Accomplishments of the U.S. Global Change Research Program

DETAILS

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ACCOMPLISHMENTS OF THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

Committee to Advise the U.S. Global Change Research Program

Board on Atmospheric Sciences and Climate
Board on Environmental Change and Society
Division on Earth and Life Studies
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Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions nor did they see the final draft of the report before its release. The review of this report was overseen by **David M. Karl**, University of Hawaii, Honolulu, and **Gary W. Yohe**, Wesleyan University, Middletown, CT. They were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution. The committee would also like to Tom Karl, National Oceanic and Atmospheric Administration (ret), Asheville, NC; Virginia Burkett, U.S. Geological Survey, Reston, VA; Susanne Moser, Susanne Moser Research & Consulting, Santa Cruz, CA; and Tony Busalacchi, University Corporation for Atmospheric Research, Boulder, CO for their input to the committee's deliberations. In addition, the committee would like to thank Michael Bernstein, Arizona State University, Tempe, who provided support to the committee through a number of research tasks.

Preface

The United States is a complex nation in a complex world. In many countries, economic growth has brought undreamed-of prosperity. At the same time, the industrial economy on which the global economy was founded burns fossil fuels, clears forest lands, spreads fertilizers, and releases industrial chemicals unknown in natural ecosystems. Urbanization drives transformations in land use, agriculture, and resource exploitation. These and other transformative forces are altering our ocean and atmosphere—and the climate that is the product of their interactions—in unprecedented ways. These global changes are increasingly visible in our everyday affairs, for example in droughts and storms, and their associated threats to individual and community well-being.

Acquiring knowledge of our changing planet, and the risks and opportunities that those changes bring to the United States and the world, is also a complex enterprise. It is a collaboration among scientists and analysts from across many disciplines, around the nation and the world, utilizing instruments in outer space, the deep ocean, and every social and economic setting. Within the U.S. government, this collaboration has brought together agencies and departments across the federal family. From their work has come an understanding of global environmental change that did not exist just a few decades ago. Global change science has led to a more sophisticated view of humans' role in altering environmental processes, and this includes a scientific consensus that anthropogenic changes can now be clearly discerned in the observational record. This scientific knowledge has informed many decisions, in households, businesses, and local, state, and national governments, as well as in the international arena, making these decisions more effective and efficient. There is much still to be learned, but no doubt remains that humans exert a powerful force on climate and other forces driving global change.

Much of this scientific effort was mandated by the Global Change Research Act of 1990, a law implemented initially by President George H.W. Bush and continued by every administration since then. This is a significant act of presidential leadership, coordinated by the U.S. Global Change Research Program (USGCRP) in the White House. Some of the major achievements of this Program are described in this report.

The Committee to Advise the U.S. Global Change Research Program is the body within the National Academies responsible for advising the USGCRP. We are indebted to the independent reviewers who read our final draft and provided comments, which the committee took into account in preparing the final version of the report. These experts are listed in the Acknowledgments, whom we thank again for their rigorous critique.

In providing this advice, the committee worked under the guidance of the presidents and governing board of the National Academies. We wish to acknowledge in particular our colleague, Dr. Ralph Cicerone, the late president of the National Academy of Sciences. Ralph was a leader of the scientific study of global environmental change, and he worked with us and many others to explore how those changes might become part of a transition to a durable, sustainable and humane future. We cherish the memory of his calm and rigorous presence and the twinkle that lit his eye from time to time.

Warren M. Washington, Chair
Kai N. Lee, Vice-Chair
Committee to Advise the U.S. Global Change Research Program

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Summary

The U.S. Global Change Research Program (USGCRP or "Program") is an interagency program, established by the Global Change Research Act (GCRA) of 1990, mandated by Congress to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change" (P.L. 101-606). Since the Program began, scientific understanding of global change has increased and the information needs of the nation have changed dramatically. At the request of the USGCRP, the National Academies' Committee to Advise the USGCRP prepared this report to provide a brief overview of the Program's contributions to global change research through multiagency planning and coordination.

The federal agencies' responses to provisions in the GCRA have resulted in two primary value-added activities of the USGCRP: (1) strategic planning and coordination of global change research activities across the many federal agencies engaged in global change research and (2) high-level synthesis of global change research results and sharing them with decision makers and the American public. These two primary activities of the USGCRP—guided by the Subcommittee on Global Change Research, the National Coordination Office, and numerous interagency working groups—have shaped the program priorities of the individual participating agencies and contributed to many advancements in scientific capabilities, understanding, and applications.

The research planning and coordination activities of the USGCRP culminate in the production of decennial strategic plans, the most recent one covering the period 2012-2021. Accomplishments in global change research guided by the strategic planning of the Program are synthesized in the Program's annual report to Congress and in assessments, including the periodic National Climate Assessments, with a core focus on the observed and projected challenges to the United States posed by global change. Both the strategic plans and the assessments are collaborative products of the 13 agencies and departments that participate in the Program. The Program has also played a leadership role in international cooperative efforts, including participation in collaborative research programs, development of global observation systems, and participation in intergovernmental assessment activities.

Through interagency partnerships and collaborations with leading experts, the USGCRP has worked since its inception to advance global change science and to improve the understanding of how global environmental changes are impacting society today and how they could affect society in the future. The ways that the Program has enabled these advancements have been documented in a large body of existing literature, including products of the Program and participating agencies, national and international assessments, previous National Academies reports, and many other reports from the scientific community. This report highlights several examples of scientific accomplishments that resulted from multiagency collaborations enabled by the USGCRP: the development of global Earth observing systems, improvements in Earth system modeling capabilities, and understanding of carbon cycle processes. The USGCRP has also been a leader in bringing the understanding of society and social dynamics to the study of global change, both directly in its assessments and through fostering learning across its member agencies and departments, although progress in this area has been uneven at times.

For these efforts, and many others, the USGCRP provides a platform for the agencies to coordinate their global change research and to share information that helps to inform decisions at every level of society in ways that have provided great value to the nation. In addition to the highlighted accomplishments mentioned above, the report includes a series of schematics that illustrate the role the USGCRP plays in supporting research and application that provide this value. For example, USGCRP activities enable guidance to farmers on the use of fertilizers for their crops to increase yield while

maintaining environmental quality, and guidance to community officials, emergency managers, and citizens on excessive heat events to help reduce morbidity and mortality.

Despite the advancements in global change research, the USGCRP has faced and is facing challenges. The Program is a coordinating structure across different agencies with no authority over individual agency missions or budgets, which imposes limitations on the Program's abilities to plan and support research. Additionally, although the need to integrate social science research within the Program's global change research portfolio is recognized and was recommended early in its existence, there remain obstacles to this effort, such as lack of sustained funding and commitment to data resources, and the need to actively engage the larger environmental social science community beyond the participating agencies.

