual co-benefits of air quality and GHG regulatory actions and a changing energy system.*

Science Challenge 3. *Identify and evaluate long-term, sustainable solutions for both the causes and consequences of climate change, including assessing the environmental impacts of emerging energy technologies and climate change adaptation and mitigation approaches, improving understanding of the nature of resilience in natural and human systems, and exploring the key role of communities as the nexus of both vulnerability and responses.*

Broadly, these Science Challenges refer to the research needed to inform (1) *adaptation* actions to enhance resilience across a broad range of environmental and social stresses, (2) *mitigation* actions to limit GHG emissions and slow the rate of climate change, and (3) the transition to *sustainability* across the full spectrum of climate change impacts and solutions. These "big bins" of ORD climate research span media and systems, highlighting both the crosscutting nature of climate change and the need to address climate impacts across EPA programs. Because the boundaries between these Science Challenges are fluid, ORD's evolving climate change research portfolio also encompasses the critical intersections between them.

This Roadmap presents ORD's current research and that planned in the StRAPs, within and across these Science Challenges and subdivided as appropriate by media or system (e.g., air, water, land, ecosystems, human health, communities). It also articulates outstanding scientific issues that currently challenge ORD in fully meeting the needs of its Program and Regional Office partners. These gaps relate to the lack of process-level understanding for key media- or system-specific problems. They also relate to needs for exploring particularly critical integrated science problems more fully, such as the intersection between climate, wildfires, air quality, and health. Further, they relate to missing perspectives from the social sciences that would support improved problem formulation and move research into action around concrete decisions and policies for responding to the threat of climate change.

This Roadmap also highlights examples of, and opportunities for, integration across the research portfolio on climate change. Integration across individual research efforts is critical for several reasons, including not only the fundamentally integrated nature of the climate change problem but also the need for consolidation and centralization to serve, most efficiently, the decision support needs of Program and Regional Office partners. Multiple dimensions of integration are important in the context of ORD climate research, beginning with the identification of common needs across Program and Regional Offices and the need to support decision-making across multiple media or managed systems over different spatial and temporal scales. Integration across the different modes of research within the overall portfolio is also critical: from work that provides the foundation for or is applied within other projects and tasks, to work that resides at the boundary between ORD and the Program and Regional Offices and therefore carries primary translational responsibilities for ORD climate change research.

Going forward, ORD's research endeavor on climate change must continue to evolve toward a wholly integrated effort embodying the following guiding principles:

- Predicated on a *systems* science approach that prioritizes research that is inherently cross-media, cross-scale, and cross-discipline.
- Explicitly considers the *social* dimensions of change, both as part of the fundamental socioenvironmental nature of climate change as a science problem and as an essential element for moving the results of that science into action.
- Focuses ultimately on *solutions* to the threat climate change poses to EPA's mission and to society, moving from the current focus on risk identification and characterization to the science needed to support responses.

These principles are major integrative elements that cut across the three Science Challenges. They provide context for understanding the most important gaps, opportunities, and priorities for ORD's climate change research going forward:

- meeting the near- and long-term needs of ORD's partners to inform adaptation actions that will enhance resilience across a broad range of environmental and social stresses;
- informing mitigation actions to limit GHG emissions and slow the rate of climate change; and
- supporting the transition to sustainability in the face of both the transformational impacts and transformational responses that will characterize the problem of climate change over the long term.

I. Introduction

Climate Change, along with Environmental Justice, Nitrogen and Co-pollutants, and Children's Environmental Health, is one of four topics having a formal roadmap that cuts across the six National Research Programs. The U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD) identified these crosscutting topics as needing in-depth, formal roadmaps to enhance program coordination and integration. This *Climate Change Research Roadmap* presents an overarching, integrated vision of science in ORD that supports the Agency in protecting human health and the environment in the face of climate change. The Roadmap places climate change science in the six National Research Programs—recent, ongoing, and planned—in the context of this vision, identifying major focus areas, opportunities for integration, and critical research gaps to inform the evolution of ORD's Strategic Research Action Plans (StRAPs). It highlights EPA's unique role within the overall Federal portfolio for climate research, in partnership with the other Federal agencies comprising the U.S. Global Change Research Program (USGCRP). Further, the Roadmap elucidates how EPA leverages this interagency research expertise to advance understanding of climate change and its impacts and responses in the context of EPA's mission as the Federal agency primarily responsible for protecting human health and safeguarding all aspects of the environment, including air, water, natural ecosystems, and land.

A. Background

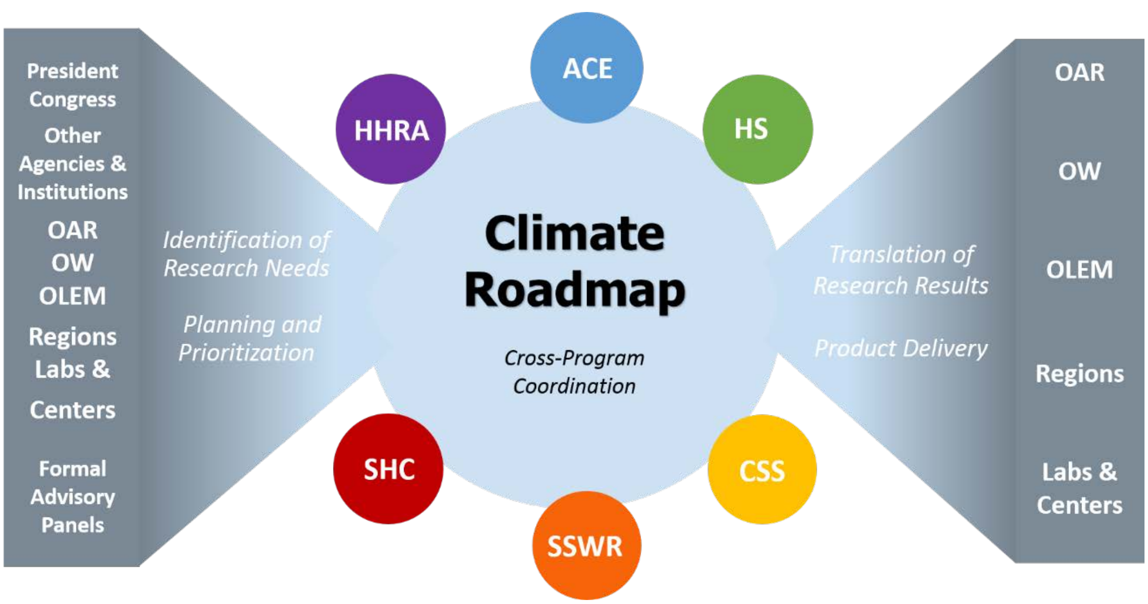
Climate change as an issue will continue to grow in importance and visibility for the Agency, and taking action on climate change is a major strategic priority for EPA. "Addressing Climate Change and Improving Air Quality" is one of five strategic goals in *Fiscal Year 2014–2018, EPA Strategic Plan* because climate change directly impacts the Agency's mission to protect human health and the environment, and because EPA has a principal role in developing policies and regulations for its control. The Strategic Plan specifically calls on the Agency to minimize the threats posed to public health and the environment by acting to reduce greenhouse gas (GHG) emissions and helping communities and ecosystems become more sustainable and resilient in the face of climate change impacts.[1]

This mandate also is reflected in several major executive actions the current Administration has recently implemented. The President's Climate Action Plan (PCAP) urges the Nation to reduce GHG emissions, prepare for climate change impacts, and provide international leadership on global solutions to meet this threat.[2] The plan directs EPA to work closely with states, industry, and other stakeholders to establish carbon pollution standards for new and existing power plants and to help communities take action on climate change. The PCAP builds on the President's 2009 Executive Order 13514 requiring EPA to develop an Agency-wide Climate Change Adaptation Plan to ensure EPA can achieve its mission under a changing climate.[3] This Adaptation Plan and the 17 Office-specific Climate Adaptation Implementation

[1] https://www.epa.gov/planandbudget/strategicplan
[2] https://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf
[3] https://www.whitehouse.gov/assets/documents/2009fedleader_eo_rel.pdf

Plans identify key climate-related risks to EPA's mission and highlight corresponding research needs for understanding and responding to climate change.

Fulfilling these mandates necessitates that EPA harness the best-available science on climate change and its impacts to inform Agency decisions and actions. Doing so requires a research program that integrates EPA's unique strengths in the study of air quality, water quality, human health, and ecosystems with cutting-edge climate science carried out by our partner Federal agencies. The research program also must work closely with partners and stakeholders, both within the Agency and externally, to identify and conduct the research needed to make real progress on responses to climate change. EPA's Program and Regional Offices are responsible for developing and implementing regulations and other actions in accordance with Federal environmental laws, many of which are now, and increasingly will be, influenced by climate change issues. ORD thus works closely with the Office of Air and Radiation (OAR), Office of Water (OW), Office of Land and Emergency Management (OLEM), Office of Chemical Safety and Pollution Prevention (OCSPP), Regional Offices, and other key partners and stakeholders in EPA to understand their highest priority climate-related research needs and those of their State and local stakeholders. The research articulated in this Roadmap directly reflects those priorities. The Roadmap spans ORD research programs, Laboratories, and Centers to help coordinate and consolidate that research and guide translation and delivery of its outputs to meet the needs of ORD's Program and Regional Office partners and the networks of State and local stakeholders they serve. Externally, EPA's Science Advisory Board (SAB) and the ORD Board of Scientific Counselors (BOSC) provide independent, expert guidance on the near-term and long-term climate-related science issues they perceive as critical to EPA. Figure 1 illustrates how the Roadmap reflects coordinated input from ORD's research partners, external research organizations, and advisory groups to provide consolidated guidance on climate change research needs and priorities to the ORD research programs.



HHRA = Human Health Risk Assessment, ACE = Air, Climate, and Energy, HSRP = Homeland Security, SHC = Sustainable and Healthy Communities, SSWR = Safe and Sustainable Water Resources, CSS = Chemical Safety for Sustainability

Figure 1. Schematic of the role of the Climate Change Research Roadmap

B. The Challenge of Climate Change for EPA's Mission

Over the next few decades, climate change is expected to intensify current air and water quality issues and increase stresses on ecosystems and human 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, and rising seas. It also will involve assessing the systemic environmental threats to the Nation that unchecked climate change poses and designing and implementing actions to mitigate these threats. Characterizing the specific and system-wide risks associated with climate change so that appropriate response options are developed is therefore a critical charge for EPA science. The unique nature of the climate change problem presents significant challenges for this effort that ultimately must be overcome if the Agency is to maximize the efficiency and effectiveness of its policy and decision-making in the face of these threats.

> *Climate change threatens air and water quality and the health of people, ecosystems, and communities.*

Developed over a long and successful application to critical environmental problems, risk assessment methods, practices, and tools have provided the foundation for EPA's ability to leverage the best-available science in meeting its mission to protect human health and the environment. Combining approaches and methodologies from fields such as human exposure research and epidemiology, the risk assessment paradigm has served the Agency well, helping identify hazardous exposures in populations and ecosystems to air toxins and other chemicals in the environment. Nevertheless, the expected impacts of global climate change, now and into the future, challenge traditional risk assessment in fundamental ways.

First, climate change calls into question the assumption of *stationarity*, which underpins a wide array of risk assessment tools and methods.[4] That the future is a close analogue of the past, and that past conditions therefore provide the basis for projecting future impacts and developing corresponding policy and regulatory responses, can no longer be assumed. Increasingly, background weather and climate conditions will move beyond the envelope within which all of EPA's regulations and environmental management practices have been developed and implemented. Climate change also is likely to alter causal links between meteorological or hydrological processes and subsequent health and ecosystem effects. Further, because climate change is a global phenomenon—potentially affecting everything, everywhere, with impacts that are ubiquitous in terms of geographic region, ecosystem type, population group, and socioeconomic sector—the inability to rely on stationarity cuts across all media and systems relevant to EPA's mission, as well as traditional media-specific regulatory boundaries.

[4] Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer, 2008: Stationarity is dead: Whither water management? *Science*, **319**, 573-574.

Second, this challenge is compounded by the large and often poorly characterized uncertainties associated with future climate change and its impacts.[5] These uncertainties result from lack of predictability of climate change due to inadequate understanding of key climate system processes and forcings, including potentially large and poorly understood climate feedbacks, the uncertain trajectory of future GHG emissions, and natural, internal variability of the climate system. The limits on climate system predictability are experienced most strongly at precisely the space and time scales most relevant for environmental management, such as the regional and local scales of watersheds and communities, or for short-term extremes such as stagnation episodes and heavy rainfall events. What this means in practical terms is, not only is the past no longer a reliable guide to the future, but also our ability to project into the future through other means, such as model simulations, is also limited. In other words, we can no longer rely on historical probability distributions in our Monte Carlo simulations, benefit-cost analyses, or related tools and methods, nor do we have a ready replacement. Exploring and creating novel risk assessment and risk management approaches are necessary to overcome these constraints.[6]

Climate change poses unique challenges for the foundational tools EPA uses to implement its mission, such as risk assessment and benefit-cost analysis.

Third, even if feasible analytically, basing long-term planning on expected or “best-guess” future values might no longer be desirable. In fact, wisdom might dictate transitioning to planning approaches based on limiting the risks of catastrophic damages.[7] What is clear is that climate change will shift the distributions of key state variables like temperature, significantly increasing the frequency of extreme meteorological conditions locally, as well as the potential for “worst-case” scenarios regarding ice melt and carbon cycle feedbacks.[8] This shift is critically important for assessment and management of risk, given that the distributions of possible outcomes for climate-related risks are highly asymmetric and heavily skewed toward low-probability conditions and events with large consequences.

Fourth, the impacts of climate change result not from the direct toxicity of GHGs but through the diversity of effects due to warming-induced shifts in weather patterns and baseline climatic conditions. Such shifts can be direct (e.g., flooding due to heavy rainfall or sea level rise) or indirect (e.g., changes in ecosystem structure and function), each of which can affect human health and human systems.[9] Although the proximal effect of increasing GHG emissions is a global increase in GHG concentrations and global mean temperature, the impacts are local and highly spatially heterogeneous, with the populations experiencing the greatest impacts often not those generating the most significant GHG emissions. Furthermore, climate change impacts on a particular management endpoint will be the result

[5] Lempert, R., N. Nakicenovic, D. Sarewitz, and M. Schlesinger, 2004: Characterizing climate-change uncertainties for decision-makers. *Climatic Change*, **65**, 1-9.
[6] Weaver, C.P., R.J. Lempert, C. Brown, J.A. Hall, D. Revell, and D. Sarewitz, 2013: Improving the contribution of climate model information to decision-making: The value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews Climate Change*, **4**, 39-60.
[7] Kunreuther, H., G. Heal, M. Allen, O. Edenhofer, C.B. Field, and G. Yohe, 2013: Risk management and climate change. *Nature Climate Change*, **3**, 447-450.
[8] National Research Council, 2013: *Abrupt Impacts of Climate Change: Anticipating Surprises*. National Academies Press, 188 pp.
[9] Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, 841 pp.

of complex interactions among these climatic stressors and other, non-climatic stressors that also change over time. These interactions include the intersection between phenomena occurring over multiple space and time scales: for example, the implications for terrestrial ecosystems of an increasing frequency of heat waves, leading to heat stress, drought, and vegetation-damaging high ozone events, combined with a longer growing season and expanding ranges of pest and invasive species. Also included are interactions between the impacts of a changing climate and socioeconomic trends, such as in population and demographics, land use, economic growth, technological innovation, and even adaptation responses to climate change. The interconnectedness of myriad natural and human systems means that many of the potentially greatest risks of climate change will be driven by cascading impacts and feedbacks among these interlinked components in ways that are very difficult to anticipate. These degrees of complexity confound simple causation models, making the development of robust exposure assessments and risk characterization in support of rulemaking much more difficult.

Fifth, the climate change problem challenges our ability to value impacts quantitatively in support of key tools such as benefit-cost analysis.[10] For example, because of the all-encompassing nature of climate change, some impacts, such as loss of cultural heritage, are likely intangible (i.e., without physical substance) and therefore difficult to define, quantify, and measure. In addition, the most severe climate change impacts challenge fundamental assumptions of marginality, along with other core precepts of economic analysis, and are thus very difficult to capture accurately as damage functions in large-scale economic models. Further, because of the long lag built into the climate system (e.g., between emissions and the experience of the largest impacts), the consequences of both climate change, and the policy choices made today in response, will span decades to generations. The result is an unprecedented degree of long-range thinking that will be required in policy and planning, with close attention paid to the challenging economic problems of intergenerational equity and discounting.[11]

The inertia of the climate system is such that impacts are projected to remain manageable, if increasingly severe, for the next few decades for all reasonable scenarios of GHG emissions. Beyond this time, however, as cumulative GHG concentrations continue to build in the atmosphere, rapidly increasing global temperatures will begin to drive changes in extreme weather, sea level, and ecosystem response that are likely to have impacts beyond what we now consider societally manageable.[12] Avoiding the worst of these impacts, and averting potentially catastrophic tipping points in physical, biological, and socioeconomic systems, implies that within a few short decades we will need to restructure our energy system to bring emissions of GHGs rapidly to zero. This enormous undertaking itself will profoundly affect society and the environment. Because of the interconnectedness of natural and human systems, the environmental effects of technologies and interventions deployed to mitigate the causes of climate change likely will create challenges for environmental health and human well-being that also will need to be managed. In other words, we soon will be faced with either

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[10] Sussman, F., C.P. Weaver, and A.E. Grambsch, 2014: Challenges in applying the paradigm of welfare economics to climate change. *Journal of Benefit-Cost Analysis*, **5**, 347-376.
[11] Heal, G., 2009: The economics of climate change: a post-stern perspective. *Climatic Change*, **96**, 275-297.
[12] Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, **105**, 1786-1793.

transformational impacts or transformational responses (or a combination thereof), and either will challenge EPA's mission in ways that transcend any policy or regulatory precedent.

Implicit throughout the above discussion is the need to understand linked biophysical and social processes of change, and to do so in a way that supports societal responses to this change. This means that addressing the challenge of climate change within EPA will require integrating the full range of disciplinary perspectives and contributions from across the scientific enterprise, including the disciplines spanning the social, behavioral, and economic sciences. After all, it is people, and their communities, institutions, and governments, who are the drivers of climate change. In addition, climate change impacts ultimately depend on social context, and climate change solutions, both in terms of reducing emissions and increasing resilience, will require greater understanding of how decisions are made by individuals and communities, the key characteristics of socioenvironmental systems that lead to reduced vulnerability and enhanced resilience to climate change impacts, and the nature of sustainable environmental management under conditions of change, transition, and transformation. This Roadmap thus explicitly recognizes that the social sciences (1) are an important part of the integrated knowledge base for understanding the causes of, consequences of, and solutions for climate change and its impacts; and (2) can identify the principles that will help put this knowledge to work for EPA and society.[13]

These aspects of the climate change problem as it intersects with EPA's mission to protect human health and the environment define the space for ORD's climate research effort. The following sections of this *Climate Change Research Roadmap* describe the scope of current and planned ORD research to address this challenge, in the context of the needs articulated by ORD's partners, and highlight critical gaps and needed new research directions to inform ORD's StRAPs continuously as they evolve.

II. Research Scope

This section describes the expanded problem statement for climate-related research across ORD's National Research Programs. Three Science Challenges associated with addressing the overarching problem are then identified and briefly explained. Finally, the section addresses how the research needed to address the Science Challenges is aligned across the National Research Programs, in coordination with the other crosscutting roadmaps, and with other Federal agencies.

A. Expanded Problem Statement

The impacts of climate change threaten the Nation's health, economy, security, and overall wellbeing. Climate change is an issue central to EPA's mission, both because of its direct impacts on air quality, water quality, communities, and ecosystems, and because of EPA's primary role in developing policies and regulations to control it. Responses to climate change, whether to minimize GHG emissions or to prepare for and adapt to climate change impacts, also will affect the environment. The purpose of ORD's climate change research is therefore to advance understanding of the impacts of climate change on

[13] Weaver, C.P., S. Mooney, D. Allen, N. Beller-Simms, T. Fish, A.E. Grambsch, W. Hohenstein, K. Jacobs, M. Kenney, M.A. Lane, L. Langner, E. Larson, D.L. McGinnis, R.H. Moss, L.G. Nichols, C. Nierenberg, E.A. Seyller, P.C. Stern, and R. Winthrop, 2014: From global change science to action with social sciences. *Nature Climate Change*, **4**, 656-659.

public health and environmental media and systems to support Agency planning and rulemaking; to inform the development and implementation of GHG regulations; and to identify sustainable solutions for the causes and consequences of climate change, including the environmental impacts of response strategies.

B. Science Challenges

As articulated above, climate change poses significant near- and long-term challenges to EPA's mission and to the traditional methods and practices by which EPA conducts science-informed policy and decision-making. This Roadmap presents a climate research portfolio through which ORD will address these challenges, organized around three distinct Science Challenges that directly respond to the needs of ORD's Program and Regional Office partners.

Science Challenge 1. *Develop the knowledge base to support planning in the Program and Regional Offices to maintain water quality, air quality, the health and welfare of people and their communities, and ecosystems, in the face of non-stationarity in the climate system and uncertain future changes in key variables such as temperature, precipitation, and sea level.*

Science Challenge 2. *Inform the development, implementation, and benefits assessment of GHG control regulations through improved understanding of current and future U.S. emissions, the aggregate impacts of climate change across regions and sectors, and the mutual co-benefits of air quality and GHG regulatory actions and a changing energy system.*

Science Challenge 3. *Identify and evaluate long-term, sustainable solutions for both the causes and consequences of climate change, including assessing the environmental impacts of emerging energy technologies and climate change adaptation and mitigation approaches, improving understanding of the nature of resilience in natural and human systems, and exploring the key role of communities as the nexus of both vulnerability and responses.*

Broadly, these Science Challenges refer to the research needed to inform (1) *adaptation* actions to enhance resilience across a broad range of environmental and social stresses, (2) *mitigation*[14] actions to limit GHG emissions and slow the rate of climate change, and (3) the transition to *sustainability* across the full spectrum of climate change impacts and solutions. These "big bins" of ORD climate research span media and systems, highlighting both the crosscutting nature of climate change and the need to address climate impacts across EPA programs. Each Science Challenge can be disaggregated, as appropriate, into media-specific (or media-spanning) research activities relevant to that Challenge. To support EPA's needs fully in responding to climate change, the work completed under these Challenges will need to represent a balance across different modes of research, including model development, synthesis and assessment, development of decision support tools, and long-term exploratory research in

[14] In the context of climate change, "mitigation" generally refers to GHG reductions and changes in land use and cover designed to reduce the magnitude of climate change. In other contexts, mitigation might focus on reactive responses to the impacts of an environmental stressor; here we consider such responses to climate change effects to fall under the broad heading of adaptation.

anticipation of future partner needs. It also must represent consultation and science translation around ORD data, tools, and findings.

The boundaries between these Science Challenges are fluid. For example, quantitatively assessing the range of benefits of GHG regulation to inform mitigation policy, under Science Challenge 2, will require leveraging the full suite of media-, system-, and sector-focused climate impacts research carried out under Science Challenge 1. Similarly, research related to vulnerability, resilience, and sustainable adaptation options and practices provides a critical bridge between Science Challenges 1 and 3. These intersections are discussed further in the sections below.

As described above, the challenges climate change poses to environmental protection and management are most appropriately characterized as *socioenvironmental* challenges,[15] rather than simply problems for the environmental sciences. Because EPA's mission is inherently for societal benefit, the Agency's actions on climate change are defined by the role that society plays in exacerbating or alleviating the impacts that arise in combination with the biophysical aspects of the problem. Thus, the need is strong for systematic, targeted integration of expertise from across the range of social, behavioral, and economic science disciplines into each of the three Science Challenges. Although some effort has been made to add a social sciences dimension to research programs through, for example, incorporation of socioeconomic status as a variable of interest, a much more comprehensive range of social sciences knowledge is needed and a much greater degree of integration is called for. In particular, the social sciences are essential for helping structure and guide the ways in which physical or natural science is deployed in search of policy or resource management answers. This premise has been recognized recently by the BOSC, which called for ORD to expand the use of social sciences as part of its overall research program. Similarly, USGCRP and the National Academies also encouraged consideration of the social sciences in the broader U.S. Federal climate research enterprise. Integrating social sciences also aligns with a recent Executive Order[16] calling on Federal agencies to seek ways to use social sciences principles to improve the effectiveness and efficiency of policies and programs. This Roadmap therefore considers ORD's current efforts to integrate the social sciences within its climate research portfolio and the ways in which ORD will need to expand on those efforts to ensure critical contributions from the social sciences are not overlooked. The proposed path forward begins with the principle that the most effective approach is to integrate social science perspectives and expertise at the stage of research problem formulation, rather than as a later addition to an ongoing effort.

Integration of the social sciences at the problem formulation stage of research carried out under each of these three Science Challenges will be critical for achieving the goals of this Roadmap.

[15] Hubbell, B., 2016: Strengthening the Foundation for Interdisciplinary Social-Environmental Research in ACE. ORD/ACE White Paper, EPA-601/R-16-003. Draft in review.
[16] E.O. 13707: "Using Behavioral Science Insights to Better Serve the American People" (https://sbst.gov/uploads/exec-order-signed.pdf).

C. Research Alignment and Coordination

The development of this research portfolio is guided by the StRAPs prepared for each of the six National Research Programs within ORD. The portfolio illustrates how ORD applies its expertise in the arenas of air and water quality, ecosystem behavior and services, and community and environmental health in the context of a changing climate. To meet the Science Challenges that fall to ORD, climate-related research is conducted as part of these six Programs, at this time primarily within the Air, Climate, and Energy (ACE) and Safe and Sustainable Water Resources (SSWR) Research Programs. Climate-related research is also embraced in the Sustainable and Healthy Communities (SHC), Homeland Security (HSRP), Human Health Risk Assessment (HHRA), and Chemical Safety for Sustainability (CSS) Research Programs, but it currently comprises a smaller fraction of those Research Programs at present. In general, work in ACE focuses on air quality-climate interactions; emissions; energy systems; climate change impacts on watersheds and ecosystems; development of climate, population, land use, and other climate-relevant scenarios; and decision support methods and tools. Complementing this work, SSWR investigates climate change impacts as one of several stressors on aquatic ecosystems, watersheds, and drinking water and wastewater infrastructure, with a focus on preparedness and adaptation. SHC focuses on community-level information and decision tools that incorporate climate change as a multiplying stressor and conducts research on the vulnerability and resilience of human systems in this multistressor context. HSRP focuses on the resilience of water systems to disasters, including those caused by climate change. HHRA incorporates climate change considerations into evaluations of human health risks of exposure to pollutants. CSS research considers the impacts of new compounds that might be introduced in the environment or existing compounds whose adverse effects might be increased because of climate change or responses (Table 1).

Table 1. Key Climate-Related Research Topic Areas across the National Programs*

Research Topic	ACE	CSS	HHRA	HSRP	SHC	SSWR
Water Quality and Aquatic Ecosystems	✓✓		✓	✓	✓	✓✓✓
Air Quality	✓✓✓		✓			
Human Health	✓✓✓		✓✓		✓	✓
Ecosystems and Land	✓				✓✓✓	✓
Mitigation and Associated Environmental Impacts	✓✓		✓		✓	✓
Social Science	✓✓	✓	✓	✓	✓✓	✓
Uncertainty	✓	✓	✓	✓	✓	✓

* More checkmarks indicate a relatively larger contribution to research in a particular science challenge area.

Within the three overarching Science Challenges, the current ORD portfolio has the most work related to Science Challenge 1, followed by Science Challenge 2. Research related to Science Challenge 3 is just beginning. Over the long term, we expect the portfolio to evolve, with substantial new research in Science Challenge 3 in particular, with its focus on sustainable solutions to climate change. This sustainable solutions research will provide significant opportunities (and a critical need) for increasing integration of SHC, CSS, HHRA, and HSRP into the overall ORD climate research portfolio.

Research coordination also extends across the other crosscutting roadmaps (Children's Environmental Health, Environmental Justice, and Nitrogen and Co-pollutants). The need to consider the impacts of climate change on vulnerable populations highlights the connections between this *Climate Change Research Roadmap* and those for Children's Environmental Health and Environmental Justice. As noted in the *Environmental Justice Roadmap*, Tribal communities could be more vulnerable and disproportionately impacted by climate change, especially when it disrupts their ability to depend on surrounding ecosystems for food sources, cultural practices, and unique lifestyles. Other environmental justice communities also are expected to face disproportionate risks from the impacts of climate change, as are children in all communities. In addition, anthropogenic alteration of the nitrogen cycle interacts in many complex ways with climate change, with profound implications for ecosystems.[17] Coordination of work across research programs requires ongoing efforts to ensure these crosscutting issues are effectively incorporated into research design and activities.

Communication of the research needs of ORD's Program and Regional Office partners is essential for helping define a relevant research portfolio for climate change that produces actionable knowledge, information, data, and tools to support the many facets of EPA's mission. The development of the StRAPs is at the core of these partner engagement efforts, building on annual, in-depth discussions between National Research Program teams and relevant partner offices to plan upcoming research activities. ORD and its programmatic partners across all organizational levels engage in regular discourse. Partner Alliance and Coordination Teams (PACTs) have been initiated across ORD's programs to provide a structured venue for interactions between ORD and its EPA partners at the research project level. Quarterly, monthly, and weekly discussions, as appropriate, allow for formal and informal exchanges of perspectives, results, and issues. Program teams provide guidance and input to the strategic and annual planning efforts of other research programs, and crosscutting topic leads review and contribute to the planning of each program. **Appendix C** presents a table of identified research needs that have emerged from these focused discussions. The research needs reflect the issues a given Office is currently facing, or expects to be facing in the near future, and for which additional scientific information is needed to inform decisions. The EPA Climate Change Adaptation Plan and the Adaptation Implementation Plans developed by each EPA Office provide additional context for these research needs. The research articulated in this Roadmap directly reflects these priorities.

This Roadmap also illustrates how EPA leverages the research carried out under the auspices of the other Federal agencies engaged in the broader climate science enterprise. These agencies include the National Oceanic and Atmospheric Administration (NOAA); Department of Energy (DOE); National Aeronautics and Space Administration (NASA); National Science Foundation (NSF); Department of Agriculture (USDA); U.S. Geological Survey (USGS) and other Department of Interior (DOI) bureaus and

[17] Greaver, T.L., C.M. Clark, J.E. Compton, D. Vellano, A.F. Talhelm, C.P. Weaver, L.E. Band, J.S. Baron, E.A. Davidson, C.L. Tague, E. Felker-Quinn, J.A. Lynch, J.D. Herrick, L. Liu, C.L. Goodale, K.J. Novak, and R.A. Haeuber, 2016: Key ecological responses to nitrogen are altered by climate change. *Nature Climate Change*, **6**, 836-843.

services; and others. ORD's unique research responsibilities focus on scientific topics that directly affect air quality, water quality, waste management, ecosystems, and human health. Because climate change research is scientifically broad and must be systems-based, however, EPA relies on these external partners to provide critical aspects of fundamental understanding for those areas falling outside the scope of EPA's legislated authorities or for which other agencies have been assigned the lead. This interagency leveraging and coordination is primarily carried out under the auspices of USGCRP, within which EPA is one of 13 Federal agencies that contribute to an integrated portfolio of climate change research designed to "understand, assess, predict, and respond to human-induced and natural causes of global change," as mandated by the Global Change Research Act of 1990.[18]

> *EPA is a key participant in the interagency U.S. Global Change Research Program (USGCRP), which is directed to implement and coordinate research to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."*

At the working level, USGCRP coordinates the activities of more than a dozen working groups that foster cross-agency integration and collaboration among research programs, with active participation from ORD staff and staff from other EPA Offices (see **Appendix D**). The ACE Associate Director for Climate serves as the EPA Principal to the Committee on Environment, Natural Resources, and Sustainability (CENRS), Subcommittee on Global Change Research (SGCR), which provides oversight for and strategic guidance to USGCRP. Through these mechanisms, ORD can leverage the evolving knowledge base of companion USGCRP agencies that conduct research addressing the fundamental science underlying climate-related shifts in atmospheric and oceanic circulation, extreme weather events, the carbon cycle, fish and wildlife habitats, water supply risks, transportation, energy production and demands, and agriculture, among others.[19]

ORD integrates its unique strengths in water and air quality, human health, and ecosystem research with this cutting-edge climate science. Critically, EPA interpretation of climate science is necessarily from a risk-based perspective, which has important implications for the specific demands EPA makes on the Federal climate research it leverages. These demands are rooted in the explicit recognition that characterizing scientific uncertainty about the nature and severity of future climate change might be quite different from assessing the associated societal risks, which will depend strongly on the unique vulnerabilities of people, human systems, and critical ecosystem services. As discussed, such risks will often tend to be dominated by low-probability but high-consequence events. EPA's perspective also requires evaluating the impacts of regulatory or other programmatic actions in light of these changing risks. In turn, EPA makes significant contributions to USGCRP by adding value to the primary climate research and increasing its societal relevance, and by grappling rigorously with the true nature of climate and global change—not simply as a problem of the biophysical sciences— but as a complex socioenvironmental problem for which novel, innovative, interdisciplinary, and transdisciplinary research approaches are necessary.

[18] http://www.globalchange.gov/about/legal-mandate
[19] http://www.globalchange.gov/browse/reports/our-changing-planet-FY-2016

Additional relevant interagency coordination occurs through other CENRS subcommittees, including the Air Quality Research Subcommittee, Subcommittee on Water Availability and Quality, Subcommittee on Ecological Systems, Subcommittee on Disaster Reduction, U.S. Group on Earth Observations, Interagency Arctic Research Policy Committee, and Subcommittee on Ocean Science and Technology. EPA also coordinates research through non-National Science and Technology Council (NSTC) committees, less formal bodies such as the Climate Change and Water Working Group (CCAWWG), and directly interactions with other agencies at working levels.

III. Crosscutting ORD Research

A. Current and Planned ORD Research

This section presents ORD's current research on climate change and the planned research described in the StRAPs. The discussion is organized according to the three major Science Challenges, subdivided as appropriate by medium or system (i.e., air, water, land, ecosystems, human health, communities). This section articulates outstanding scientific issues related to the Challenges that currently preclude ORD from fully meeting the needs of ORD's Program and Regional Office partners. These gaps stem from a lack of process-level understanding for key media- or system-specific problems, as well as the need to explore particularly critical integrated science problems more fully, such as the intersections between climate, wildfires, air quality, and health. In addition, as described above, the gaps are related to missing perspectives from the social sciences that would support improved problem formulation and spur research around concrete decisions and policies for responding to the threat of climate change.

This section also highlights examples of current integration and opportunities for additional integration across the climate change research portfolio. Integration is critical for several reasons, including the fundamentally integrated nature of the climate change problem and the need for consolidation and centralization to serve the decision support mandates of ORD's Program and Regional Office partners most efficiently. Multiple dimensions of integration are important in the context of ORD climate research, beginning with the identification of common underlying needs across partners to support decision-making across multiple media or managed systems over different spatial and temporal scales. Integration also is key across the different modes of research within the overall portfolio, from work that provides the foundation for or is applied within other projects and tasks, to work that resides at the boundary between ORD and the Program and Regional Offices, and that therefore carries primary translational responsibilities for ORD's climate change research.