The first 25 years of the USGCRP have been marked by a series of major accomplishments. Unprecedented efforts have been made to observe the natural and built environments and to document changes. Equally important, impressive advances have been made in the understanding of global change and the capacity to model it. In addition, the availability of scientific knowledge to decision makers has been significantly improved. In the coming decades, the impacts of global change will become increasingly apparent, and the Program will need to augment the knowledge base for exploring options to protect the nation's interests in the face of accelerating global changes. The Program should build on its accomplishments by sustaining, expanding, and coordinating observations of the Earth system and maintaining a balanced program of discovery-driven and use-inspired research to support the needs of the nation at local, regional, national, and global scales. The Program is well poised to tackle this task.

1
Introduction

The U.S. Global Change Research Program (USGCRP) is the nation's principal contribution to the worldwide effort to understand our changing planet and the implications of those changes for the people of the United States and the world. It is an interagency program established under the Global Change Research Act (GCRA) to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change" (P.L. 101-606).

Global change means changes in the Earth's environment (including alterations in climate, land productivity, ocean or other water resources, atmospheric chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life (NRC, 2012a). Processes of global change include climate variability and change, but also other changes in ecosystems that can have substantial effects on the supply of natural resources, on the economy, and on human well-being (NASEM, 2016). *Global change research,* as defined in the GCRA, means the study, monitoring, assessment, prediction, and information management activities to describe and understand

- the interactive physical, chemical, and biological processes that regulate the total Earth system;
- the unique environment that the Earth provides for life;
- changes that are occurring in the Earth system; and
- the ways these system changes are influenced by human actions.

A better understanding of what is changing and why can help decision makers in the public and private sectors cope with ongoing change. For example, the Program has documented substantial increases in heavy downpours in most regions of the United States over the past 50 years (see Figure 1). These heavy precipitation events can cause flooding and overwhelm infrastructure such as sewers and roads that were not designed to handle such extreme events. By being aware of this trend, government and businesses can design facilities that can cope with current and future extreme events.

The Program has contributed to a significant increase in scientific understanding of global environmental change since its establishment in 1990, even as the pace of global change has continued to accelerate in response to human influences—including a globalizing economy, rapid urbanization, and increased emissions of greenhouse gases. During this time, significant questions about the rate and causes of change were answered. The Program's scope expanded to address multiple impacts to human and natural systems and societal responses, and made significant investments in actionable information to assist decision makers at every level of society, from households to global corporations, as well as local, state, and national governments. The Program's coordinating function plays a key role in synthesizing diverse results from agencies and offices to provide relevant and timely information to decision makers and the public.

In addition to the new scientific knowledge produced by its coordinated research, the USGCRP provides the nation a range of benefits resulting from use of this information. This value chain is illustrated with examples throughout this report. One example is research on the cycling of carbon, nitrogen, phosphorus, and other key elements, which have, among other things, led to advice to farmers on how to optimize fertilizer use to maintain high yields while reducing their costs and ecological damage from the runoff of excess fertilizer into streams (see Figure 2). Another example is knowledge about changes in the frequency, intensity, and duration of some extreme weather and climate events, which is being used to

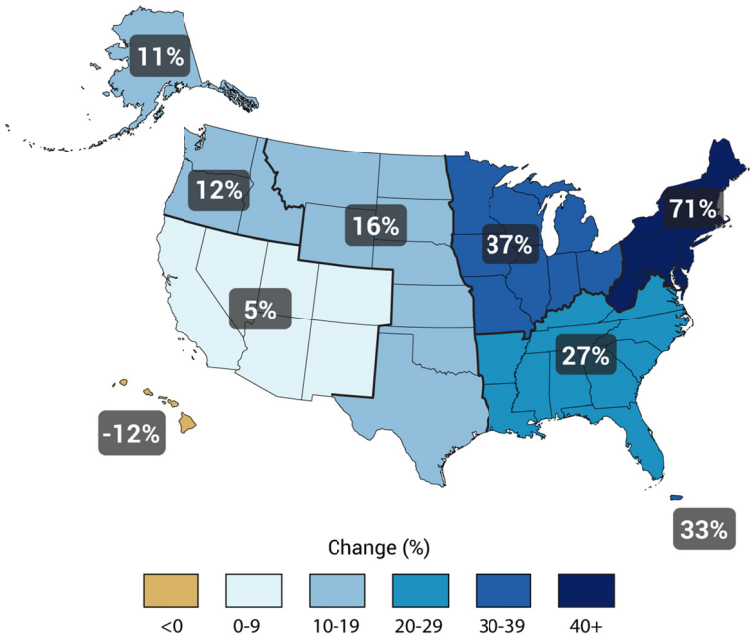

FIGURE 1. This map shows percent increases in the amount of precipitation falling in very heavy events for each region of the continental United States from 1958 to 2012. Very heavy precipitation events (downpours) are defined as the heaviest 1% of all daily events. Trends are larger than natural variations for the Northeast, Midwest, Puerto Rico, Southeast, Great Plains, and Alaska. Trends are not larger than natural variations for the Southwest, Hawai'i, and the Northwest. SOURCE: Melillo et al., 2014.

reduce their human and financial costs. Research on the effects of climate variability and climate change on the hydrologic cycle has allowed for the development of drought early warning systems and other aids to practical decisions (see Figure 4, on p. 20). Yet another example is how research on the impacts of heat waves on human health led to the development of the National Integrated Heat Health Information System; decision-support tools such as heat-wave early warning systems have reduced morbidity and mortality (Ebi et al., 2004; see Figure 5, on p. 30).

The contributions of the USGCRP to achieving these results, and many others, can be seen in various stages throughout the process of research, development, and use, as indicated in Figures 2, 4, and 5. The USGCRP coordinates research among its agencies to address key questions identified by the scientific community and stakeholders. It synthesizes what we learn from this research and provides this information to decision makers in its reports and assessments. These reports inform decision makers at all levels, as well as support the development of resources to protect lives and property, advance economic prosperity, and improve environmental quality. These interactions then help to direct new research in the most useful directions.

This report highlights the growth of global change science in the quarter century that the USGCRP has been in existence, and documents some of the Program's contributions to that growth through its primary functions of interagency planning and coordination, and of synthesis of research and practice to inform decision making. The report begins with the committee's task and approach. We include a short history of the Program. Its accomplishments are then discussed in terms of the two functions: (1) strategic planning and coordination of global change research activities across the many federal agencies engaged in global change research and (2) high-level synthesis of global change research results and sharing them with decision makers and the American public. The report concludes with comments on future directions for the Program, building on these accomplishments.