Summary of Research Efforts: Science Challenge 1

Science Challenge 1. *Develop the knowledge base to support planning in the Program and Regional Offices to maintain water quality, air quality, the health and welfare of people and their communities, and ecosystems, in the face of non-stationarity in the climate system and uncertain future changes in key variables such as temperature, precipitation, and sea level.*

The large-scale, long-term changes in Earth's climate due to increasing GHG concentrations in the atmosphere manifest themselves, locally and over shorter timescales, as shifts in the statistics of a wide array of weather and climate extremes. That such extremes, including heat waves, heavy rainfall events, droughts, wildfires, stagnation events, hurricanes, and winter storms, strongly influence air quality, water quality, human health, community vulnerability, and ecosystem integrity and services is well understood, even though the pathways connecting these meteorological and climatological phenomena with ecological and human systems can be complex. In addition, increasing global temperatures and GHG concentrations drive trends in key baseline environmental conditions closely tied to EPA's mission, including increased proportions of precipitation falling as rain versus snow, lengthening of the growing season, elevated stream temperatures, sea level rise, permafrost melting, and ocean acidification.

EPA's challenge is to understand how these profound changes in driving climate conditions, both means and extremes, will adversely affect water and air quality, human health and communities, and terrestrial ecosystems, given the challenges related to loss of stationarity and the deep uncertainty about future climate changes. These insights into the diverse impacts of climate change are needed to inform the application of EPA's regulations, guidance, tools, and capabilities for managing these impacts. Such insight also is necessary to provide the appropriate information needed to inform the basis for GHG regulations and to assess the possible space of sustainable solutions, in line with Science Challenges 2 and 3.

Because EPA per se does not conduct much of the primary research on physical climate science needed to understand and predict shifting baselines and extremes, Science Challenge 1 relies on integrating EPA's unique strengths with the complementary leading-edge climate science of our partner Federal agencies. ORD research uses the scientific information on changing statistics of climate, for both mean conditions and extremes, leveraging analysis of observed trends as well as outputs from climate model simulations, and integrates this knowledge base with EPA observational and experimental data, modeling tools, and analytic approaches.

For example, to support the evaluation of climate change impacts, ORD climate research builds on core strengths in air pollution, watershed, and exposure modeling—areas in which EPA leads scientifically. A key task in the ORD climate change portfolio is the adaptation of existing EPA models (e.g., the Community Multiscale Air Quality [CMAQ] model and other air quality models, watershed models, human exposure models, ecosystem models) for use in targeted assessment of vulnerabilities and emerging risks for water and air quality, people, and ecosystems. Model adaptation involves building capability within the models to assess climate change effects: for example, by revising them to receive future scenarios of key driving climate variables as inputs or by modifying climate-sensitive model parameterizations. Other critical tasks include developing improved climate-related vulnerability and risk assessment methodologies, innovative decision analytic approaches and frameworks to help decision-makers manage the large uncertainties associated with future climate change, scenario products for use in these new approaches and frameworks, new indicators of system change to support monitoring and adaptive management under climate change and interacting stressors, and scientific syntheses of integrated climate change effects relevant for regulation and management.

The ongoing research in ORD with respect to Science Challenge 1 is substantial and can be organized according to its focus on specific media and type of impacts. In the text that follows, current research efforts relevant for addressing this Challenge are discussed for water quality, air quality, health, and ecosystems and land; key knowledge gaps relevant to each topic also are presented. In addition, several conceptual and analytical challenges common to all media and systems described here are discussed. These include dealing with multiple interacting stressors beyond climate change alone; overcoming the difficulties associated with non-stationarity in weather and climate statistics as climate changes; developing effective approaches for managing large and irreducible uncertainties associated with these non-stationary future changes; and advancing beyond simply characterizing impacts and potential risks to identifying and designing effective adaptation approaches and adaptive management strategies. These crosscutting gaps also are discussed in more detail below.

Water Quality

Changes in global climate during the next century are expected to cause or contribute to effects on watersheds, wetlands, estuaries, and coastal environments by altering temperature, precipitation, runoff, flow, sea level, chemical and microbial dynamics, and other variables.[20] Human settlements and ecosystems for which water resources are already stressed could become even more vulnerable under climate change, and new vulnerabilities in previously unstressed systems and locations might emerge. The effects of climate change in different watersheds will vary due to regional differences in climate, physiographic setting, and interaction with land use, pollutant sources, and water management, including climate adaptation actions. Further, a foundational principle of managing water systems likely no longer holds: systems fluctuate within an envelope of variability that remains stable over time, allowing for confidence that future flows will return with a consistency similar to that in past records.

Overall, we know less about the potential effects of climate change on water *quality* than the impacts on water *supply*. Changes in flow per se are, of course, important to water quality, but, coupled with temperature changes, they can also lead to changes in other stressors relevant for ecosystem and public health, such as nutrient processes, dissolved oxygen, chemical toxicity, and pathogen viability. Harmful algal blooms (HABs) are related to nutrient loads and water temperature and adversely affect drinking water supplies and public health. Changes in coastal and ocean characteristics such as sea level rise and acidification create further stresses on watersheds and aquatic ecosystems and contribute to issues such as saltwater intrusion into coastal aquifers and rivers important for drinking water supplies. Importantly, climate-driven changes in water quality can be exacerbated by other major changes such as land use, population change, shifting trends in energy production and agriculture, and associated competition for water resources; conversely, management of these interacting stressors could provide critical opportunities for effective and sustainable climate change adaptation. Overall, the impacts of climate change present an uncertain but potentially significant challenge for key EPA programs, including those that establish total maximum daily loads, issue National Pollutant Discharge Elimination System permits,

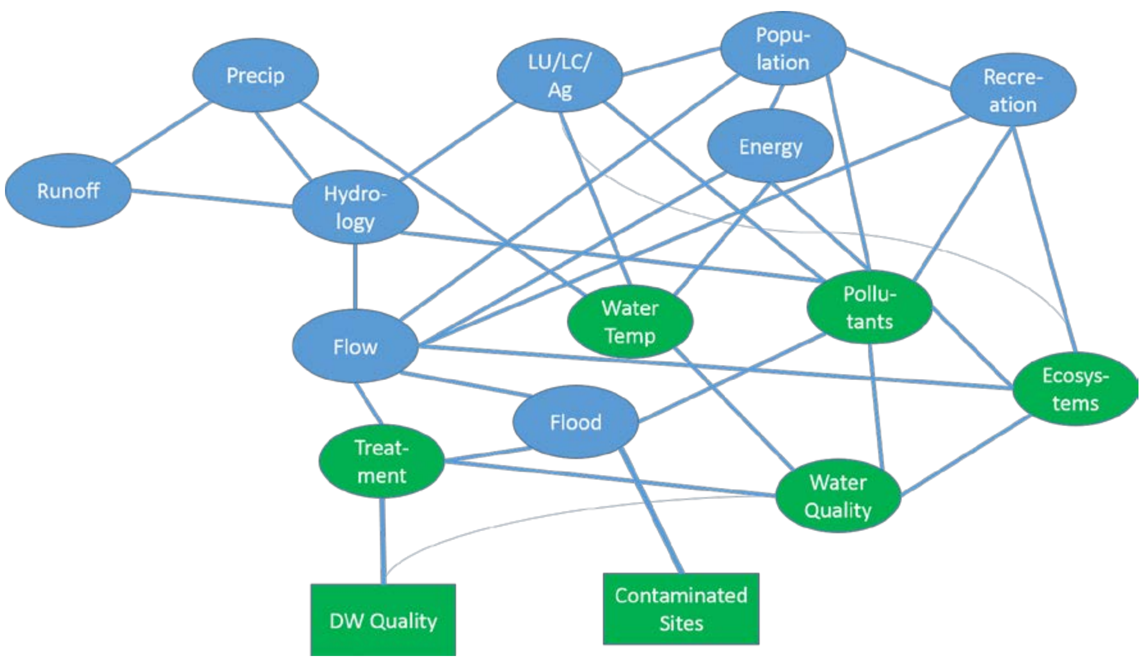
[20] U.S. EPA, 2012: National Water Program 2012 Strategy: Response to Climate Change. U.S. Environmental Protection Agency, Washington, DC, 124 pp. Available at: https://www.epa.gov/sites/production/files/2015-03/documents/epa_2012_climate_water_strategy_full_report_final.pdf.

and manage or administer wetlands, stormwater, gray and green water infrastructure, drinking water quality, and aquatic ecosystems.

Examples of Ongoing Efforts in Water Quality
Research to assess hydrologic and biogeochemical sensitivity to climate and land use change and to develop indicators of watershed condition and attributes that promote watershed integrity, allowing for the application of a range of future climate and land use conditions to examine how such changes might affect watershed and resource integrity and sustainability. ACE 4.02.5, 4.02.7, 4.02.8; SSWR 3.01B, 3.01C, 3.01D
Research to understand the impacts of climate change on aquatic ecosystems and associated ecosystem services, including development of indicators of ecological condition, studies to evaluate how climate (among other drivers) is related to nutrients and impacts on ecosystems, development of regional monitoring networks, and research on the vulnerability of estuarine and near-coastal species, habitats, and ecosystem services to climate change. ACE 4.02.1
Research to examine the impacts of sea level rise on nearshore ecosystems and the interactions among sea level rise, hydrology, and storm surge. ACE 4.02.1
Research on climate change and nutrients to improve understanding of how climate change influences nutrient flows and the impacts of both on critical environmental endpoints (including hypoxia in the Gulf of Mexico) and on the connections between the carbon and nutrient cycles at regional scales. SSWR 4.02B
Research to evaluate the effects of increased water temperature on the frequency and characteristics of harmful algal blooms, such as bloom biomass increases and spatial distribution, and impacts on cyanotoxin production. SSWR 4.01C, 4.02A, 4.02B
Research to evaluate the capability of existing wastewater and drinking water treatment technologies to control and treat cyanobacterial and algal toxins associated with expected warmer water temperatures due to climate change. SSWR 4.01C, 4.03C
Extramural research on how drought and related events, such as wildfires and changes in runoff, affect aquatic ecosystems, drinking water sources, and drinking water treatment. SSWR 3.01E
Development of an assessment of the overall impacts of climate change on water quality to provide the scientific foundation for consolidating and synthesizing information needed by OW and others to develop effective responses; for example, this work includes specific applications to develop guidance for incorporating changing temperatures into regulatory programs in collaboration with Region 10. SSWR 3.01C
The Climate Ready Estuaries program, part of the OW National Estuary Program, is one example of how climate change affects EPA actions and how ORD can provide information to help EPA respond. ORD provided technical guidance on the use of expert judgment to inform local decision-makers about approaches for developing climate adaptation plans for estuaries. ACE 4.02.1
Collaboration between OW and ORD to identify wetland types and functions vulnerable to climate change impacts and assessment of approaches to integrate climate science into OW programs (e.g., Clean Water Act Section 404 Program, Healthy Watersheds Initiative, and National Wetlands Condition Assessment). To date, accomplishments include a technical framework for assessing relative wetland vulnerabilities, demonstration of a vulnerability inventory for a pilot region in the Mid-Atlantic, and a stakeholder workshop to obtain feedback on utility of the results for informing program adaptations. ACE 4.02.2, 4.02.9

Examples of Ongoing Efforts in Water Quality
Strong collaboration with USGS to estimate critical streamflow statistics, such as 7Q10, at gaged and ungaged stream sites and understand the potential effects of flow alteration on aquatic life uses. ACE 4.02.10, 4.02.11

Several key knowledge gaps exist in developing the science needed to support water quality management and watershed protection in the face of climate change. First, although the effects of climate change on flow have been much studied, a critical need remains to improve understanding of climate change impacts on flow metrics relevant to water quality and aquatic ecosystems, such as the lowest 7-day flows over a 10-year period (referred to as 7Q10). Achieving this improved understanding will depend significantly on improving the representation of critical processes in watershed modeling tools, particularly evapotranspiration, snowmelt, and groundwater dynamics. Improved representation of stream temperature also is especially important for assessing climate change impacts on the cost, complexity, and performance of wastewater treatment; the potential for increased occurrence of HABs; and threats to vulnerable aquatic species. Systematically incorporating shifts in storm statistics into the intensity-duration-frequency curves used in many water resources applications also would provide important benefits for planning and decision-making.



Green items represent topics for which EPA has programmatic responsibility. Blue items represent topics for which EPA relies on data and analyses other Federal and State agencies develop. This schematic is intended to indicate the scope of needed cross-organization interactions and does not show all the topics, connections, or collaborative efforts. Note: LU = land use; LC = land cover; Ag = agriculture; DW = drinking water

Figure 2. Schematic illustrating connections among topics related to climate change and water-related impacts

Other critical research issues include understanding how climate change, land use change, and ecosystem processes will interact to influence surface and groundwater hydrology; how climate change will affect disturbance regimes such as fire and pest outbreaks in both managed and unmanaged ecosystems; and how these impacts will, in turn, affect water quality. Improved observations (and representation in models) of the engineered part of the water cycle also are needed, as are improved data on the effectiveness of water quality-related best management practices in different types of watershed systems (e.g., urban, agricultural, forested). Water quality managers need more and better information to determine which practices to implement to manage anticipated increases in loads due to climate change. Continued development of modeling tools that link hydrology and socioeconomic factors also will help support these needs. Finally, the threats to water infrastructure posed by climate change impacts such as sea level rise, extreme storms, inland flooding, and thawing permafrost require improved assessment and quantification. How changes in water quality and aquatic ecosystems might affect their ability to serve as carbon sinks is addressed below under Science Challenge 3.

Air Quality

Shifting weather patterns due to climate change, including increases in heat waves and stagnation and changes in precipitation extremes, likely will alter the rates of pollutant-forming chemical reactions, affect deposition rates, and influence long-range transport. Changing weather patterns also likely will affect anthropogenic, biogenic, and geogenic emissions, in turn potentially worsening background air quality and the frequency, severity, and duration of air quality episodes. Such impacts have the potential to confound current strategies for managing air quality, making meeting air quality goals and relying on existing approaches and models to demonstrate compliance with standards more difficult. Systems for air quality management will need to be adapted to cope with these challenges. For example, air quality planning simulations to determine the extent of emissions reductions needed to meet a given target will need to account for climate-induced changes in air pollution meteorology, background concentrations, and precursor emissions. Similarly, approaches for monitoring air pollution will have to account for climate change effects. Moreover, today's "exceptional events" could become part of regular seasonal exposures in the future.

Current research on the impacts of climate change on air quality includes how changing weather patterns alter pollutant formation and affect anthropogenic, biogenic, and dust- and wildfire-based emissions, with corresponding implications for human health. As with water quality, other agencies develop the fundamental understanding of climate change impacts on temperature and precipitation; the frequency, duration, and intensity of extreme events; and the occurrence of wildfires and the area they burn. EPA leverages and integrates this research with its own research in air pollution meteorology and chemistry, anthropogenic and biogenic emissions of pollutants and precursors, long-range transport, and the impacts of wet and dry deposition of pollutants on ecosystems. Research on the health-related impacts of climate-driven shifts in air quality is discussed in the Human Health subsection. In addition, the critically important issue of links between air quality management and GHG mitigation, including their mutual co-benefits, is a significant area of focus within the ORD climate research portfolio and is discussed in detail under Science Challenge 2.

As with water quality, several important gaps occur in our knowledge to support air quality management. First, consideration of meteorological episodes (on a regional and seasonal basis), rather than simply shifts in mean climate, continue to be essential for understanding climate change impacts on ozone and particulate matter (PM). We need an improved understanding of the links among climate change, atmospheric circulation patterns, local stagnation, and frequency of precipitation. This includes improving our understanding of the potential for increased meteorological and climatological variability in the future and its ability to confound current air quality management approaches. In addition to these interactions among atmospheric processes, changes in meteorological conditions can also affect anthropogenic emissions of GHGs and other air pollutants as people respond to heat and other impacts. Furthermore, the expectation that climate change will lead to a lengthening of the ozone season has important health and ecological implications that require improved quantification and risk assessment. We also need improved understanding and better means to quantify how changes in climate might affect biogenic emissions of precursor species. In the context of PM, in particular, several critical but understudied links occur between climate research and aerosol research, including changing emissions from wildfires and dust and atmospheric processing of organic aerosol precursors.

With respect to modeling, improved representations of future large-scale meteorological boundary conditions need to be incorporated into simulations of the effects of changing climate on air quality. Altered chemical boundary conditions resulting, for example, from climate change impacts on long-range transport and stratospheric ozone also must be considered. In addition, such simulations need to incorporate recent advances in the representation of organic aerosols and related processes. Simulations of the changing patterns of pollen exposure specifically, and climate impacts on aeroallergens broadly, are urgently needed to support improved assessment of the effects of climate change on health. Improved modeling of land-use change and of ecosystem responses to climate change will aid in assessing climate-wildfire links, and improved representation of interactions between climate change and atmospheric deposition will allow for quantification of impacts on ecosystems and ecosystem services.

An important emerging area in climate and air quality is the potential for climate change to affect indoor air quality. Improving understanding of the mixture of chemical and biological pollutants present in indoor air, including molds, pollens, and pathogens; the tradeoffs associated with reduced mixing of indoor and outdoor air as an adaptation response to climate change; and the critical role of humidity, are important and broad research gaps.

Examples of Ongoing Efforts in Air Quality

Applying the Weather Research and Forecasting and Community Multiscale Air Quality (CMAQ) models to future climate and emission scenarios. This work involves developing techniques to downscale global climate model results to spatial scales at which CMAQ can be applied to incorporate regional-scale meteorological data and emissions to understand how air quality might change under different possible climate conditions and emissions scenarios. Incorporation of atmospheric chemistry and evaluation of air pollutant concentrations is unique to EPA. This research effort leverages global-scale climate modeling results from other federal agencies, which are downscaled for CMAQ application to evaluate potential future air quality and for use in other regional-scale

Examples of Ongoing Efforts in Air Quality
modeling efforts to understand watershed or other environmental responses. Additional efforts are being conducted to improve our understanding of possible changes in organic aerosol formation as the climate changes. ACE 4.01.1, 4.01.3
Coupling emissions, air quality modeling, and effects to improve the understanding of impacts on air quality and air quality-related health as a consequence of climate change (including combined effects of air pollution exposure and higher ambient temperatures) and changing energy technologies; Science to Achieve Results (STAR) grants on extreme weather events and how they can affect air quality, the impacts of climate change on particulate matter, and the impacts of climate change on indoor air quality. ACE 4.01.2, 4.01.4
Evaluating the potential health impacts of increased biofuel use and examining various emissions control scenarios to identify more effective strategies for air quality management that reduce climate forcing and health effects associated with exposure to air pollutants; collaborative effort between ORD and OAR and among several ORD Laboratories and Centers. ACE 8.02
Incorporating potential impacts of climate change and future energy technologies into the multidisciplinary ACE Centers supported by the STAR program. This represents an evolution of the Centers' prior focus, which now explicitly account for climate change in investigations of air quality and health. ACE 7.01.9
Increasing emphasis on the impacts of wildland fires on air quality and health, including developing approaches to predict changes in ozone and particulate matter concentrations during fire events, understanding the health impacts of acute exposures, and incorporating approaches to communicating the risks associated with wildfires to citizens and healthcare professionals. ACE 4.01.2, 4.01.7, 7.04.3

Human Health

The scientific challenge related to climate change and human health encompasses several dimensions, including understanding the (1) climate-driven exacerbation of effects associated with exposure to environmental stressors already of concern; (2) effects of new, climate-related environmental stressors and the combined effects of existing and new stressors; and (3) emerging health threats due to climate change.[21]

Climate change is expected to increase the risks of heat-related illness and exposure to other life-threatening extreme events such as severe storms and floods. Risks to human health from degraded air quality, resulting from both more frequent and extreme air pollution episodes and increasing exposures through factors such as the lengthening of the ozone season, are also expected to increase, as are health impacts associated with aeroallergens. Changes in exposure as people change behaviors in response to climate change could also affect health. Indirect impacts of climate change on air quality via increases in the number and severity of wildfires and possible worsening of indoor air quality are potentially significant emerging issues. Vulnerability to air pollution also is likely to be affected by the interactions among all of these impacts. Potential health impacts are associated with changing conditions on contaminated lands, such as environmental releases caused by flooding or higher temperatures. Wastewater control and water treatment failures, expanding ranges of invasive pathogens and vector-

[21] USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp.

borne diseases, and mental health issues related to disruptions caused by extreme weather events represent other potentially significant impacts of climate change on human health. Climate change might exacerbate currently experienced issues, or new health threats could emerge in previously unaffected locations or at new times of the year (e.g., new occurrences of HABs or waterborne pathogen exposures). Certain populations are at higher risk from this broad range of potential health impacts, including children, the elderly, pregnant and postpartum women, people with preexisting physical or mental illness, the economically disadvantaged, the homeless, and first responders.

Current ORD research on the impacts of climate change on human health focuses on the health impacts of climate-driven air quality degradation, including the interacting effects of high temperatures on air quality-related health outcomes. It also focuses on aggregate health outcomes across the population as a whole and for particularly susceptible subgroups. The development of modeling tools that support health effects assessment under climate change, and synthesis products that encapsulate the overall picture of climate change's influence on health, also are key components of ORD's effort. Note that considerable research is underway across ACE and other programs to evaluate the health impacts associated with exposure to air and water pollution that does not explicitly focus on climate as stressor. Although not addressed here, that work significantly contributes to understanding the health impacts of climate change.

Examples of Ongoing Efforts in Health
Research that is explicitly designed to address climate change as a stressor is investigating the links between climate change and health through more "conventional" stressors such as air quality and weather events, changes in allergens, and waterborne and infectious disease. ACE 4.01.3, 4.01.7, 4.01.9
ORD's participation in the recent multiagency USGCRP effort involving EPA (OAR and ORD), the Centers for Disease Control and Prevention, NOAA, USDA, and other agencies was a major milestone toward assessing the state of understanding of climate change-related health effects. It also provided a starting point for further interagency collaborations on climate and health. The collaborative networks developed for the assessment are being used to expand interactions between air quality modelers and health researchers to advance the understanding of health impacts related to climate change and air quality. ACE 4.01.3, 4.01.7, 4.01.9
ORD is investigating the health impacts of extreme weather events related to climate change, including temperature extremes and flooding. This work also will address the impacts on susceptible subpopulations when appropriate data are available. ACE 4.01.7, 4.01.9
Researchers are examining the health impacts of wildfires and dust storms, both of which are expected to become more frequent and severe because of climate change. ACE 4.01.7, ACE 7.04.3

Key gaps are associated with each major exposure pathway linking climate change and health: poor air quality and cardiopulmonary illness; extreme heat and heat-related illness; infectious agents and resulting food-, water-, and vector-borne disease; and mental health consequences and stress associated with climate impacts. For example, although the body of work related to heat and health is significant, a comprehensive understanding of the combined effects of heat exposure and poor air quality on health outcomes is lacking, including regarding the potential for complex interactions among multiple pollutants, such as ozone, and allergic responses to aeroallergens. In addition, we need improved understanding of the critical role humidity plays in modulating climate-induced increases in heat- and air quality-related illness; how climatic and non-climatic factors interact to drive vector-borne disease emergence; how ocean acidification and altered runoff affect toxin production and the distribution of marine HABs and pathogens; and how climate change impacts on drinking water infrastructure affect the risks of waterborne diseases.

In general, the mental health consequences of climate change are even less well understood, beginning with our understanding of how other climate-related health risks might exacerbate existing mental health conditions or lead to the emergence of new mental health issues. The mental health impacts of long-term displacement, relocation, or loss of culturally significant geographic features, particularly for indigenous populations, also are not well understood. Improving understanding of interacting and reinforcing effects among multiple health impacts is a major need as well, as is bounding the potential for increased frequency and intensity of extreme events to strain the capacity of public health systems.

The gaps in understanding mental health consequences, interacting effects, and impacts on public health systems highlight an even broader gap: understanding the social and behavioral factors—and the environmental and institutional context within which health outcomes occur—that determine the sensitivity of individual or population response to a particular health impact of climate change. We also currently lack the capacity to develop effective adaptive responses and build long-term resilience at the community level. For example, we need improved understanding of the socioeconomic factors contributing to observed relationships between heat and morbidity/mortality so that outcomes associated with warming temperatures can be extrapolated to future heat extremes with greater confidence. In addition, the role of future population migration and demographic change is just beginning to be elucidated in assessments of the health burden of climate change. More comprehensive and robust projections of factors that contribute to population vulnerability also would enhance the value of quantitative models of health impacts associated with climate change, as would exploring ways to incorporate future adaptive measures and behaviors into such models. Finally, improved across-the-board surveillance is needed of illness and of risk factors contributing to vulnerability, including indicators of social and economic resilience, for each major exposure pathway linking climate change and human health.

Land and Ecosystems

Climate change is expected to have a broad range of impacts on land, terrestrial ecosystems, and critical ecosystem services. Extreme weather events such as heavy precipitation and floods can cause releases of hazardous materials from contaminated lands to soils, groundwater, streams, and coastal waters. Widespread warming could increase revolatilization of hazardous materials. Rising seas will eventually compromise the integrity of water and wastewater treatment facilities located in the coastal zone. In addition, climate change, in conjunction with human use of the landscape, could compromise the ability of ecosystems to buffer the adverse impacts of extreme events or process environmental pollutants. Changes in the frequency and intensity of wildfires will have direct impacts on wildlife, vegetation, and water quality; such changes also could affect secondary impacts associated with increased risk of flooding or landslides resulting from the destruction of stabilizing vegetation, which could promote the spread of contamination or compromise remediation efforts. Shifting patterns of extreme weather events need to be evaluated for their potential to generate storm debris—and the ensuing need for debris collection and disposal—as well as for their impacts on emergency response efforts.

As with the previous topics, other Federal agencies conduct research on climate change-driven shifts in temperature, precipitation, floods, droughts, wildfires, and sea level, with particular relevance of research related to shifting extremes. EPA adds value to this research specifically related to ecosystem structure, function, and services; contamination by hazardous materials; and community health and wellbeing. Areas of current research include the development of mapping tools and indicator systems to evaluate ecosystem and community vulnerabilities associated with changing environmental conditions; assessment of the resilience of waste containment and treatment systems; and support for integrated management of nitrogen in ecosystems. Improving understanding of populations likely to be disproportionately affected by climate change in conjunction with other environmental stressors, including socially and economically disadvantaged groups in urban areas and Tribal communities, is also an important emphasis within the current research portfolio.

Examples of Ongoing Efforts in Land and Ecosystems
Research on the environmental impacts of extreme weather events is addressed in a series of STAR grants under the solicitation, "Extreme Event Impacts on Air Quality and Water Quality with a Changing Global Climate." This work explicitly addresses air quality and water quality but also is applicable to OLEM needs in promoting a better understanding of extreme event frequency and magnitude. ACE 4.03.7; SSWR 3.01F
ORD is conducting work to understand how the behaviors of contaminants in sediments might change as environmental conditions are affected by climate change; this work is being conducted relative to remediation activities. SHC 3.61.5
This research addresses development of methods, tools, and indicators that can be applied in specific cases. The work includes developing scenarios and land use tools and datasets, climate indicators, and assessment methods and frameworks. This research complements interagency research on ecosystem impacts of climate change, particularly through standing USGCRP interagency working groups. SHC 2.64.4; ACE 4.02.2, 4.02.4, 4.02.9, 4.03.2
Understanding how climate change affects Tribal communities is the focus of a series of STAR grants investigating ecological and human health for Tribal sustainability and well-being. SHC 2.63.5
Ongoing development of the EnviroAtlas enables improved understanding of environmental conditions and stressors. Efforts to incorporate projected impacts of climate change, including changes in precipitation patterns, flooding, sea level, and potentially invasive species, provides information at decision-relevant scales on the environmental changes associated with climate change and other environmental stressors. SHC 1.62.2

As with the other media-specific topics discussed under Science Challenge 1, our understanding of the impacts of climate change on land and ecosystems has several gaps. Changes in forests and other land ecosystems that are driven, directly or indirectly, by climate change could affect water quality by reducing the natural capacity of those ecosystems to process pollutants. These changes include the impacts of extreme weather and climate events, even when the characteristics of those ecosystems have not yet been significantly altered by more gradually shifting baseline climatic conditions. Changes also include the potential impacts of invasive species on ecosystems and possible modifications in pesticide and herbicide uses as means to control their prevalence in new areas.

Further work is needed, in collaboration with the HSRP, to understand and develop strategies for managing post-disaster debris in ways that are safe and environmentally sound. Finally, climate change is likely to alter the fate and transport of toxic chemicals in the environment and the sensitivity of humans and other organisms to their effects.[22] Work with the CSS and HHRA programs will be needed to understand more fully the possible risks associated with such changes.

Cross-Media Challenges

Many conceptual and analytic challenges are common to all media and systems addressed under Science Challenge 1. The challenges include dealing with multiple interacting stressors beyond just climate change; overcoming the difficulties associated with non-stationarity in weather and climate statistics as climate changes; developing effective approaches for managing the large and sometimes irreducible uncertainties associated with non-stationary future climate changes; and advancing beyond simply characterizing impacts and potential risks to identify and design effective adaptation approaches and adaptive management strategies. In addition, fully addressing these crosscutting challenges will be impossible without leveraging needed knowledge and expertise from the broad range of social, behavioral, and economic sciences disciplines. Also worth noting is that advances across all efforts under Science Challenge 1 will continue to result from improved characterization of the underlying drivers of climate-related impacts, including changes in extreme temperatures and precipitation, in storm frequency and intensity, in other climatic extremes such as drought. Such advances also will help characterize long-term shifts in mean conditions that are closely tied to EPA's mission, including the ratio of precipitation falling as rain versus snow, lengthening of the growing season, rising stream temperatures, sea level rise, permafrost melting, and ocean acidification. Close coordination and engagement between EPA and our partner Federal agencies with the primary responsibility for addressing these fundamental climate research topics, through USGCRP and associated interagency mechanisms and processes, will help ensure the alignment of their research investments with the climate science needed to support EPA's mission.

Our focus in this Roadmap is on climate change and its impacts. Climate change, however, is only one of several linked, local-to-global changes that will affect the environment. These include changes in population and demographics, economic growth, land use, biogeochemical cycles, technology, and other large-scale trends. A critical element of ORD's climate change research program must be to improve understanding of how these stressors interact and co-evolve with climate change to worsen (or in some cases alleviate) climate-driven impacts. These interactions could be complex and nonlinear, leading to cascading impacts system wide. Improved ability to conceptualize and model these dynamic interactions can lead to better understanding of the potential variability and uncertainty in future outcomes, including the possibility for surprises and unintended consequences of response actions. In addition, accounting for shifts in population and demographics over time is critical for comprehensively

[22] Noyes, P.D., M.K. McElwee, H.D. Miller, B.W. Clark, L.A. Van Tiem, K.C. Walcott, K.N. Erwin, and E.D. Levin, 2009: The toxicology of climate change: Environmental contaminants in a warming world. *Environment International*, **35**, 971-986.

assessing climate risk, as changing population exposures in terms of total population or vulnerable population groups will strongly condition the findings of any climate change risk assessment.

In addition, as highlighted earlier, climate change calls into question the assumption of stationarity, which bases assessment of future outcomes on the premise that the future is a close statistical analogue of the past. This assumption underpins a broad range of Agency risk assessment tools and approaches. Addressing this challenge in evaluating potential climate change impacts on air and water quality, and corresponding health and ecosystem effects, is substantially complicated by the large and hard-to-characterize uncertainties about the magnitude and exact nature of future climate change, especially regarding the largest and most consequential potential impacts.

Although challenging, these realities of the climate change problem do not preclude effective risk assessment and risk management. Much progress can be made by critically examining the problem of climate change in the context of core risk assessment principles and adapting and applying those principles to overcome the unique challenges climate change presents for decision support. These core principles include focusing first on understanding system behavior, system sensitivity to climate change, and key management endpoints, rather than beginning with the hard-to-quantify climate-related uncertainties, as has been traditional practice for climate change impacts assessment. Working with decision-makers to focus on the type and magnitude of climate change impact that would need to occur to present a problem, and then assessing the risks associated with such threshold-crossing often will be a useful approach in the face of deep uncertainty about future climate change. Beginning with a focus on risks relative to objectives and an understanding of what to avoid makes identifying policy vulnerabilities under uncertainty about the future and proposing strategies for minimizing regret in the event of broken assumptions – rather than becoming locked into an "optimal" solution for a single, "best-guess" future that might never emerge. Such frameworks also allow climate change to be considered more readily in the broader context of multiple stressors acting on a system and enable a more explicit consideration of nonlinear and threshold responses.

Working backward in this way from evaluations of the type and magnitude of impacts that would cause a problem, and subsequently examining the scientific plausibility of climate change triggering those risks, helps clarify the necessary extent and timing of preparation and adaptation actions and creates new and important demands for the kind of information traditionally requested from our climate-modeling colleagues. Large ensembles of climate model simulations, encompassing multiple scenarios of climate change drivers and impacts, are needed to bound, quantitatively, the uncertainty space of the given climate impacts, vulnerability, and adaptation problem being explored. To be most relevant for EPA's climate change risk assessment needs, however, these simulation datasets should span all important dimensions of future climate uncertainty. These dimensions encompass emissions and land use/land cover change trajectories, natural climate system variability, and alternative model formulations and parameters, especially for processes where our understanding is limited but to which climate impacts are highly sensitive, such as ice sheet dynamics or carbon cycle feedbacks. The variables most important for EPA's issues of concern should be reported and archived, including not only temperature and precipitation but also humidity, wind, solar radiation, and other critical variables for estimating risks to human health, watersheds, and fire-sensitive ecosystems, among others. Further, these variables should be reported and archived at sufficient spatial and temporal resolution to be useful in EPA contexts. Finally, the potential for low-probability, high-consequence climate outcomes that are likely to result in impacts to human and natural systems with which we have little or no experience should be explored much more thoroughly. This bounding of the problem from above—that is, the greatest risks that we are likely to face—is of paramount importance in assessing the true societal threat from climate change and often requires expert judgment, beyond simply relying on the model outputs.

Successfully evaluating the long-term risks from climate change also will require a much greater effort to understand potential systemic risks, in terms of complex cascades of impacts through multiple, interconnected systems, and feedbacks among these components. With climate change, indirect impacts across linked systems might be more severe (or have more widespread consequences) than the originating event or condition. Such cascades are just one example of nonlinear relationships between stressor and response as conditions move beyond historical ranges. The rapid pace and multifaceted nature of climate change in the Arctic is a clear and early example of such behavior, and it provides opportunities to gain understanding of complexities, cascades, and how to develop response options. Threshold and tipping point behavior likely will be evident in both natural and human systems individually, as well as in larger, connected, socioenvironmental systems, which also encompass adaptation and mitigation actions. These requirements, for new and enhanced climate and global change science, represent an important request from EPA to the larger U.S. Federal research enterprise.