HISTORICAL CONTEXT

Growing out of interagency activities and planning under President Ronald Reagan, the U.S. Global Change Research Program (USGCRP) was formally established by Congress in 1990 under the Global Change Research Act (GCRA; full text of the Act is included as Appendix A).[1] Congress tasked the USGCRP to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change" (P.L. 101-606). Its creation was a milestone achievement in organizing administrative and political resources in response to growing concern about issues of global change. The USGCRP was built on a foundation of cooperation begun in the 1980s among agencies and departments of the federal government engaged in initiating research around the then newly emerging field of Earth system science.

The USGCRP has been sustained through successive administrations, with the Executive Office of the President participating in coordinating its activities from the outset, although the administrative structure involved in its coordination changed over time. During the presidency of George H.W. Bush, the Program was coordinated by the Committee on Earth and Environmental Sciences (CEES). The CEES was disbanded under President William Clinton as part of a larger science and technology reorganization effort and reconstituted as the U.S. Global Change Research Program under a subcommittee of the National Science and Technology Council (NSTC). The U.S. Climate Change Science Program (CCSP) and the Climate Change Technology Program were established under President George W. Bush; the CCSP incorporated the USGCRP along with the Climate Change Research Initiative established by President Bush in 2001. Under President Barack Obama the CCSP effort continued forward once again as the USGCRP. Today, the USGCRP includes 13 agencies and departments (see Box 1 for current participating entities).

BOX 1
Current Participating Agencies and Departments in the USGCRP

The current participating agencies and departments are the:

- National Science Foundation,
- National Aeronautics and Space Administration,
- National Oceanic and Atmospheric Administration,
- Environmental Protection Agency,
- Department of Energy,
- Department of State,
- Department of Defense,
- Department of Interior,
- Department of Agriculture,
- Department of Transportation,
- Department of Health and Human Services,
- U.S. Agency for International Development, and
- Smithsonian Institution.

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[1] For more on the administrative development of the Program, see Pielke (2000a, 2000b).

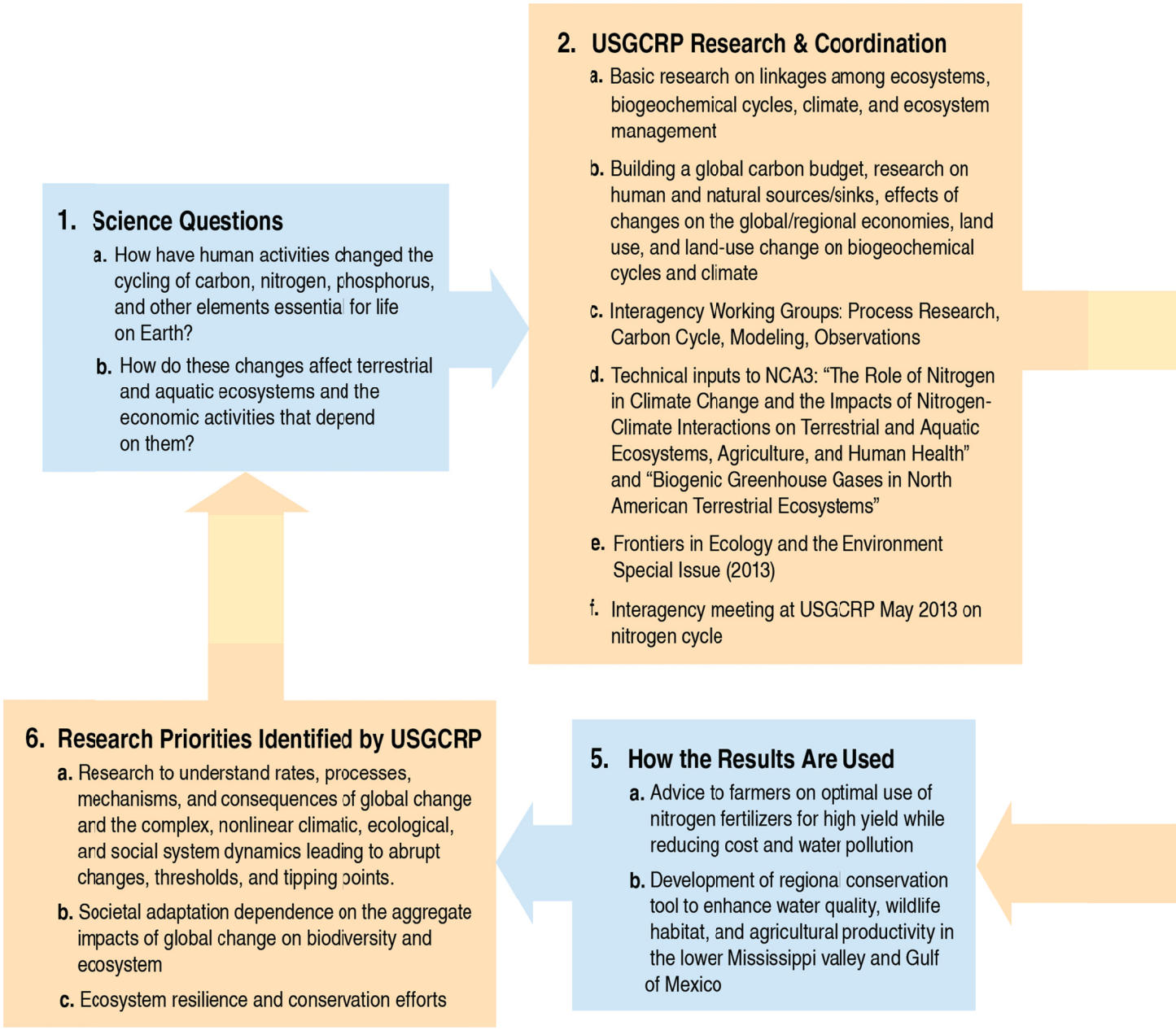
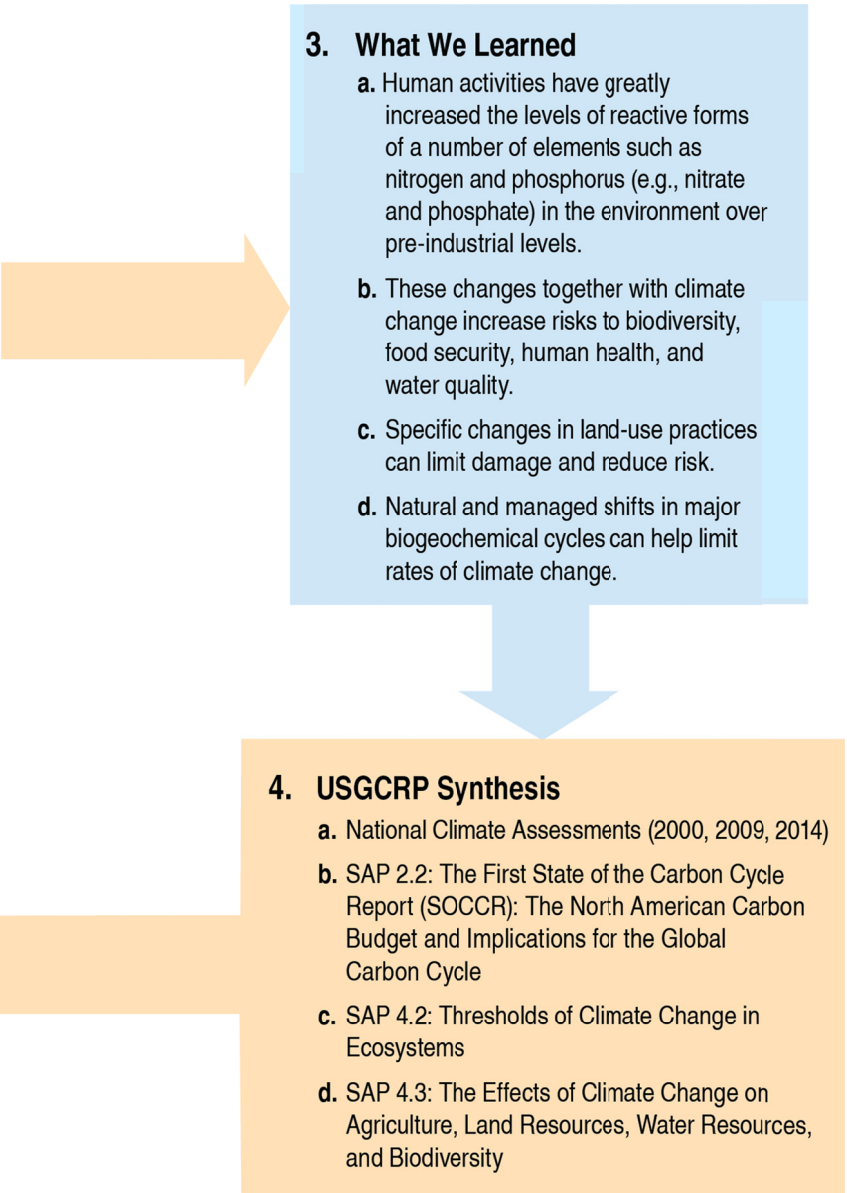


FIGURE 2. This schematic illustrates the ways the USGCRP contributes to scientific advancements in global change research and the value of that information in stimulating a broad array of applications, including for agriculture and conservation purposes. As an example, addressing the question of how human activities affect nutrient cycling has led to the development of a geospatial tool for conservation in the Gulf coast as well as advice for farmers on optimal use of nitrogen fertilizers. Orange boxes indicate points of specific USGCRP contributions: Research and coordination, synthesis of what was learned through that process, and identification of new research priorities. Citations for selected bullets are included in Figure Notes.

NOTES:
1. **Science Questions** includes examples of basic research questions from the scientific community in this area.
2. **USGCRP Research and Coordination** includes examples of activities and mechanisms for research and coordination by the USGCRP.



a/b. For example, research by the U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, Department of Energy, Department of the Interior, Environmental Protection Agency, National Aeronautics and Space Administration, and National Science Foundation can be found in the USGCRP's annual reports to Congress and strategic plans (e.g., CCSP, 2002, 2008a; Subcommittee on Global Change Research, 1996; USGCRP, 2012a, 2015).

c. See http://www.globalchange.gov/about/iwgs for more on the interagency working groups. See also Example 3 on page 22 of this report.

d. A special open access issue of the Ecological Society of America's (ESA's) *Frontiers in Ecology and the Environment* on Biogenic Greenhouse Gases in North American Terrestrial Ecosystems (2012) incorporates eight papers with the support from the Carbon Cycle Interagency Working Group member agencies and others (ESA, 2012). See also Suddick and Davidson (2012).

e. A 2013 special issue of ESA's *Frontiers in Ecology and the Environment* was an output of the NCA3 Ecosystems chapter team (ESA, 2013)

f. A group of 21 agency and USGCRP representatives met for a full day meeting at USGCRP office on May 29, 2013 in order to improve interagency coordination of nitrogen cycle research and to identify opportunities for interagency collaboration. For more, see http://cpo.noaa.gov/ClimatePrograms/EarthSystemScience/AtmosphericChemistryCarbonCycleandClimate/AC4Archive/TabId/543/ArtMID/1405/ArticleID/156/Nitrogen-cycle-interagency-group-meets-at-USGCR.aspx

3. **What We Learned** includes examples of high-level findings from the research and coordination in box 2. Citations for the work to support these statements can be found in the products included in box 4, USGCRP Synthesis.

4. **USGCRP Synthesis** includes examples of Assessments conducted by the Program that communicate the findings to decision makers and the public.

a. National Synthesis Assessment Team (2000, pp. 72-88); Karl et al. (2009, pp. 74-88, 149); Melillo et al. (2014, pp. 350-368).
b. CCSP (2007).
c. CCSP (2009).
d. CCSP (2008e).

5. **How the Results Are Used** includes examples of the use of this information to provide benefits for the nation.

a. See Hong et al. (2007).

b. The Mississippi River Basin/Gulf Hypoxia Initiative Precision Conservation Blueprint is a tool that contains a number of geospatial products, including water quality layers, agricultural system layers, geophysical layers, fish and wildlife focal areas, and others. For more, see https://tallgrass prairielcc.org/resource/mississippi-river-basingulf-hypoxia-initiative-precision-conservation-blueprint.

6. **Research Priorities Identified by USGCRP** includes examples of priorities highlighted in the USGCRP strategic plan (USGCRP, 2012b).

BOX 2
Research Elements of the Global Change Research Act

The five research elements included in the Global Change Research Act (GCRA; §104(c)):

1. Global measurements, establishing worldwide observations necessary to understand the physical, chemical, and biological processes responsible for changes in the Earth system on all relevant spatial and time scales.
2. Documentation of global change, including the development of mechanisms for recording changes that will actually occur in the Earth system over the coming decades.
3. Studies of earlier changes in the Earth system, using evidence from the geological and fossil record.
4. Predictions, using quantitative models of the Earth system to identify and simulate global environmental processes and trends, and the regional implications of such processes and trends.
5. Focused research initiatives to understand the nature of and interaction among physical, chemical, biological, and social processes related to global change.