These inherent complexities and uncertainties highlight the importance of ultimately moving beyond a primary focus on characterizing climate impacts, vulnerabilities, and risks to formulating effective response options. Major knowledge gaps, however, significantly limit our ability to develop such responses and solutions. For example, we lack sufficient understanding of the characteristics of socioenvironmental systems that lead to reduced vulnerability and enhanced resilience in the face of climate impacts, both to support the design of strategies to increase resilience and to develop methods for prioritizing interventions given resource limitations. We also lack systematic review and evaluation of actual, on-the-ground adaptation practices, including for adaptive management approaches that enable ongoing evaluation and adjustment as information is gained—something that is particularly important with the long time horizons and deep uncertainties of climate change. Such approaches require flexibility in the environmental management paradigm and an understanding of the risks that are to be managed and the risks inherent in the management strategies. They also require an enhanced capacity for monitoring and an ability to adopt alternative approaches within an overall management portfolio as the monitoring reveals more about how the future is unfolding.

Ultimately, climate change will force the Agency to move beyond incremental changes to existing programs (Science Challenge 1) to more transformational actions (Science Challenge 3). Research into the nature of sustainable environmental management under conditions of change, transition, and transformation will be needed to meet this challenge over the next few decades and provide the necessary bridge across this divide.

Finally, as discussed above, a greater role for knowledge and expertise from a broad range of social sciences disciplines in research related to climate change has been recommended by multiple review bodies—from the ORD BOSC and EPA's SAB to the National Academies. ORD has been increasing its efforts to integrate social sciences into its research programs for several years in response to advisory body recommendations and the needs identified by our EPA partners, but substantial additional efforts are called for. Several research needs relevant for Science Challenge 1 have been explicitly identified by ORD's partners that require incorporation of social sciences into the ORD research portfolio. One example is knowledge for improving community capacity to identify and apply best practices to adapt to climate change in the context of understanding the factors related to its disproportionate impacts on environmental justice and Tribal communities. For instance, incorporating traditional ecological knowledge could improve the resilience of communities affected by climate change; Alaskan native communities, in particular, offer promising opportunities for such approaches.

In addition, efforts to incorporate expertise from areas such as the decision sciences and community dynamics are needed. Some initial activities in these areas are underway in ORD. For example, research is ongoing in ACE to develop methods to apply so-called "robust decision-making" concepts to environmental decisions. In addition, changes in population and demographics have been incorporated into integrated climate and land use scenarios developed by ACE to support projections of climate impacts on environmental endpoints in both ORD assessments and the U.S. National Climate Assessment. ORD is expanding its efforts in the area of community support through additional climate-focused research within the SHC program, begun in Fiscal Year 2015, which will provide more resources to improve understanding of the information communities need to develop sustainable approaches to climate change adaptation and mitigation and how ORD can help provide that information. Increased efforts in these and related areas would be beneficial for addressing key needs under Science Challenge 1.

Additional areas in which knowledge and expertise from the social sciences can be helpful in increasing the usefulness of other disciplinary research include:

- understanding of the social aspects of decision contexts;
- risk perception and risk communication;
- the role of behavioral economics in improving decision-making about adaptation and mitigation responses;
- informing the development of more effective ways to transmit information and tools to individuals, communities, and decision-makers and to receive information from those stakeholders (through application of methods for public participation); and
- understanding the social determinants of vulnerability and resilience to air pollution and climate, e.g., community social support systems, social capital, distributional effects, and economic diversification.

Integration: Examples and Opportunities

Although integration across EPA's research portfolio for climate change needs to improve, several current efforts exemplify integrative approaches to climate research within the context of EPA's mission. These efforts fall into several categories: (1) tools relevant to multiple media or systems; (2) measurement methods or campaigns to inform multiple media or systems; (3) tools and methods that are media independent; and (4) cross-program or cross-agency collaborations.

An example of the first type of integrative effort is the development and application of the environmental Benefits Mapping Analysis Program (BenMAP), which enables users to combine gridded (or any other spatial format) air quality data with population, health, and economic valuation information to compute health impacts and economic benefits associated with changes in air quality. BenMAP uses specific methods to allocate population and other data to different spatial units and, as with any such tool, the research team evaluates the methods to determine whether they are appropriate given the research questions examined and the types of data collected and integrated. For climate change, BenMAP application relies on the ongoing development of the Weather Research Forecast-Community Multiscale Air Quality (WRF-CMAQ) model (another good example of integrative research and development) to downscale global model results. This downscaling allows evaluation of the detailed atmospheric chemistry and transport processes to investigate multiple, interacting health and environmental impacts such as exposure to ozone and high temperatures.

The second type of integrative effort has been demonstrated in the measurement of methane emitted from biogenic sources in temperate-zone reservoirs. Measurements designed to evaluate the effects of reservoir management practices on water quality in areas subjected to agricultural runoff have identified substantially higher methane emissions than expected. Understanding the importance of these emissions led to the development of a cross-Program research effort that addresses issues originally anticipated to be completely unrelated.

The third type of integration relates to efforts that are independent of specific environmental media and are therefore applicable across Programs. One recent example of such media-independent research is the development of an adaptation framework that incorporates stakeholder perspectives, demonstrates approaches for addressing uncertainty, identifies critical vulnerabilities, and enables collaborative decision-making. This adaptation framework is currently being applied in the Chesapeake Bay, but the approach is potentially generalizable to other locations.

The last type of integrative effort identified above assembles expertise from across different organizations to address multiple specific aspects of issues jointly. Recent efforts to produce the USGCRP Climate and Health Assessment is a clear example of such integration. ORD researchers conducted original modeling efforts to evaluate possible health impacts of changes in air quality due to climate change, and combined these results with a range of other original research and syntheses to create a much fuller understanding of the potential impacts of climate change on human health. This effort connected research from several different agencies and different EPA Offices, on topics from heat to water quality to mental health, and has set a baseline for future evaluations.

Research Syntheses

Integration, however, is about more than cross-organization or multidisciplinary research. Research syntheses in particular can provide greater understanding of the big-picture implications of detailed research results for EPA. OAR relies on quantitative assessments of climate change impacts on air quality, water quality, human health, and ecosystems to inform climate change policy, rulemaking, and communication. For example, the 2009 ORD climate change and ozone assessment provided the strong scientific basis for including the health impacts of ozone in the 2009 Endangerment Finding. ORD is moving forward with the development of several such synthesis products, both internally and with external partners, one example of which is the USGCRP Climate and Health Assessment. Other examples include collaboration with HHS, NOAA, USDA, and other USGCRP agencies, and the Climate Change-Water Quality Assessment, currently in development in collaboration with OW.

Because EPA leverages the work of other Federal agencies rather than conducts much of the primary physical climate science research (due to its regulatory and management mission), the role of synthesis, assessment, and translational activities to support the needs of Agency partners in the Program and Regional Offices is a particularly important element of the overall ORD portfolio. The STAR program is placing increased emphasis on developing synthesis documents that summarize and contextualize the research conducted across each Request for Application, and the ACE and SSWR programs are working to make such synthesis products a common component of all projects.

Recognizing the considerable value in developing synthesized insights by examining a body of work and communicating those findings to decision-makers and the research community, further efforts are needed to plan and develop syntheses that cut across research programs, consistent with the crosscutting nature of the climate change problem. Given the volume of research conducted on climate change and its impacts (and potential responses), peer-reviewed syntheses that consolidate and evaluate a body of research from an EPA perspective can play a substantial role in supporting effective actions regarding climate change. In this context, opportunities for further integration of the work under Science Challenge 1 are available, several of which are being actively pursued. These include evaluations of interactions between climate change and nutrient cycles, focusing initially on nitrogen, and a growing effort to understand the impacts of climate change on wildland fires and subsequent air quality and health impacts. Integration of efforts across ORD’s Programs to develop innovative approaches for managing the long-term risks of climate change is a further opportunity that remains to be developed at a significant activity level. Both the climate-nutrient and wildland fire issues provide opportunities for expanded integration across media and systems and pursuit of a systems approach to critical research questions. Several questions associated with the relationships between climate change and health present additional opportunities to integrate across Programs, media, and systems.

Summary of Research Efforts: Science Challenge 2

Science Challenge 2. *Inform the development, implementation, and benefits assessment of GHG control regulations through improved understanding of current and future U.S. emissions, the aggregate impacts of climate change across regions and sectors, and the mutual co-benefits of air quality and GHG regulatory actions and a changing energy system.*

The basic need under this Science Challenge is for research to (1) inform the development, implementation, and assessment of actions, regulatory and otherwise, that effectively control emissions of GHGs and short-lived climate forcers (SLCFs) such as black carbon over the long term; and (2) improve understanding of the potential for both co-benefits and adverse impacts of these actions. Although regulatory actions addressing GHG mitigation (e.g., the Clean Power Plan, vehicle emissions standards) are a relatively recent development, such efforts are expected to expand substantially at the Federal level going forward. In addition, they are complemented by more aggressive mitigation activities in a growing number of states.

Current ORD research related to this Science Challenge mainly falls into the following categories: (1) emissions measurements and projections; (2) benefits assessment to evaluate GHG regulation effectiveness; and (3) analysis of the mutual co-benefits of air quality and GHG regulatory actions and transitions to alternative energy technologies. Research on emissions and co-benefits are the most active of these efforts at this time.

Emissions

Emissions-related research is a relatively broad category that is concerned with two primary topics. The first is to understand how both emissions and atmospheric formation and transport of air pollutants can affect climate change: For example, changing concentrations of aerosols, ozone, and methane all affect Earth's radiation budget and regional-to-global radiative forcing. This work is distinct from research examining global-scale effects on radiative forcing; the research in this area leverages long-standing, core ACE strengths in emissions measurement and atmospheric modeling of pollutants associated with air quality, in particular aerosols, ozone, and organic compounds. ORD's emissions research focuses on GHGs other than CO_2, including those exhibiting strong radiative forcing such as methane, black carbon, and nitrous oxide. The sources currently evaluated are generally those that are most difficult to measure, such as area and fugitive emissions and emissions that are temporally stochastic. Examples of such sources include oil and gas production activities, landfills, coalmines, manure management, agricultural activities, and wildland fire. Measurements of emissions from mobile sources and small stationary engines are also under way, with a focus on black carbon emissions. Emissions from each of these sources can affect ambient ozone, PM, and regional haze, highlighting the connection to the air quality research under Science Challenge 1.

The second major component of climate change-related emissions research is technology assessment, and efforts in this area center on evaluation of performance and emissions associated with specific mitigation technologies. Although DOE conducts much of the research and development related to mitigation technology, synthesis and consolidation of the resulting information is beneficial to both EPA and regulated sources. Technology assessment also encompasses research on emissions and performance of residential cookstoves, particularly those in widespread use in developing countries. These efforts both provide information on emissions of climate-relevant pollutants, such as black carbon, and identify opportunities for emission reductions to improve health and reduce radiative forcing. More broadly, assessment of mitigation technologies can inform policy and regulation development by providing information on cost, performance, applicability, and environmental impacts. Examples include evaluation of carbon capture technologies for gas-fired electric generating units, non-geologic sequestration of CO_2 through its utilization in cement or other products, and monitoring and verification of geological sequestration. Research to evaluate technologies having indirect emissions impacts, such as advanced building ventilation systems, is also relevant to the broader research portfolio on technology assessment.

Benefits assessment

Development of GHG control regulations requires understanding the net benefits to the United States associated with those regulatory actions. ORD can help inform evaluations of net physical and monetary benefits associated with avoiding aggregate impacts of climate change through the implementation of mitigation policies. Estimation of benefits involves research to generalize and extend the results of quantitative impacts research to a nationwide scale and research to monetize those impacts. Also included is research to quantify and monetize the risks of inaction and the benefits to the United States of global GHG mitigation.

In addition to drawing on the substantial impacts research conducted under Science Challenge 1, this effort requires estimating the much broader scope (e.g., beyond ORD and EPA) of impacts and adaptation research to estimate costs and benefits as fully as possible. Critical to this effort is developing damage functions and projecting future impacts, which will require close engagement with OAR's work on the Climate Impacts and Risk Assessment reports and interaction with the Office of Policy's efforts on the social cost of carbon. The current amount of ORD research on this topic is modest, but the need is expected to increase.

Co-benefits of GHG and non-climate regulatory actions

The third area under Science Challenge 2 addresses the interactions among EPA regulatory actions and how, in combination, they can reduce GHG emissions and improve non-climate environmental endpoints, such as air quality. Much of the work in this area focuses on the projected improvement in air quality due to the adoption of GHG emission controls. Some estimates suggest that the direct, monetized health benefits of reduced air pollution associated with GHG mitigation strategies could offset a large fraction of GHG mitigation costs. For example, reducing emissions of black carbon and methane reduces the risk of health impacts related to PM and ozone exposure. Application of energy system models, combined with modeling tools for estimating air quality and radiative forcing, can provide estimates of combined climate and air quality benefits and how they change with different assumptions of technology and policy development. The research on cookstoves is one example of quantitatively estimating health and climate benefits by reducing both indoor exposure to PM and radiative forcing by the black carbon component of PM.

Evaluating these co-benefits requires a systems-based approach that considers multiple endpoints, likely across multiple media and over a range of time scales. Changes in tilling practices, for instance, might reduce emissions of nitrous oxide and reduce nutrient runoff into rivers and other water bodies. Understanding the magnitude of these co-benefits can support the development of better information about the net benefits of actions taken to mitigate climate change (or to address other environmental problems). The converse situation, of negative consequences of mitigation strategies, is also important to consider in the development of GHG mitigation policies, which we address under Science Challenge 3.

Examples of Ongoing Research Relevant to Science Challenge 2
Expertise on measurement of particulate matter (PM) and development and application of remote sensing technologies is applied to climate-relevant emissions of black carbon and methane, two important short-lived climate forcers (SLCFs). Research in this area focuses on black carbon emissions from diesel and aircraft engines and biomass burning, and on methane emissions from oil and gas production and processing sources, in close coordination with OAR and interagency efforts. Regional Applied Research Effort grants are in place with several EPA Regions to conduct research on both black carbon and methane emissions. ACE 4.01.10, 5.01.1, 5.01.2, 5.01.3
ORD is working with the Office of Air Quality Planning and Standards (EPA/OAR) to support the growing interest of partner offices to develop and understand future scenarios of energy production and use related to future strategies for air quality. The use of energy system modeling provides OAR with insights into possible future conditions given the significant uncertainties associated with future technology advancement and policy directions. Interactions with both the Office of Air Quality Planning and Standards and the Office of Atmospheric Programs (EPA/OAR) and with the National Center for Environmental Economics in the Office of Policy provide guidance to ORD regarding scenarios of interest. Growing interactions with DOE in particular, and with industry and the academic community, will be an area of emphasis. ACE 8.01
Possible scenarios of the U.S. energy system and the potential effect on emissions of key air pollutants and water demand are being evaluated using the MARKAL model. Life-cycle approaches are also being used to understand the broader environmental implications of different energy technologies more fully. Work is progressing to enable these two approaches to be combined, so that a more complete understanding of future configurations of energy systems can be developed. At the community level, research on community sustainability and associated CO_2 emission reductions provides information that can be applied locally. ACE 8.01
Complementing this work is research to evaluate performance of energy-related technologies. The greatest current effort in this area is evaluation of cookstoves (and including heating stoves) used primarily in developing nations, but with some application in the United States. Efforts in this area are supported by internal testing and grants through the STAR program. Additional efforts are evaluating the potential environmental impacts, applicability, and retrofit potential of carbon capture technologies for power generation. ACE 8.03, 8.02
STAR grant on the role of black carbon in climate and air quality. ACE 4.01.10
A STAR grant Request for Applications is under development to solicit research related to environmental implications of a changing energy infrastructure. This effort supports options to consider the “energy paradox” noted in the needs above. ACE 8.03.4
Research to evaluate opportunities for GHG emissions reductions through materials and land management practices. SHC 3.63.1

Gaps remain in our understanding of these three major components of Science Challenge 2. For emissions, these gaps include the efficacy/permanence of non-geologic sequestration of CO_2 (e.g., CO_2 utilization in cement, industrial use of CO_2); monitoring and accounting options; and non-CO_2 sources for the U.S. GHG Inventory (e.g., oil and gas production, landfills, coalmines, manure management). In addition, for direct and indirect nitrous oxide emissions from agricultural soils, we need to improve our ability to estimate emissions (e.g., more in situ measurements, data inputs, and process modeling) and identify opportunities to reduce emissions in the context of other environmental benefits of improved efficiency in nitrogen fertilizer use.

Although much of this discussion has focused on emissions sources, the need also exists to understand GHG sinks more comprehensively. Of particular interest are forests and water bodies, which can act as either sources or sinks, depending on conditions. Although work is ongoing in ORD to evaluate methane and nitrous oxide emissions from certain types of water bodies, the role of forests and water bodies as sinks needs to be better understood. Additional work is also needed to understand emissions of black carbon, with particular emphasis on emissions that ultimately deposit on snow and ice and result in more rapid melting. Although ORD is conducting some work to understand measurements and emissions of black carbon, the work does not focus on the contributions of tropospheric ozone and black carbon to Arctic climate change. The capabilities of other agencies (especially NASA and NOAA) will be needed to address this topic effectively.

Gaps in understanding also remain regarding mitigation technology assessment. Identified needs include information related to application of carbon capture to natural gas-fired electric generating units and evaluation of advanced residential or commercial ventilation technologies that improve energy efficiency while maintaining adequate flow of fresh air. More generally, syntheses of currently available information on cost, performance, applicability, and potential adverse environmental impacts of GHG mitigation technologies are needed.