Full text of the GCRA is provided in Appendix A.

The federal agencies' responses to provisions in the GCRA have resulted in two primary value-added activities of the USGCRP: (1) strategic planning and coordination of global change research activities across the many federal agencies engaged in global change research and (2) high-level synthesis of global change research results and sharing them with decision makers and the American public. Our discussion below of Program contributions is organized around these two themes. We draw upon review of USGCRP products mandated by the GCRA, specifically its strategic plans and assessments, which are produced collaboratively among the 13 agencies, and its reports to Congress, entitled *Our Changing Planet,* a document produced annually to highlight recent accomplishments and provide associated budgetary information.

OUR TASK

At the request of the USGCRP, the committee prepared this report as a broad-brush review to identify, in the context of the Program's mission and mandates, the most significant and consequential science and research accomplishments of the USGCRP, and what lessons can be learned from these accomplishments with respect to future Program planning (the committee's full statement of task is provided in Appendix B). This report is not a comprehensive program evaluation; rather, the committee's intent is to inform those unfamiliar with the program, using examples to illustrate some of its most valuable contributions to the science of global change and the applications of that science. The examples provided also illustrate what mechanisms have worked well for the Program and where challenges remain that bear upon the future of the Program.

To prepare this report, the committee reviewed many documents produced by the Program (see Appendix C for an extended list of USGCRP products), as well as prior National Academies' reports that commented on various aspects of the Program (see Appendix D for a list of relevant reports). The committee also consulted a small number of scientists, analysts, and former government officials with deep knowledge of the USGCRP for their views on the accomplishments of the Program, barriers to progress, and opportunities to advance global change research. The committee received research support from an external consultant in reviewing products of the Program. The contributions of all these individuals, who are listed in this report's Acknowledgments, are greatly appreciated. With this background, the committee drew upon its members' broad expertise in the science and policy of global change, as well as knowledge

of the USGCRP and its history, to select some of the most significant accomplishments of the Program in response to its mission and mandate since its inception.

The committee has employed the statutory framework of the GCRA as a way to select a small fraction of the activities and accomplishments of a large federal research effort, so that a non-specialist reader can quickly obtain an overview of this program. The GCRA (see Appendix A) provides the mandate and priorities for the USGCRP; the committee chose examples to illustrate how the Program has responded to this mandate. Specifically, this report discusses how the Program has conducted strategic planning and coordination, provides examples of accomplishments relevant to the research elements of the GCRA and strategic plans of the program, and describes the Program's efforts to assess the state of knowledge and connect that knowledge with decision makers.

The Program's major areas of effort have cross-cut a number of elements of the GCRA in sensible and productive ways. This report discusses accomplishments that span these elements: (1) Global Observation Systems, which correspond to research elements 1 and 2 (§104(c); see Box 2) and information management requirements (§104d); (2) Earth System Modeling, which corresponds to research elements 3 and 4 (§104(c)); and (3) Carbon-Cycle Science, which provides a direct example of the Program's response to research element 5 (§104(c)). These examples also discuss the intersections with the Program's international and assessment functions (§102(e) and §106, respectively). The fourth example in this report, Integrating Human Dimensions into Global Change Research, discusses an area recommended to the Program as necessary to incorporate into the nation's portfolio of research as the scope of global change has evolved and expanded, and that the Program subsequently recognized in its strategic planning (§104(e)). Last, the report discusses accomplishments through the Program's assessments and assessment process (§106).

Together, these examples, along with the schematics described above (Figures 2, 4, and 5), provide a sense of the different kinds of accomplishments that the agencies and departments of the government achieved through the coordination and leadership of the Program, and how the Program has evolved to meet the needs of the nation. The development of a complete list of accomplishments of the Program was beyond the scope of the committee's task; thus, our selection is meant to be illustrative rather than representative in an analytical sense.

This report highlights areas of scientific progress, the value of the information obtained, and the role played by the USGCRP in generating the information through its planning and coordination of global change research across the federal agencies. There are many other examples of accomplishments that could have been identified for a program as wide-ranging as the USGCRP, but the examples highlighted by the committee in this report are particularly impactful and emblematic of the Program's role in advancing global change science over the past 25 years.

2
Strategic Planning and Coordination

STRATEGIC PLANNING

The U.S. Global Change Research Program (USGCRP) in its various organizational incarnations has consistently focused on building scientific knowledge and making it useful. While the Program has invested the largest share of its budget in advancing the scientific understanding of the Earth system, informing decisions has become increasingly important. The latter priority reflects a growing awareness across American society, through individual experience and media coverage, of severe storms, heat waves, and droughts, changes in agricultural yields, and rapid urbanization. In addition to these localized impacts, there has also been coverage in conventional and social media of global phenomena including unprecedented changes in Arctic environments, rising sea levels, and a continued increase in greenhouse gas emissions within and beyond the borders of the United States. Global environmental change is only one part of a complex and dynamic context; as scientists' understanding has advanced, knowledge generated by federally sponsored research has also become increasingly important to those making critical economic and life-saving decisions, such as relocating facilities vulnerable to flooding, preparing for heat waves in poor neighborhoods, or knowing what crops to plant (Petkova et al., 2016; Upbin, 2013; Winkler et al., 2010).

At the Program's inception, the federal leadership in Congress and the Executive Branch realized that the phenomena of global environmental change, including climate change, were important but incompletely understood. Looking back, one can see that the scientific community had limited and sparse observations of the Earth system, and that the scientific community's understanding of basic Earth system processes was far less complete than now. Something now largely taken for granted, the ability to model or project future trajectories of the Earth system, was in its infancy. In addition, the notion that the physical/natural sciences and the social sciences both had important roles to play in the Program had yet to be recognized. The initial effort was accordingly put into developing a scientifically compelling and societally useful program that spanned the diverse capabilities of federal departments and agencies.

The early 1990s was a pathfinding era for the Program. In 1988, the Committee on Earth Sciences prepared the first *Our Changing Planet: A U.S. Strategy for Global Change Research*, which provided goals, scientific motivation, and the research budget of the U.S. Global Change Research Program to accompany the President's fiscal year (FY) 1990 budget (CES, 1988). This document was followed up by *Our Changing Planet: The FY 1990 Research Plan*, which served as the first strategic plan for the Program and stated the Program's goal: "To gain a predictive understanding of the interactive physical, geological, chemical, biological, and social processes that regulate the total Earth system and, hence, establish the scientific basis for national and international policy formulation and decisions relating to natural and human-induced changes in the global environment and their regional impacts" (CES, 1989). The document also included an implementation strategy that described specific scientific objectives (the monitoring, understanding, and predicting of global change), the importance of disciplinary integration, and the coordination of communities involved with the science of global change (national and international scientific community, government agencies, and intergovernmental science bodies).

The interagency process of preparing the annual *Our Changing Planet* report—produced to explain the president's annual appropriations request to Congress—facilitated coordination across the participating agencies around the priorities highlighted in the annual documents. In addition, to ensure that the global change research community had input to the formulation of the USGCRP's research objectives,

the Program commissioned studies from the National Academies on various global change topics (e.g., data management, hydrology, ecology, and modeling capabilities; see Appendix D for a list of reports from the National Academies for the Program). These studies helped guide the USGCRP's development during that period and through to the present.

The second strategic plan for the Program was produced in 2003, in a process that started during the Clinton Administration and completed under the George W. Bush Administration. This plan focused specifically on advancing research on climate change (CCSP, 2003). An update to this strategic plan was published in 2008, outlining progress since the 2003 plan and identifying priorities moving forward. A third strategic plan was published in 2012 by the USGCRP to provide guidance for the period to 2021 (USGCRP, 2012b). This 2012 plan focused on increasing the attention to decision support. The Program just produced an update to that strategic plan, a draft of which was reviewed by this committee early in 2016. Appendix E provides a brief overview of the evolution of the goals and objectives included in the original 1989 planning documents, and the 2003 and 2012 strategic plans.

COORDINATION

The USGCRP has fostered relationships and coordination among its 13 member agencies on topics related to global change research. This coordination has attempted to minimize duplicative efforts, support initiatives too great for any one agency to tackle (e.g., creating and maintaining global observing systems), address issues that cross the mission mandates of multiple agencies (e.g., the global carbon cycle), and provide a focal point within the federal government for global change research. The fruits of the coordination led by the Program are illustrated in the examples discussed later in this section.

The USGCRP provides a platform for the agencies to coordinate their activities. This coordination is facilitated through development of the strategic plans, routine meetings of representatives from participating agencies, and interagency working groups (IWGs) that focus on specific Program priorities.[1] For example, the Adaptation Working Group and the Climate Change and Human Health Working Group were very active in the most recent National Climate Assessment (NRC, 2015), and the Carbon Cycle IWG has facilitated significant progress, as discussed later in Example 3. In addition, these structured interactions have created informal cross-agency relationships that led to other collaborative activities. Although those relationships are incompletely documented, the committee judges them to have been significant as catalysts to collaboration and greater efficiency in the use of public resources.

The committee recognizes, however, that coordination can be a difficult challenge, particularly given that the Program does not have budgeting authority. Quantifying and documenting the benefits stemming from the Program's coordination role is difficult. While inclusion of priorities in strategic planning documents or agencies' agreements to undertake a coordinated effort can be tracked and assessed, these represent only the initial steps in the scientific process, which require individual agencies' funding of research efforts and investigators' years of inquiry before research findings are generated initially, replicated, and translated into a form relevant for policy action. Nonetheless, numerous examples illustrate how the coordination function of the Program has enabled key advances.

In this section, we highlight four such examples: (1) the development of global Earth observation systems, (2) improvements in Earth system modeling capabilities, (3) the incorporation of process-level understanding within carbon-cycle science, and (4) the integration of human dimensions within global

[1] There are currently 11 interagency working groups or coordinating committees catalyzing work on the Program's goals: Integrated Observations; Process Research; Integrative Modeling; Carbon Cycle; Adaptation Science; Climate Change and Human Health; Social Sciences; National Climate Assessment; Scenarios and Interpretive Science; International Research and Cooperation; and Education, Extension, and Training.

change research. These examples were chosen because they represent significant advances in knowledge of value to the United States in response to the Global Change Research Act (GCRA) mandate and provide a sense of USGCRP priorities and contributions made by the Program to its members' mission to serve the nation.

In addition to national coordination, the USGCRP has aided the United States in playing a leading role in international partnerships to organize and facilitate global change research. The World Climate Research Programme (WCRP) is the oldest, and it is devoted to analysis and prediction of Earth system variability and change. The USGCRP has participated in WCRP through its projects, such as CLIVAR (Climate and Ocean—Variability, Predictability, and Change), whose mission is to understand the dynamics, the interaction, and the predictability of the coupled ocean-atmosphere system. The U.S. CLIVAR office is co-located with the USGCRP National Coordination Office, providing enhanced integration of international, national, and individual agency priorities related to observing, predicting, and understanding climate variability and change. Close coordination with other WCRP core projects has also been provided by the USGCRP process.

The USGCRP provided similar support to three sister organizations: the International Geosphere-Biosphere Program that coordinated research on biological, chemical, and physical processes and how they are influenced by human activities and institutions; the International Human Dimensions Program that focused on anthropogenic drivers of environmental change and the factors that contribute to vulnerability and resilience of societies; and DIVERSITAS, an international program of biodiversity science that linked biological, ecological, and socioeconomic sciences. More recently, these three organizations were reorganized into a single entity, Future Earth, which is focused on providing the wide range of knowledge needed to support a sustainable and resilient world. These international partnerships have contributed substantially to the productivity of the USGCRP, and continuing participation will be important in meeting the GCRA mandate, and to provide information needed by decision makers at all scales in the United States.

The Program has also participated in international efforts to align funding and funding priorities. Beginning 1990, the International Group of Funding Agencies for Global Change Research helped coordinate the efforts of those nations that fund global change research. Reorganized over the past decade as The Belmont Forum, it continues to add value to national investments and co-fund international partnerships, helping make best use of available resources to deliver the knowledge needed for action to avoid and prepare for environmental change.

EXAMPLE 1: GLOBAL OBSERVATION SYSTEMS

Earth system science cannot be done on a bench in a laboratory—it is an observational science where the laboratory is the planet. Without continuous global observations that are quality controlled for long time series analysis, it is impossible to make progress on documenting and understanding global environmental changes. Since the inception of the USGCRP, addressing the need for observations from space and *in situ* has been a top priority. Observations provide new eyes and scientific insights into how our planet works. They allow scientists to propose ideas and test them, enabling new understanding that is represented mathematically and incorporated into models. Models are the integrating tools of understanding, but they also can be used to run experiments to explore the consequences of alternative futures based on alternative plausible scenarios. This constant synergy between observations, data analysis and synthesis, and models and simulation has greatly expanded since the inception of the USGCRP. Various aspects of global change, including climate change, are among the most challenging scientific problems and at the same time are associated with the most pressing societal issues. Our ability to take this

new scientific knowledge and develop information products for decision makers has grown significantly over the past decade.