Furthermore, damage functions need to be improved to support benefit analyses. Development of effective damage functions involves considerably more than estimating dollars per unit impact; information is needed for a wider range of impacts and to represent existing impacts more accurately (e.g., quantifying spatial and temporal variation), including impacts that cut across, or involve interactions among, sectors. Substantial work will be needed to improve estimates of benefit and impact valuations. The efforts to better quantify ecosystem goods and services in the SHC program and to develop valuation approaches for water in SSWR contribute to improved valuation estimates. Even so, the need remains for methods and data to value climate change impacts.

Finally, gaps remain in our ability to evaluate many co-benefits, especially those that cross sectors, systems, or media, or are associated with changes in ecosystem function. Approaches to quantify and value co-benefits are also needed, particularly for benefits other than reductions in air pollution.

As with Science Challenge 1, important needs for improved integration of social sciences expertise cut across Science Challenge 2. The questions related to valuation inherently require application of economics knowledge, for which numerous key gaps exist. These include the challenges associated with valuation of nonmarket impacts, such as culturally important sites or activities, which might require additional disciplinary expertise to address. Co-benefits of climate mitigation likely will involve benefits to social and cultural systems that are difficult to quantify, but which can be as important as economically quantified benefits. In some cases, evaluation of such benefits might need to incorporate information such as traditional ecological knowledge of Tribes or social values of importance to other groups. Other critical gaps exist regarding intergenerational equity and discounting, dealing appropriately with non-marginal climate change impacts, and aggregating damages over multiple regions, sectors, or impact types.

Valuing benefits is critical, and the social sciences can provide information to support planning processes and the design of policy mechanisms that better account for the deep uncertainties associated with climate change and lead to robust decision outcomes despite the uncertainties. The integration of social science expertise into the research related to Science Challenge 2 is also crucial for understanding the processes of technology innovation, evolution, and adoption, including how individuals and institutions respond to economic, policy, and other drivers of change. More broadly, as with Science Challenge 1, full integration of the social sciences at the problem formulation stage of research ultimately should lead to the identification of additional questions of importance to this Science Challenge, and is thus a critical aspect of programmatic design going forward.

Integration: Examples and Opportunities

One example of integration under Science Challenge 2 is the cross-organizational integration of cookstove performance research. Cookstove research is conducted in close collaboration with the Global Alliance for Clean Cookstoves (GACC), for which the Department of State (DOS) is the lead agency. Input from DOS and DOE has helped guide ORD in developing and implementing the testing program, and the cookstoves STAR solicitation was developed with input from GACC, DOS, DOE, HHS, and OAR within EPA. ORD has focused its research program on developing cookstove testing approaches, evaluating life-cycle impacts of biomass-based cookstove use, and understanding the ambient and indoor health impacts of exposure to cookstove emissions. Other agencies have focused on new technologies and population-level health impacts, while the GACC coordinates efforts with other countries and provides guidance on implementation issues.

Another example of integration relevant to Science Challenge 2 is the cross-media integration exemplified by investigations of methane emissions from reservoirs. Research to evaluate emissions of methane from reservoirs integrates nutrient management work originating in SSWR with measurement methods for area source emissions in ACE to develop a more holistic perspective of how management strategies for water quality can influence emissions. In addition, Science Challenge 1 presents a substantial opportunity to leverage research in support of benefits assessment and the development of improved estimates of climate change-related damages.

Summary of Research Efforts: Science Challenge 3

Science Challenge 3. *Identify and evaluate long-term, sustainable solutions for both the causes and consequences of climate change, including assessing the environmental impacts of emerging energy technologies and climate change adaptation and mitigation approaches, improving understanding of the nature of resilience in natural and human systems, and exploring the key role of communities as the nexus of both vulnerability and responses.*

The fundamental, long-term challenge of climate change is the choice between transformational impacts or transformational responses—or, perhaps more likely, a combination of the two. Science Challenge 3 seeks to address the transformational nature of climate change and our responses to it through improved understanding of the inherent complexities and interactions among affected systems, both natural and human. The scope of Science Challenge 3 is to look farther into the future and more broadly across systems in an effort to understand, holistically, the impacts of climate change on human health and the environment and to apply that understanding in developing sustainable responses to those impacts.

Research categorized under Science Challenge 3 should be considered more aspirational than the research under Science Challenges 1 and 2. Important aspects of this longer-term research, however, are needed in the near term to begin laying the groundwork for supporting organizational, institutional, and societal responses to the most severe projected impacts of climate change and responses that are long term and for which the long-term consequences must be anticipated. In this context, the major categories of research that address Science Challenge 3 are:

- the environmental and societal impacts of mitigation and adaptation actions;
- the aspects of socioenvironmental systems leading to reduced vulnerability and enhanced resilience in the face of climate impacts;
- the nature of sustainable environmental management under conditions of change, transition, and transformation;
- applying this knowledge in the design, development, and evaluation of sustainable mitigation and adaptation solutions (which might be fundamentally interlinked);
- incorporating a community focus into the development of response actions, recognizing the importance of social and institutional structures and the potentially important differences among regions, urban areas, and vulnerable communities; and
- quantifying vulnerability, risk, and resilience to the most severe potential impacts of climate change.

The basic long-term Science Challenge for GHG mitigation-related research is to develop the information needed to inform effective mitigation strategies that do not cause other, unacceptable environmental impacts. The examples of increased production of biofuels and natural gas demonstrate that adoption of approaches to reduce CO_2 emissions could have adverse environmental impacts (e.g., changes in land use and nutrient runoff and potential corrosion and leakage of underground fuel tanks for biofuels; potential impacts on groundwater and air quality related to natural gas production). Explicit regulatory actions at the national scale to mitigate GHG emissions (e.g., the Clean Power Plan and vehicle GHG standards) are relatively recent and represent only initial reductions relative to those needed to limit global warming effectively over the long term. Such actions, and potentially any associated environmental consequences, are expected to expand substantially. As was the case with biofuels and natural gas, these consequences might not be explicitly perceived as associated with mitigation strategies but, nevertheless, must be accounted for.

Part of the challenge is that the U.S. energy system is intricately connected with many other major systems—water, transportation infrastructure, agriculture, and ecosystems, among others—as well as globally; as such, it is fundamentally linked to the overall structure of the U.S. and global economies. Large-scale changes in any of these complex systems will have consequences for the others in ways that might not be immediately apparent. Life-cycle and systems analyses, including complex systems behavior (e.g., chaos, self-organization, consequence cascades), can provide insight into critical and inflection points to inform decision-makers. Such efforts are inherently integrative and require close interaction with researchers across EPA and across other agencies and organizations. This area of research, particularly, needs collaboration with social scientists, given the interplay between social and technological change related to energy, which remains a fundamental component of today's economic and social systems. As an example, smart-growth communities designed to improve community sustainability also tend to have reduced CO_2 emissions, but they also need to design and implement their smart-growth policies in ways that address the unique needs and contexts of each community and its individual members. Distributed energy production is another example of co-evolution of technologies and social systems (e.g., improved solar panels and batteries along with financing and regulatory structures) that can affect, and be affected by, climate change. Understanding the potential for both co-benefits and adverse impacts, social as well as biophysical, provides important information for decision-makers as they develop mitigation strategies.

Developing and applying approaches to understand systems and their complexities also advances the ability to respond to climate change with sustainable solutions. From development of sustainable energy- and water-efficient infrastructure, to a more holistic integration of ecosystems and social systems into adaptation and mitigation responses, the basic components of sustainability need to form the core of a comprehensive evaluation of and response to climate change and its impacts. The focus of research under Science Challenge 1 is on the impacts of climate change on the environment, but much of that work also can provide a starting point for understanding the ability of ecosystems to increase adaptive capacity or to act as CO_2 sinks. Similarly, efforts to understand the performance of mitigation technologies and approaches provide the starting point for developing a more comprehensive, sustainability-focused approach to mitigation. The Clean Power Plan and mobile source emission standards, which are in early stages of implementation, are opportunities to evaluate their potential environmental impacts and to understand more fully how consumer and producer behavior might respond to increased efficiency. The "energy paradox"—the potential for increased total energy use as efficiency increases—is one of numerous social drivers and impacts having direct implications for climate mitigation and adaptation, including governance, behavior, institutional dynamics, communication, education, and public engagement.

Sustainability, social drivers and impacts, and connections between adaptation and mitigation come together most visibly at a community level. For example, management of air and water quality, water availability, and adaptation are often community-level responsibilities. Communities represent the nexus of climate change drivers, impacts, vulnerability, and resilience and climate change responses (in terms of both adaptation and mitigation). Approaches such as smart growth can be inherently integrative with respect to mitigation, adaptation, sustainability, and human health and welfare, but implementing such approaches requires adequate institutional capacity to identify and incorporate a broad range of information that often cuts across traditional governance structures. In many instances, a community-based approach can serve as an organizing framework for development and evaluation of decision-making approaches that integrate many important social science topics, from governance and community engagement to communication and education. Research in SHC is developing approaches for incorporating information on sustainable approaches, ecosystem goods and services, and community-based decision-making that provides a foundation for building community capacity to adapt to the impacts of climate change. A community focus also provides a strong connection to the environmental justice aspects of climate change. The greater vulnerability of environmental justice communities to the impacts of climate change must be considered when evaluating climate risks and developing response strategies. Strategies that make sense at a national level need to be evaluated in the context of those communities that could be at greater risk, and with less economic and social capacity to implement those strategies.

> *Research in the SHC program creates the foundation for building communities' capacity to adapt to the impacts of climate change. This community focus provides a strong connection to the environmental justice aspects of climate change.*

Finally, much of the work under Science Challenges 1 and 2 is implicitly rooted in the types and extent of climate change impacts projected as most likely to occur. As the climate moves increasingly outside its historical range, the potential for transformational impacts also grows. Transformational impacts could be considered worst-case scenarios for single impacts, or they might be the consequence of complex system dynamics resulting in cascading impacts that ultimately might create substantially more severe hazards than any single initiating event. Transformational impacts are those we would consider unmanageable given our current state of preparation, tools, governance, and institutional infrastructure. An example is sea level rise that is higher and occurs more rapidly than indicated by the central modeled projections, leading to abandonment of a substantial amount of occupied or densely populated coastal area. Such abrupt, severe climate change impacts, which also might include precipitous collapse of Arctic sea ice cover, sudden release of methane from permafrost, or the onset of decades-long megadrought conditions, are all within the range of scientific plausibility this century, and would have very large direct and indirect socioenvironmental impacts should they occur.

Similarly, complex, interconnected systems also could be subject to cascading failures that reveal previously unknown vulnerabilities, such as those experienced during Superstorm Sandy when gasoline supplies were rendered largely unavailable after electric power for pumping systems was lost. Impacts to emergency response or backup power from similar events can put healthcare systems at risk when they are needed most. Cross-government and interagency efforts to describe, evaluate, and incorporate the lessons learned from events such as Sandy and Hurricane Katrina represent an important starting point for understanding climate-related disruptions to complex, integrated systems such as urban areas —understanding that will become ever more necessary as the risk of such disruptions grows. Even so, the current research effort, within EPA and more broadly, is only just beginning to develop more holistic approaches for understanding these types of complex systems and their critical linkages and feedbacks. Likewise, in-depth evaluations of the risks and risk management options associated with catastrophic impacts are generally lacking. Although general awareness of the potential for such impacts might exist, substantial research is needed to understand more clearly the national, regional, and local implications on governance and infrastructure, population relocation, economic disruption, and national security. Such efforts go well beyond ORD and EPA, although we have important roles in conducting evaluations of the vulnerabilities, risks, and responses.

Examples of Ongoing Research Relevant to Science Challenge 3
Research related to more sustainable water infrastructure. Includes efforts to advance the use of green infrastructure for mitigating sewer overflows during high precipitation events, "net-zero" utility operations and sustainability indicators, water reuse treatment technologies, technologies that reduce energy consumption in water treatment, and processes for energy production from water treatment wastes. SHC 3.63.4; SSWR 6.03A
Research to provide guidance to OW and water utilities concerning the development of sustainable water systems, focusing on a systems perspective of water resources and water systems in the context of a changing climate. Much of this research is place-based, with the intent of evaluating real-world systems and developing system-based concepts broadly applicable to other communities. Taking a sustainability approach can provide information that guides resource managers toward the appropriate balance of active intervention (e.g., storm sewers) and reliance on natural adaptability (e.g., natural wetlands). This work includes developing a comprehensive, systems-based approach to management of Narragansett Bay and regionally based case studies of water resource and treatment systems. ACE 4.01.1, 4.02.6; SSWR 5.01D
Research to evaluate the impacts of land use change associated with biofuel production, which could affect water quality and aquatic ecosystems. SHC 4.61.4
Research to advance the identification and treatment of pathogens expected in warmer source waters and increased runoff in regions experiencing wetter climates; research to support the development of treatment processes, such as anaerobic ammonia oxidation for ammonia removal in wastewater, which might decrease energy consumption. SSWR 6.03C
Research on the potential leakage of biofuels into groundwater due to corrosion and leaks of underground fuel storage; work on monitoring and contaminant transport related to this leakage is being conducted in SHC. SHC 3.62.3
Development of life-cycle analysis methods conducted under the CSS program informs approaches for evaluating life-cycle GHG emissions and the environmental impacts of mitigation and adaptation strategies.
Effort to incorporate water demand into evaluations of future energy scenarios. This work is examining how changes in energy production technologies for GHG reduction might affect water demand for cooling or production (in the case of biofuels), or, alternatively, how constraints on water could affect the mix of energy production technologies for mitigation. ACE 8.01.5
Research on the evaluation, design, and development of urban resilience indicators to support planning and prioritization. ACE 4.03.4; SHC 2.64.1
Research on the development of adaptation frameworks appropriate for linking climate change vulnerability and risk assessment with systematic approaches for identifying, selecting, and implementing adaptation actions and for evaluating their effectiveness over time or as new information becomes available. ACE 4.03.3, 4.03.4

Much of what is included under Science Challenge 3 represents research needs or gaps, given the longer-term, aspirational focus of the work envisioned in this area. EPA's expanding efforts to reduce

GHG emissions ultimately will need to be matched by equivalent increases in understanding the environmental impacts of proposed and alternative mitigation approaches. Although much of the technology evaluation work to date has been conducted by DOE or industry, syntheses that focus on the environmental impacts of the evaluated technologies can be of considerable value to inform policy development and the technology evaluation programs. Expanding from such syntheses to life-cycle and supply-chain analyses of renewable technologies provides important information for developing sustainable energy production. Understanding the social dimensions of technology evaluation is also essential, for example, understanding barriers to adoption of new technologies and the social and economic consequences of technologies, given their effects on the net environmental impacts and benefits of energy production and use. A further gap in research related to mitigation is the need to understand, more fully, GHG reductions (and the potential for future reductions) related to EPA activities other than those associated with OAR. Such efforts include reducing methane emissions from landfills and water treatment facilities, improving energy efficiency of water treatment, enhancing materials management strategies, and expanding green chemistry. Although initial efforts have been made across EPA to quantify such reductions, methodologies that are more consistent are needed to develop more comprehensive and consistent estimates.

Current ORD research focusing on sustainability and communities' needs to account more comprehensively for the projected impacts of climate change and how those impacts might affect, and be affected by, efforts to reduce GHG emissions and to adapt to potential changes in climatic conditions, including drought and extreme weather events. More research is needed on thresholds, tipping points, and other state-change processes associated with complex systems behavior, in the context of both climate impacts and climate responses. Other community-level concerns that would benefit from additional emphasis center on vulnerable populations regarding the impacts of climate change. These concerns include environmental justice issues, including issues related to impacts on Tribal communities. Although we often focus on health impacts when considering population vulnerabilities, Tribal communities are additionally vulnerable in their ability to maintain subsistence hunting and fishing and other cultural practices at risk due to climate change. Of particular concern are the Alaskan Tribes, which are facing much more severe changes in climate to date than those experienced elsewhere in the United States.

Additional effort is needed to begin evaluating the potential scope of the most severe impacts of climate change, as understanding of such impacts is critical to developing adequate evaluations of the risks of climate change to EPA's mission. Several specific examples illustrate the need to understand the risks associated with impacts that are more severe than the central projected tendencies, especially given those impacts are likely to respond highly nonlinearly with respect to global average temperature. More rapid warming than the projected mean could lead to truly extreme heat—perhaps beyond the physiological coping capacity of large segments of the population—extended severe drought, torrential rainfall events, superstorms, and massive pressure on ecosystems. More rapid melting of the land-based ice sheets than projected (for a given level of warming), now viewed as increasingly possible, would lead to many additional feet of sea level rise this century, with devastating consequences for coastal communities. Continued changes in the ocean due to accelerating warming and acidification could result in major alteration, or even collapse, of the ocean biosphere—and, in the context of human needs, its vast ecosystem services.

The potential for impacts at the worst end of the projected range is not without precedent, as perhaps previewed by experience in the Arctic. For a variety of reasons, ORD's current research portfolio has few efforts that address Arctic issues. Although climate change impacts are measurably more severe in the Arctic (which, in the context of this Roadmap is limited to northern Alaska and adjacent coastal waters), not much ORD research is related to such impacts. Issues such as biogenic methane, coastal erosion, habitat loss, and other climate change-related impacts are essential to EPA and are the subject of research in other agencies, and EPA works within several interagency bodies to convey research needs and facilitate exchange of research results. Although EPA research priorities require continued focus on issues other than the Arctic, recognizing the needs for scientific and technical information is critical for emissions of SLCFs, such as black carbon and methane, and for climate-related impacts on water quality, ecosystems, and human health that might be unique to Arctic environments. Furthermore, the growing interest in climate intervention as a strategy to reduce the impacts of climate change,[23,24] in part motivated by growing awareness of rapid Arctic change, indicates that ORD should maintain an awareness of such proposed approaches, and their many potential issues, that could be relevant to EPA policies and programs.