From the beginning of the USGCRP, one of the important challenges of global change research was to develop and secure a comprehensive set of observations of global change (e.g., CES, 1989). There were examples of data sets from single locations that represented global processes, the CO_2 record from Mauna Loa being the best known. Yet there were very few data sets that were truly global in extent or had been measured for long enough to provide time series against which change could be measured. In the 1980s, the scientific community had begun its international planning for global change research, and was seeking ties to existing programs coordinated under the WCRP. Within the United States, the National Aeronautics and Space Administration's (NASA's) Science Advisory Committee developed a research and observational agenda for understanding global change (NASA, 1986). The foundation of the agenda was the assertion that it was possible to construct a global, space-based observational system dedicated to the task of understanding and documenting global change.

At the time, existing global space-based observational programs were primarily weather satellites (both polar orbiters and geostationary) operated by the National Oceanic and Atmospheric Administration (NOAA), which had a primary mission of providing data for numerical weather prediction models. In general, these sorts of measurements lacked the accuracy and precision over long time periods needed for global change studies. NASA began formulating plans for the Earth Observing System (EOS) in the 1980s and received its "start" from Congress in October of 1990. EOS was instituted as an integral element of the USGCRP, and its objectives, and associated critical measurements, were designed to address many of the priorities outlined by the Program (King, 1999a). The stated intent of EOS was to produce 30-year time series of a wide suite of global measurements of critical elements of the Earth system, including land-cover change, ocean color, aerosol concentrations, stratospheric ozone concentrations, sea level, and many other important chemical and physical properties. In 1996, the National Space Policy (September 19, 1996 revision) required NASA to undertake continual measurements from EOS and assigned related roles to the Department of Defense, Department of Energy (DOE), and U.S. Geological Survey (USGS). These and other agencies partner with NASA in the conduct of the USGCRP. Landsat-7,[2] which provided global imagery of land cover archived by USGS, was among the first instruments of EOS launched in 1997 (King, 1999b).

Greatly improved understanding of land-cover change was an early success of the global observing system. The first consistent, replicable measurement of loss of humid tropical forest in the Amazon basin, for example, was a direct consequence of USGCRP investments both in data (Landsat) and in methods for analysis (Skole and Tucker, 1993). Today, the ability to calculate terrestrial ecosystem processes globally, such as net primary productivity (e.g., Verma et al., 2014), or measure changes in the length of the growing season and terrestrial productivity (e.g., Mao et al., 2016), can only be accomplished with the global satellite data record initiated by the USGCRP. These global surveys of land use and biological productivity inform decisions ranging from economic intelligence to warn of famine, to diplomacy relating to deforestation in the Amazon River basin, to commercially valuable estimates of fish harvest.

Now, 25 years after the inception of the USGCRP and aided by the ongoing coordination of the Program through mechanisms such as the Integrated Observations Interagency Working Group (ObsIWG), there is a large and growing portfolio of global measurements from space. There are eight missions currently operating in near-Earth orbit, with more than 30 instruments measuring or allowing the calculation of a wide suite of conditions including wind speeds and circulation patterns, atmospheric concentrations of CO_2 and other important chemical constituents, land-cover change, ice sheets, cloud properties, ocean

[2] Landsat is a joint NASA/USGS program that provides the longest existing continuous space-based record of Earth's surface. More information can be found at http://landsat.gsfc.nasa.gov/.

salinity, sea ice, and the biosphere's net primary productivity on both land and ocean.[3] NOAA provides additional global observations with the accuracy needed to estimate global change effects through its growing weather data that adheres to climate data requirements and proper climate data curation methods.[4] While its investments are still oriented around the primary objective of providing information for numerical weather prediction, NOAA remains a critical part of the U.S. contribution to global change research and observations. The international community has also stepped forward, working within parallel international organizations such as the Committee on Earth Observing Satellites, to provide significant observational contributions from the European Union (and individual nations within the EU), China, India, Brazil, Japan, South Korea, and others.

As global Earth observations from space were expanding, some of the same USGCRP agencies, and others as well, were planning and implementing airborne, ground, and ocean-based observing systems. The Tropical Ocean-Global Atmosphere (TOGA) Tropical Atmosphere Ocean Array[5] in the western Pacific (a program of the WCRP supported by the USGCRP; Subcommittee on Global Change Research, 1994), the expansion of the ocean Argo floats[6] including Bio-Argo (an internationally coordinated effort), the development of AmeriFlux[7] (a DOE coordinated network of observations from previously uncoordinated observations of terrestrial CO_2 fluxes), and the creation of a nationally consistent archive of observations of temperature and atmospheric chemistry are prime examples. One important accomplishment was the leadership of the United States in the development and implementation of the World Ocean Circulation Experiment (WOCE), within which the USGCRP provided major support for ocean sampling and analysis, that provided the first ever global and scientifically structured data set on the key physical characteristics of the global ocean (Subcommittee on Global Change Research, 1999). Prior to WOCE, there were only regional efforts to characterize parts of the global ocean.

The resulting observations of these *in situ* regional and global observing networks have informed questions that have arisen in policy debates about the consistency of observations, as happened in the case of surface and satellite-based temperature measurements (Box 3). Answering these questions was achieved by having the data available for the scientific community to analyze, interpret, and resolve the issue, as well as having the USGCRP's interagency coordinating mechanisms in place to facilitate research directions for the scientific community.

Most of the civilian observational data from surface-based and orbiting platforms are available not only to all federal agencies, but more broadly to the scientific community and the public. It is important to note that data collected by other nations are also available worldwide, a result of international collaboration on open data policy. The USGCRP has supported free and open access to data through resources like Data.gov[8] and the U.S. Climate Resilience Toolkit,[9] which has improved the ability of scientists and their user communities to see important connections in the Earth system, such as between land-use change and local/regional drought and rainfall changes, or the differential sensitivity of the Earth system to albedo changes at different latitudes, or the complex interaction of ocean currents, ice sheets, and atmospheric warming in Greenland. In addition, just as the international community benefits from data

[3] Current and completed missions of the NASA Earth Observing System can be found at https://eospso.nasa.gov/mission-category/3.
[4] See, e.g, NOAA's National Centers for Environmental Information online climate data sets: https://www.ncdc.noaa.gov/cdo-web/datasets.
[5] See http://www.pmel.noaa.gov/tao/.
[6] See http://www-argo.ucsd.edu/.
[7] See http://ameriflux.lbl.gov/.
[8] Find data and resources related to coastal flooding, food resilience, water, ecosystem vulnerability, human health, energy infrastructure, transportation, and the Arctic region at https://www.data.gov/climate/.
[9] See https://toolkit.climate.gov/.