Finally, as with the previous two Science Challenges, Science Challenge 3 can be effectively addressed only if it integrates across the range of both biophysical and social sciences. The topics of sustainability and community resilience inherently concern social systems. Similarly, the energy system, while often considered only in a technological context, is so closely intertwined with social systems that it cannot be effectively studied without broad, interdisciplinary understanding.[25] Overall, much greater insight is needed into how individuals, institutions, and other social systems respond to climate change and its impacts and responses. Many important questions remain, for example, about impacts on cultural resources or understanding organizational structure and dynamics under conditions of significant change. Adaptation and mitigation responses can be adequately evaluated over the long term only through evaluations of community networks and relationships. Similarly, adaptation actions in many cases might not be easily distinguishable from actions undertaken to address environmental protection in general, which introduces additional challenges to evaluation of effectiveness. Innovative approaches, such as agent-based modeling, might be needed to untangle these interconnections and provide the insights needed to evaluate the potential effectiveness of those responses most comprehensively.

IV. Summary of Gaps, Opportunities, and Future Priorities

This Roadmap articulates an integrated framework for current and planned ORD research relevant for understanding the many complex ways in which climate change now, and increasingly in the future,

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[23] National Research Council, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. National Academies Press, Washington, DC, 154 pp.

[24] National Research Council, 2015: *Climate Intervention: Reflecting Sunlight to Cool Earth*. National Academies Press, Washington, DC, 260 pp.

[25] Sovacool, 2014: Diversity: Energy studies need social science. *Nature*, **511**, 529-530.

intersects with EPA's fundamental mission to protect human health and the environment. This framework is based on the needs of partners in ORD's Program and Regional Offices for actionable knowledge, information, data, and tools to support their responses to the risks posed by climate change, as well as the similar needs of their many diverse stakeholders at the State and local level. This framework has described the major scientific challenges, knowledge gaps, and opportunities for continued progress that characterize ORD's climate-related research efforts. Synthesizing from this discussion and the many associated examples, we propose that ORD's research endeavor on climate change continue to advance, becoming a truly integrated effort that embodies the following three guiding principles:

1. Predicated on a *systems* science approach that prioritizes research that is inherently cross-media, cross-scale, and cross-discipline.
2. Explicitly considers the *social* dimensions of change, both as part of the fundamental socioenvironmental nature of climate change as a science problem and as an essential element for moving the results of that science into action.
3. Focuses ultimately on *solutions* to the threat climate change poses to EPA's mission and to society, moving from the current focus on risk identification and characterization to the science needed to support responses.

The "three S's" (systems, social, solutions) are major integrative elements that cut across the three Science Challenges. They provide context (and a useful shorthand) for understanding the most important gaps, opportunities, and priorities for ORD's climate change research, to meet the near- and long-term needs of ORD's partners to inform:

- adaptation actions to enhance resilience across a broad range of environmental and social stresses;
- mitigation actions to limit GHG emissions and slow the rate of climate change; and
- ultimately, the transition to sustainability in the face of both the transformational impacts and transformational responses that will characterize the problem of climate change over the long term.

A. Synthesis of Existing Gaps

The near-term research needs expressed by our EPA partners and many of the related, specific research gaps noted throughout this Roadmap are generally, although not exclusively, relatively straightforward extensions of research representing ORD core strengths—but viewed through the novel lens of constantly changing environmental conditions and shifting baselines. Examples are modeling of air quality and water quality, evaluations of aquatic ecosystems, and analyses of energy technologies and systems. Such efforts are crucial for meeting our EPA partners' needs in addressing their near-term challenges, and they are equally critical as the foundation for future research efforts. The specific gaps discussed under the individual Science Challenges reflect our initial efforts to characterize more fully the most "risk-relevant" aspects of climate change for society: those impacts that pose the greatest risk to public health and environmental, social, and economic systems. For example, we need a stronger focus on translating basic climate science into environmental management endpoints that are closer to EPA's regulatory mission, such as water flow and quality.

Such a risk-based approach to climate change impacts also necessitates greater focus on identifying the largest risks we face from climate change, with respect to the kinds of low-probability but high-consequence outcomes that, while highly uncertain, often dominate risk calculations. This approach is analogous to that taken for air quality, in which risk assessments and management actions focus first on reduction of mortality. Such risks are not limited to extreme events, but also include the possibility of major nonlinearities in climate system behavior, such as a transition to long-term drought conditions in the Southwest, or much more rapid-than-expected ice sheet melting and subsequent sea level rise. To be of greatest value in increasing the understanding of climate change impacts and our ability to respond effectively, incorporating new approaches to modeling and analysis will be necessary to encompass these new dimensions, many of which might not yet be generally accepted or even developed. For example, addressing such issues will require integrating diverse lines of scientific evidence into our research and assessments that go beyond what we can glean from the current generation of climate models.

In addition, much more work is needed to appropriately position climate change within a larger, interdisciplinary "system science" framework, as one of several linked, local-to-global changes that will affect the environment, including changes in population and demographics, economic growth, land use, biogeochemical cycles, technology, and other large-scale trends. Understanding climate change in a multistressor context needs to become a more substantial part of ORD's climate change research program, so that the research ultimately can support the more complex and integrated policy and regulatory regimes that will be required in the future to adapt to the growing effects of climate change across the breadth of EPA's mission.

The inherent complexities and deep uncertainties of climate change likely will require that EPA develop and implement adaptive management strategies that enable ongoing evaluation and adjustment as information is gained, requiring regulatory flexibility, robust monitoring programs, and a portfolio of alternative management approaches that can be tapped as conditions change over time. Major gaps in understanding the social determinants of vulnerability and adaptive capacity, of both communities and individuals, and in evaluating the effectiveness of existing and proposed adaptation options across air quality management, water quality management, protection of ecosystems and ecosystem services, and public health, will need to be addressed to support ORD's Program and Regional Office partners going forward. Designing more effective policies to reduce the risks of significant harm to public health and welfare will require improved understanding of the social and behavioral factors that motivate and shape decision-making about GHG mitigation actions and actions to adapt to the impacts of climate change.

From the mitigation side, fully evaluating the risks that climate change poses to human health and the environment, and the benefits (and co-benefits) resulting from actions to control GHGs (or other, non-GHG regulations), will depend on greater progress in our ability to quantify and incorporate into benefits assessments the individual and aggregate economic damages of climate change. Such progress would include improving the accuracy and comprehensiveness of damage functions used in economic models; considering impacts that are difficult to value within current economic analysis frameworks; addressing equity across populations and nations; and dealing with the substantial challenges associated with discounting, time preferences, and intergenerational equity.

Finally, ORD research ultimately will need to be able to inform the development, implementation, and ongoing evaluation of long-term, sustainable solutions for both the causes and consequences of climate change, including assessing the environmental impacts of mitigation responses and transitions to alternative energy technologies, among other major societal transitions. A focus on communities as a fundamental unit of systems-based and solutions-oriented climate change science will be a critical element of future ORD research, as communities and their supporting environmental systems represent the nexus of climate change drivers, impacts, and responses. Critical knowledge gaps in this area relate to improving our understanding of the key characteristics of socioenvironmental systems that lead to reduced vulnerability and enhanced resilience in the face of climate change-related impacts, and of the key differences among management strategies aimed at maintaining the status quo, managing for change, or persistence of critical functions and services following a regime shift.

B. Opportunities for Further Integration

For a topic as broad and crosscutting as climate change, integration is essential—but it can always be improved. In general, integration across the various focus areas of climate-related research in ORD has improved substantially as the issue of climate change has become a higher priority for EPA. The challenge remains to find the appropriate balance of resource investments between conducting the focused research necessary for producing the knowledge needed to address specific issues, and the efforts needed for integrating across topics, programs, and organizations effectively so that long-term understanding and solutions can be developed. Because resources are always finite, judgment is needed to identify the most promising opportunities to seed and expand integrated research efforts. In the near term, several promising efforts are underway that could help provide a model and foundation for future integration efforts. The development of an assessment of climate change impacts on water quality is an example of using syntheses and assessments to integrate past research results and connect future research activities. Other opportunities for such syntheses and assessments include scenarios of energy system development, application of global climate model downscaling for use in regional impacts modeling, and decision-making under deep uncertainty. Existing cross-program interactions on topics such as drought, HABs, and community-level decision-making can be expanded and strengthened.

Integration across ORD climate research faces several challenges, but each presents opportunity for improvement. For example, EPA has numerous responsibilities that involve development and operation of infrastructure, from water treatment systems to solid waste landfills to air pollution control systems, all of which can have operational lifetimes of decades. These responsibilities include providing guidance and oversight on long-term investment and operation to local decision-makers, which means the need for information on projected impacts of climate change is immediate and growing. The great majority of ORD's research is oriented toward addressing near-term needs, but we should begin to look beyond these to prepare for the more severe, longer-term impacts of climate change that we are increasingly likely to have to face. Such major changes include loss of habitable land due to sea level rise, long-term severe drought, and major loss of forested areas, all of which are possible and all of which would require very different approaches to implementation of environmental programs compared to current practices. More broadly, the need to develop an understanding of when and how to transition from managing adaptation to incremental changes to managing major changes in the state of the environment presents an important opportunity for cross-organization dialogue, visioning, and problem formulation. In essence, this is a true paradigm shift, which will require substantial effort over an extended time to accomplish, and which is well beyond the scope of ORD's current (or the broader Federal) research enterprise.

Another organizational challenge, and opportunity, for developing an effective integrated research effort is the extensive scope of expertise that is relevant and necessary for addressing the impacts of and responses to climate change. For example, the need for expanding the role of the social sciences in the climate research portfolio has been a major theme throughout this Roadmap. Organizationally, the challenge is to find ways to increase ORD's capacity to incorporate social sciences, among other relevant expertise, while maintaining the crucial core of existing expertise needed to address current issues. Many mechanisms exist to bring new expertise into contact with ORD's research efforts, whether through STAR grants, postdoctoral programs, or collaborations between ORD researchers and outside experts. These mechanisms should be extensively explored and leveraged to expand the expertise that can be brought to bear on increasingly integrated scientific efforts to support increasingly complex partner needs.

Finally, working across organizational boundaries remains a challenge to integration. This challenge is not simply related to bureaucratic process, but is a very real consequence of different organizational missions and responsibilities. Although such differences might appear as bureaucratic barriers, the underlying reasons for cross-organizational challenges to the ideal of integration are often valid. These reasons are unlikely to disappear overnight, but approaches can be taken to conduct research in a cooperative or coordinated manner. The same premise applies for work across agency boundaries, as a truly systems- and solutions-oriented approach will necessarily recognize the importance of work within other agencies and organizations, as emphasized throughout this Roadmap. Each research need identified in this document relies to greater or lesser extent on research conducted by other members of the Federal family and the broader U.S. climate science enterprise. Ongoing efforts to coordinate through interagency working groups within USGCRP and other formal bodies, peer-to-peer interactions, formal interagency agreements, and other mechanisms are likely to become even more important for addressing these needs.

C. Prioritized Research Needs for ORD

Setting priorities for ORD's research is an ongoing process, resulting from numerous and continuing discussions with our EPA partners, who have identified numerous needs for scientific insights, technical information, and tools and data to inform decisions that they now face regarding climate change. The ongoing research described under Science Challenges 1 and 2 is largely in direct response to these near-term needs, although that research does not fully address the entire scope of those needs, and many immediate gaps need to be filled. At a high level, key near-term priority needs include continuing to develop and improve approaches to allow ORD's Program and Regional Office partners to incorporate non-stationarity regarding temperature, precipitation, sea level, and associated extremes into their media-specific policy and program actions and to quantify the individual and aggregate impacts of climate change and the monetary benefits of avoiding those impacts by reducing GHG emissions.

Over the longer term, priority research needs focus on three main topic areas: (1) understanding climate change and responses in the context of complex systems; (2) understanding the socioenvironmental impacts of, and responses to, climate change, and in particular its most severe potential impacts, within a risk-based framework; and (3) using this new knowledge to inform the development and implementation of integrated, sustainable solutions to the long-term consequences of climate change, and the actions taken in response. These topics motivate and inform the long-term research portfolio envisioned under Science Challenge 3.

Over both the near term and long term, an overarching priority will continue to be the consolidation and synthesis of research currently underway, for all three Science Challenges. Such syntheses are of substantial benefit to our EPA partners because they provide insight into both the current state of the science across a particular topic and the implications of this knowledge base for their program, policy, and decision-making needs.

D. Informing 2016–2019 ORD Research Planning

Although the physical Roadmap is a static document, its primary value is to provide a common vision of ORD climate change research, as a starting point for continuing discussions about research needs, issues, results, and activities among researchers, Program staff, and ORD partners. Informing ORD's research planning through this Roadmap involves multiple, ongoing, formal and informal activities. Major revisions to each National Research Program StRAPs were completed in early 2016; the revisions included the incorporation of climate change research issues identified during cross-ORD and cross-EPA evaluations of needs and capabilities. The development of the 2016–2019 StRAPs provided the framework for enhanced interactions across Programs and Offices, setting the stage for ongoing interactions that provide continuing communication of needs and results.

One mechanism that emerged from the StRAP revision efforts is the formation of PACTs, which bring together research task and project leads, Laboratory and Center coordination staff, National Program staff (including from multiple programs in the case of PACTs for climate-related topics), and representatives from relevant EPA Headquarters and Regional Offices. The PACTs are intended to provide a venue for ongoing interactions to identify and communicate evolving research needs and advances and to inform ORD's partners about research results earlier and in more detail. The research activities, needs, and gaps identified in this Roadmap will inform the PACTs of important climate change-related issues and activities and provide one avenue into ORD's ongoing planning and evaluation activities. Conversely, the discussions that occur within the PACTs will provide information for future revisions of the Roadmap. In addition, periodic project-level reviews within ORD enable discussion of progress and cross-program interaction at a more detailed level. These reviews include discussion of opportunities for researchers to connect across projects and Programs to address research topics identified in the Roadmap and to inform future Roadmap revisions regarding advances in understanding and discovery of new research issues.

Finally, at an interagency level, discussions within formal interagency coordinating mechanisms, such as USGCRP and other relevant CENRS bodies, provide opportunities for communicating EPA research needs and identifying prospects for interagency collaboration. Within USGCRP, for example, development of annual interagency research priorities on climate change considers issues of importance to EPA, and feedback from those discussions informs the ORD Program- and project-level discussions of future research directions. Similarly, the development of the quadrennial interagency National Climate Assessments, and the associated ongoing Sustained Assessment process, significantly expand the breadth of scientific assessments related to climate change and its impacts, which then are available to inform EPA and help meet critical EPA partner needs.

V. Wrap-up

EPA faces enormous challenges in response to climate change, as does the Nation and the world. Over the past few years, EPA and ORD have made substantial strides toward repositioning in order to face those challenges. This Roadmap represents one component of that effort: to understand more fully the integrated research portfolio needed to inform, in both the near term and long term, EPA planning, policy, and decisions about responding to the risks posed by climate change to its mission.

A roadmap serves as a fitting analogy for implementing the ideas and addressing the needs identified here. A map is no substitute for keeping one's eyes on the road immediately ahead, but looking only at what is immediately ahead is no way to make progress toward one's destination. This *Climate Change Research Roadmap* presents what is immediately ahead—the needs of our EPA partners as they work to bring the best science into their development and implementation of policies and programs. It also points toward the longer-term issues that will enable ORD to adjust its research to help EPA fulfill its mission in the years to come.

Implementing the Roadmap requires continuing the discussions and interactions that have been the basis for its development. It requires continuing to listen to the needs of ORD's Program and Regional Office partners to allow ORD to define the research questions that derive from those needs, and working with them to ensure that the resulting research is designed and implemented to meet those needs. It also requires continuing to interact with researchers in other agencies and institutions to define the research questions that derive from advances in scientific understanding. This Roadmap identifies opportunities to connect across ORD Programs, EPA Offices, and other Federal agencies on issues that are inherently crosscutting. Like any map, however, identifying the destination is not the same as moving toward it.

Actual coordination and integration is advanced by taking advantage of venues such as the PACTs, continuing interactions across Programs and Offices, and participating in Interagency Working Groups, using the Roadmap to provide context about current research activities, near-term partner needs, and long-term science questions. As was demonstrated by the efforts to develop the recent Climate Change and Human Health Assessment, these interactions have longer-term benefits: the building of relationships and connections that are the core of integration and synthesis.

Likewise, information provided in the previous Roadmap fostered the development of cross-Program research such as methane emissions from reservoirs and incorporation of downscaling methods into watershed studies, which are now tasks in ACE and SSWR.[26] The communications approaches that have evolved over the past several years provide the means to disseminate a common perspective on climate research needs and issues, assisting efforts at all levels of ORD to identify, initiate, and nurture connections between researchers that are the foundation of cross-Program integration and synthesis.

This Roadmap reflects efforts across ORD, in partnership with other parts of EPA, other Federal agencies, and the broader scientific community, to identify and communicate the challenges and opportunities for research related to climate change—all within an EPA context. This Roadmap emphasizes the overarching theme of integration, which applies not only to the research *topics*, but also to the research *activities*. Implementing this Roadmap will require ongoing efforts to encourage and enable such integration, continual evaluation of progress, and periodic adjustment. Our hope and expectation is that this document will provide ORD with a compelling vision, broad guidance on scientific priorities, and a starting point for gauging that progress and assessing the need for adjustments as the research program evolves into the future.

[26] See Appendix B: ACE Task 5.01.8, "Development of measurement methods and statistical models to predict emissions from impounded waters (reservoirs)" and SSWR Task 4.02B, "Ecosystem Response and Recovery."

Appendix A. Abbreviations and Acronyms

ACE	Air, Climate and Energy research program
BenMAP	Benefits Mapping Analysis Program
BOSC	Board of Scientific Counselors
CENRS	Committee on Environment, Natural Resources, and Sustainability
CO_2	carbon dioxide
CMAQ	Community Multiscale Air Quality model
CSS	Chemical Safety for Sustainability research program
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOS	U.S. Department of State
EPA	U.S. Environmental Protection Agency
GACC	Global Alliance for Clean Cookstoves
GHG	greenhouse gas
HAB	harmful algal bloom
HHRA	Human Health Risk Assessment research program
HHS	U.S. Department of Health and Human Services
HSRP	Homeland Security research program
MARKAL	MARket ALlocation energy systems model
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OAR	Office of Air and Radiation (EPA)
OCSPP	Office of Chemical Safety and Pollution Prevention (EPA)
OLEM	Office of Land and Emergency Management (EPA)
ORD	Office of Research and Development (EPA)
OW	Office of Water (EPA)
PACT	Partner Alliance and Coordination Team
PCAP	President's Climate Action Plan
PM	particulate matter
SAB	Science Advisory Board (EPA)
SLCF	short-lived climate forcer
SHC	Sustainable and Healthy Communities research program
STAR	Science to Achieve Results
StRAP	Strategic Research Action Plan
SSWR	Safe and Sustainable Water Resources research program
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
WRF-CMAQ	Weather Research Forecast-Community Multiscale Air Quality model

Appendix B. Climate-Related Research Tasks

The project and task titles reflect preliminary alignments in the 2016–2019 Strategic Research Action Plans. Programmatic changes might result in name changes, realignment, mergers, or splits that are not reflected in Table B-1.

Table B-1. ORD Climate-Relevant Research Tasks

ACE 4.01: Climate Impacts on Human Health, Air Quality, and Ecosystems	
ACE 4.01.1	Characterization of particulate matter indirect effects on clouds and climate using the WRF-CMAQ coupled modeling system
ACE 4.01.2	Climate impacts on human health, air quality, and ecosystems
ACE 4.01.3	Regional climate and air quality scenarios
ACE 4.01.4	GLIMPSE: A computational framework for assessing interactions among air quality, climate change and energy
ACE 4.01.5	Interactive impacts of climate change and nitrogen deposition on ecosystems and ecosystem services
ACE 4.01.6	The effects of climate change on human exposure to air pollution
ACE 4.01.7	Impact of the effects of climate change on the health of populations and susceptible subgroups
ACE 4.01.8	Development of an integrated climate and health impacts module (ICHIM)
ACE 4.01.9	Understanding relative vulnerability to climate-related health effects through maps of vulnerable populations and at-risk locations in the United States
ACE 4.02: Watersheds, Water Quality and Ecosystems	
ACE 4.02.1	Assessing impacts of individual and multiple climate stressors on near-coastal species at a regional scale
ACE 4.02.2	National vulnerability assessment methods applied to wetlands
ACE 4.02.3	National hydrologic landscape map and vulnerability assessment
ACE 4.02.4	Indicators of climate change in forested watersheds
ACE 4.02.5	Synthesis and assessment of climate change effects on water quality and aquatic ecosystems
ACE 4.02.6	Regional adaptation case studies for sustainable water resources
ACE 4.02.7	Regional coordination and implementation of climate change mitigation and adaptation, Region 10 pilot
ACE 4.02.8	Climate refugia for salmon and other cold-water aquatic taxa
ACE 4.02.9	Climate change adaptation framework for ecosystem management
ACE 4.02.10	Watershed modeling to assess the effectiveness of management practices for adapting to climate change
ACE 4.02.11	Vulnerability and adaptation assessments to support attainment of the National Water Program Strategy: Response to Climate Change

ACE 4.03: Systems-Based Approaches for Sustainable Solutions	
ACE 4.03.1	Integrated climate and land use tools and datasets for impacts, vulnerability, and adaptation assessments
ACE 4.03.2	Scenarios, valuation, indicators, and case studies in support of assessments
ACE 4.03.3	Building decision support for adaptation into agency modeling frameworks
ACE 4.03.4	Methods to assess urban resilience as a path toward sustainability under climate and land use changes
ACE 4.03.5	Smart and resilient urban systems
ACE 4.03.6	Urban resilience indicators and restoration prioritization to support implementation of the Office of Land and Emergency Management Climate Change Adaptation Implementation Plan
ACE 5.01: Methods for Measurement to Inform Policy Decisions	
ACE 5.01.8	Development of measurement methods and statistical models to predict emissions from impounded waters (reservoirs)
ACE 6.01: Multiscale, Multipollutant Air Quality Modeling	
ACE 6.01.2	Extension, application, and evaluation of CMAQ to hemispheric scales
ACE 6.02: Integrated Multimedia, Multi-stressor Systems Model Development	
ACE 6.02.3	Linkage with global climate models downscaling techniques
ACE 7.04: Translate Research into Actions that Protect Public Health and Wellbeing	
ACE 7.04.3	Integrating public health messaging with environmental models and understanding their effectiveness to reduce burden in population
ACE 8.01: Systems, Scenarios, and Life Cycles	
ACE 8.01.1	Assessing the potential role of energy technologies and fuels in meeting Agency goals
ACE 8.01.2	Development of methods and tools for supporting local- and regional-scale decision-makers in addressing energy and environmental issues
ACE 8.01.3	Energy and climate assessment using the MARKAL model
ACE 8.01.4	Life-cycle evaluation
ACE 8.01.5	Water demands and impacts of the energy system
ACE 8.02: Energy Extraction, Production, and Delivery	
ACE 8.02.1	Greenhouse Gas Mitigation Options Database (GMOD) and tool
ACE 8.02.2	Environmental implications of advanced combustion technologies
ACE 8.02.3	Environmental and economic analysis of natural gas-based technologies for the power sector
ACE 8.02.4	Assessment of alternative, low-cost, low-tech carbon mitigation technologies
ACE 8.03: End-Use Impacts	
ACE 8.03.1	Evaluation of cookstoves for developing countries
ACE 8.03.2	Exploration of evolving landscapes for the utilization of energy in the end-use sectors: Technology, behavior, environmental, and economic impacts and consequences

HSRP 4.05: Community Environmental Resilience	
HSRP 4.05.01	Evaluation of environmental indicators for community resilience
SHC 1.62: EnviroAtlas: A Geospatial Analysis Tool	
SHC 1.62.2	National component research and data development
SHC 2.61: Community-Based Ecosystem Goods & Services	
SHC 2.61.1	Integration, synthesis, and strategic communication
SHC 2.61.3	Ecological production functions for quantifying final ecosystem goods and services
SHC 2.61.5	Coordinated case studies
SHC 2.62: Community Public Health & Well-Being	
SHC 2.62.1	Community outreach and assessment tools
SHC 2.62.5	Public health conditions
SHC 2.63: Assessing Environmental Health Disparities in Vulnerable Groups	
SHC 2.63.6	Analyzing relationships between selected social determinants and chemical stressors affecting environmental justice communities
SHC 2.64: Indicators, Indices & Report on the Environment	
SHC 2.64.1	State of the practice for environmental indicators
SHC 2.64.4	Resilience and relevance indices
SHC 3.61: Contaminated Sites	
SHC 3.61.2	Contaminated groundwater research
SHC 3.61.5	Tools for evaluating temporal and spatial impacts of contaminated sites on public health and the environment for use in site remediation, restoration, and revitalization decisions
SHC 3.62: Environmental Releases of Oil & Fuels	
SHC 3.62.3	Research to support LUST program planning and backlog reduction
SHC 3.63: Sustainable Uses of Wastes & Materials Management	
SHC 3.63.1	Tools and methods for sustainable materials management decision analytics
SHC 3.63.3	Innovation and long term performance
SHC 3.63.4	Net Zero
SHC 4.61: Integrated Solutions for Sustainable Communities	
SHC 4.61.3	Community sustainability assessment and management
SHC 4.61.4	Integrated nitrogen management
SHC 4.61.5	Sustainable port communities
SHC 4.61.6	Social-ecological systems for resilience and adaptive management in communities

SSWR 3.01: Assess, Map, and Predict the Integrity, Resilience, and Restoration Potential of the Nation's Water Resources	
SSWR 3.01B	Estimating and predicting water resource condition and watershed integrity
SSWR 3.01C	Watershed resilience, recovery potential, and sustainability
SSWR 3.01D	Synthesis, development, and integration of watershed sustainability in models and tools for policy and decision-making
SSWR 3.01G	Quantifying spatial and temporal gradients of wetland landscape connectivity
SSWR 3.03: Protecting Water while Developing Energy and Mineral Resources	
SSWR 3.03B	Assessing challenges to sustainable water resource management from underground injection practices
SSWR 4.01: Harmful Algal Blooms	
SSWR 4.01C	A data intensive investigation of temperature impacts and bloom modeling
SSWR 4.02: Science to Improve Nutrient Management Practices, Metrics of Benefits, Accountability, and Communication	
SSWR 4.02A	Improved nutrient indicator development
SSWR 4.02B	Ecosystem response and recovery
SSWR 4.02C	Nutrient sources and relative contributions to impairment
SSWR 4.03B	Modeling approaches that allow for consideration of market-based policy options
SSWR 4.03C	Monitoring and multimedia modeling approaches for verifying reduction
SSWR 5.01: Green Infrastructure Models and Tools	
SSWR 5.01A	Green infrastructure model research
SSWR 5.01B	Green infrastructure decision support tools (including gap analysis, development and evaluation components)
SSWR 5.02: Green Infrastructure Community Partnerships	
SSWR 5.02A	Integrating green infrastructure into communities
SSWR 6.03: Transformative Approaches and Technologies for Water Systems	
SSWR 6.03A	Systems approaches for assessment of water reuse

Table B-2.ORD STAR Grant Climate-Relevant Research Tasks

ACE 4.01: Climate Impacts on Human Health, Air Quality, and Ecosystems	
ACE 4.01.10	Investigation of black carbon's role in global- to local-scale climate and air quality
ACE 4.01.11	Indoor air and climate change
ACE 4.01.12	Particulate matter and related pollutants in a changing world
ACE 4.03: Systems-based Approaches for Sustainable Solutions	
ACE 4.03.7	Impact of extreme events on air quality and water quality in the US from global change
ACE 7.01: Local and Regional Characteristics Influencing Public Health Impacts in Healthy and At-Risk Populations	
ACE 7.01.9	ACE Centers
ACE 8.03: End-Use Impacts	
ACE 8.03.3	Methods for mitigating public health and climatic impacts of residential cooking, heating, and lighting in the developing world
ACE 8.03.4	Alternate energy infrastructures
ACE 8.03.5	Sustainability and the energy ladder
SHC 1.63: Environmental Workforce and Innovation	
SHC 1.63.2	P3 – People, Prosperity, and the Planet
SHC 1.63.3	SBIR – Small Business Innovation Research
SHC 2.63: Assessing Environmental Health Disparities in Vulnerable Groups	
SHC 2.63.5	Research to understand ecological and human health for Tribal sustainability and wellbeing
SSWR 3.01: Assess, Map and Predict the Integrity, Resilience, and Restoration Potential of the Nation's Water Resources	
SSWR 3.01E	National Priorities: Systems-based strategies addressing the water quality impacts related to drought and wildfire
SSWR 3.01F	Extreme events impacts on air quality and water quality with a changing global climate
SSWR 5.01: Green Infrastructure Models and Tools	
SSWR 5.01D	Life-cycle costs of alterative water infrastructures

Appendix C. Partner Research Needs

Table C-1. Climate-related research needs identified by partners.

Partner	Need
OW	Water Supply Management: Identify watersheds where community water systems may be at risk of long-term shortfalls in supply as a result of climate change and other factors
OW	Sea Level Rise and Storm Surge: Projected impact of changes in sea levels and storm surges on coastal wetland area and function across the country. Which coastal and estuarine wetlands are at risk of damage, what ecosystem services do they provide, at what rate are the services expected to degrade?
OW	Water Reuse: Guidelines for “acceptable” drinking water treatment plant source water quality to serve as a target for alternative sources such as reclaimed wastewater effluents, harvested stormwater, produced water, etc.
OW	Drinking Water: Consequences of warmer water temperatures for compliance with National Drinking Water Standards. To what extent will expected changes to the condition of surface waters from warming water temperatures make treatment needed to comply with drinking water standards more complex and costly or result in lower compliance rates?
OW	Harmful Algal Blooms (HABs): relationship of increased air temperature to water temperature, and effects of increased water temperature on incidence of HABs (volume/unit time; change in efficiency to produce cyanotoxins; human toxicity of cyanotoxins) Identify expected changes in HABs under warmer water temperatures expected as a result of climate change
OW	Indicators of Changes in Water Temp and Estuarine & Coastal Acidification: Metrics for establishing a baseline for measurement of long-term trends in estuarine and coastal water temperature and other parameters (pH, total alkalinity, pCO_2, dissolved inorganic carbon, DOC, and DO)
OW	Watersheds at Risk: Identify watersheds with greatest risk of increased pollution loading as a result of climate and other stressors. Models that integrate hydrology, land cover, air quality, and economics for assessment and comparison of climate change mitigation and adaptation policies for decision-makers; tools to prioritize response actions for wetland protection and restoration
OW	Monitoring: Identify parameters and methods to monitor as indicators of impacts due to climate change; methods to identify tipping points and thresholds
OAR	Quantification of climate impacts (human health, air quality, ecosystems in the United States)
OAR	Scientific contributions to National Climate Assessment (NCA) Special Report on climate change/health and support for EPA-HHS collaboration
OAR	Investigation of the linkages between air quality and climate change
OAR	Research/modeling atmospheric transport of black carbon, other SLCFs and the role of BC as a climate forcer
OAR	Laboratory testing of cookstove performance and emissions
OAR	“Energy paradox” research that addresses consumer or producer behavior regarding energy-saving technologies

Partner	Need
OAR	Research to support OAR's emerging adaptation priorities: Air quality modeling that incorporates climate impacts; climate change influence on ecosystem vulnerability; effects of climate change on stratospheric ozone
OAR	Residential and commercial buildings advanced mechanical ventilation
OAR	Improve community's capacity to understand and take effective action to address harmful environmental impacts in their community
OAR	Understand interactions between social, behavioral, environmental, and biological factors for environmental justice and Tribal communities who are disproportionately impacted
OLEM	To what extent will rising sea levels and flooding and inundation from more intense and frequent storms lead to contaminant releases through surface soils, groundwater, surface waters, sediments, and/or coastal waters at OLEM sites?
OLEM	How will more powerful storms resulting from climate change affect storm debris that will need to be appropriately managed?
OLEM	What are the impacts of increased temperature on revolatilization of hazardous materials?
OLEM	How could wildfires at contaminated sites promote the spread of contamination or impact remedies? How could wildfires in the upland areas above contaminated sites reduce vegetative cover, thereby increasing surface water runoff and resulting in catastrophic flooding that spreads contamination or impacts remedies?
OLEM	How will the frequency and magnitude of natural disasters affect the ability of emergency response efforts directed out of OLEM?
OLEM	Life-cycle assessments related to materials management
OLEM	Emerging biofuels need to be evaluated with respect to their compatibility with and impacts on the existing fuel storage and dispensing equipment. Ensuring new fuels being developed are compatible with existing infrastructure and can be stored safely will help protect groundwater supplies from contamination by failed underground storage tanks
OLEM	What are the assessment, cleanup, and area-wide planning impacts associated with green infrastructure and brownfields?
OLEM	Models are needed that can downscale the effects of climate change to a local or community level
OLEM	Need to evaluate the cumulative health effects of climate change (e.g., the nonchemical stressors that people deal with after a storm and how it impacts their susceptibility to chemical stressors)
OLEM	What are best practices for communities to adapt and mitigate climate change?
Region	Fire emissions contribution to O_3, $PM_{2.5}$, GHGs, and regional haze (Regions 8 and 10)

Appendix D. EPA Participation in USGCRP Working Groups

Table D-1. Current and recent EPA participants on USGCRP working groups.

OAR	
Rona Birnbaum	Interagency NCA WG[1]; Climate Change and Human Health WG
Allison Crimmins	Climate Change and Human Health WG
Ben DeAngelo (on detail to USGCRP)	USGCRP Deputy Executive Director Coordinating Group on Scenarios and Interpretive Science
Allen Fawcett	Interagency Group on Integrative Modeling
Lesley Jantarasami	Adaptation Science IWG
Mike Kolian	Indicators IWG (Co-chair)
Jia Li	Social Sciences Coordinating Committee
OITA	
Tony Socci	International IWG
OP	
Joel Scheraga	Adaptation Science IWG
Leanne Nurse	Adaptation Science IWG
ORD/NCEA	
Britta Bierwagen	Process Research IWG
Chris Clark	Carbon Cycle IWG
Janet Gamble	Climate Change and Human Health WG
Anne Grambsch	Interagency NCA WG; Climate Change and Human Health WG; Coordinating Group on Scenarios and Interpretive Science
Pat Murphy	Indicators Technical Task Team
Chris Weaver	Past USGCRP Executive Director (Acting) and USGCRP Deputy Executive Director; Co-Chair, Climate Scenarios Task Force; Co-Chair, Sea Level Rise and Coastal Flood Hazard Task Force
ORD/NCER	
Vito Ilacqua	Climate Change and Human Health WG
Darrell Winner	National Climate Assessment Steering Committee
ORD/NERL	
Jim Szykman	Integrated Observations IWG
ORD/NHEERL	
David Diaz-Sanchez	Climate Change and Human Health WG
OW	
Karen Metchis	Adaptation Science IWG
ORD/IOAA/ACE	
Andy Miller	EPA Principal

[1]The Interagency National Climate Assessment (NCA) Working Group (WG) has been rechartered as the Sustained Assessment Interagency Working Group (IWG) with somewhat different responsibilities.