BOX 3. Reconciling Surface and Upper Atmosphere Temperature Trends

As the USGCRP was starting 25 years ago, among the most visible and controversial elements of global change was global warming—the observed and projected rise in the average temperature of the world's atmosphere. In the early 1990s, analysis of data from NOAA's polar orbiting satellites indicated discrepancies between the observed warming near the surface and the warming higher in the atmosphere. These unexpected results seemed problematic for climate models, which projected about the same warming near the surface and higher in the atmosphere, and provided a scientific reason to question the validity of anthropogenic climate change.

The USGCRP recognized this contradiction and took steps to develop the science to address it, first by commissioning a study from the National Academies in the late 1990s to examine observed trends of temperature near the surface and in the lower to mid troposphere, assess the biases and uncertainties in the data, describe the major conflicts in the trends, and define the actions required to reduce the uncertainties and biases (NRC, 2000). This report affirmed that "the warming trend in global mean surface temperature observations during the past 20 years is undoubtedly real and substantially greater than the average rate of warming during the twentieth century" (NRC, 2000). That is, at ground level, where people are most directly affected, the planet was observed to be warming. The next year, the Intergovernmental Panel on Climate Change (IPCC) reached a similar conclusion (IPCC, 2001). The National Academies report also made recommendations to better quantify and reduce measurement errors in estimates of global mean temperature.

The National Academies and IPCC reports helped guide research over the next 6 years. During that time, the conclusions about warming near the Earth's surface were strengthened by advances in the fundamental science and a close examination of the observational data. To summarize the outcome of a vigorous debate within the scientific community, the dynamics of the atmosphere are now better understood, including the way that different layers and regions of the atmosphere respond differently to environmental forces. In addition, the discrepancies in the original data series have been resolved, showing that observations from satellites and balloons were in fact consistent with climate models. For example, it was reported that for the troposphere, the primary cause of apparent trend discrepancies between different versions of the data sets was the result of differences in how the data from the different satellites had been merged together (CCSP, 2006). This analysis was reported by the Program in the 2006 Synthesis and Assessment Product: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences* (CCSP, 2006). Observations made in the decade following confirm the accuracy of the climate models now in use.

generated by U.S. activities, U.S. science benefits from the availability of key data from many other countries.

The connections among processes on land, sea, and air have in turn woven a more accurate and comprehensive picture of the global environment and how it is changing due to natural and human influences. Newer techniques such as "fingerprinting" have allowed for the detection and attribution of human influence in observed global environmental changes. Having this more complete portrait of our changing planet is of keen scientific interest, and simultaneously yields numerous dividends to human societies such as better forecasts of epidemic disease (Monaghan et al., 2016).

EXAMPLE 2: EARTH SYSTEM MODELING

Earth system models—mathematical representations of the physical, chemical, and biological processes across the planet—are an indispensable tool for better understanding Earth system science and in generating information needed by decision makers at all levels. Output from these models informs decisions by many different users, from farmers to public policy makers to national security planners. For example, a collaboration of Federal Emergency Management Agency (FEMA) and the U.S. Army Corps of

BOX 4. Replicating Past Climate

In 1990, state-of-the-art climate models were unable to replicate past climates—a necessary precursor for confidence in model projections. From the Program's outset, the USGCRP put high priority on this problem. Progress has been steady: longer, more accurate observations, together with increasingly powerful computers, have led to improvements in fundamental understanding and with it better models.

In 2008, at the end of the George W. Bush administration, the Program produced Synthesis and Assessment Product (SAP) 3.1: *Climate Models: An Assessment of Strengths and Limitations*. That report recognized the improvements in model abilities, including the incorporation of active vegetation on land and ocean biogeochemistry, but noted that vertical processes governing atmospheric state evolution were still problematic. The SAP stated that "some processes governing the atmospheric state's evolution are relatively well resolved by model grids and some are not" (CCSP, 2008b).

Research and development continued to improve climate modeling and process-level understanding under the auspices of the USGCRP, and by the third National Climate Assessment in 2014 the scientific consensus was that "progress is being made in the accuracy of models in representing the physics of the climate system at smaller scales. This is demonstrated, for example, by the ability of these models to replicate observed climate" (USGCRP, 2013). The Earth system is complex, and the challenge of representing its behavior accurately increases as scientists and users seek higher-resolution results. Scientists have also added complexity to their models to represent interactions that were previously ignored. This generally, though not always, produces increased accuracy of prediction and reduces uncertainty. Bringing together the diverse expertise needed to advance Earth system modeling capabilities so significantly is a notable contribution of the USGCRP.

Engineers (USACE) is producing maps of coastal flood risk that take into account model projections of sea-level rise and that are useful for infrastructure planning and emergency preparedness.[10]

These models have become increasingly sophisticated since 1990 (see Figure 3). At that time, state-of-the-art models represented only one component of the Earth system in detail, with limited interaction with other components, and had relatively coarse horizontal and vertical resolution. For example, most models used to study climate change included an atmospheric component with crude representation of clouds and radiation processes; interactions with the ocean and land surface were not well represented. These atmospheric models were useful for studying large-scale responses to changes in radiative forcing (e.g., increases in greenhouse gases, variations in solar activity) but were not able to represent smaller-scale features such as tropical storms, hurricanes, or sharply defined warm and cold fronts. Models of that day were constrained by available computer power, in that obtaining higher spatial resolution requires running models with smaller time steps, compounding the computational requirements enormously. Models were also constrained by limited understanding of many climate processes, and sparse observations for validating model results. Given these limitations, the models of this time had limited capability to replicate observed past climate conditions (see Box 4).

Many of these limitations have now been addressed. Modern Earth system models are composed of multiple interacting components and much improved horizontal and vertical resolution.[11] Today's models can simulate realistic conditions that can be compared with both satellite and *in situ* observations. This ability to intercompare model output with the observational record (discussed in the previous section) is critical for advancing model development and performance, and for giving potential users an indication of

[10] Maps for New York and New Jersey can be found at http://www.globalchange.gov/browse/sea-level-rise-tool-sandy-recovery.

[11] Generally, the horizontal resolutions for atmospheric models are roughly 1 to 2 degrees for large ensemble simulations and 30 to 60 vertical levels. Most groups have high-resolution model versions for limited studies that have 0.25 to 0.50 degree grids. Resolution of ocean models ranges from 1.0 degree (low resolution) to 0.10 degree (high resolution). Computing power has increased by 2.5 times every 4 years or so at major modeling centers.

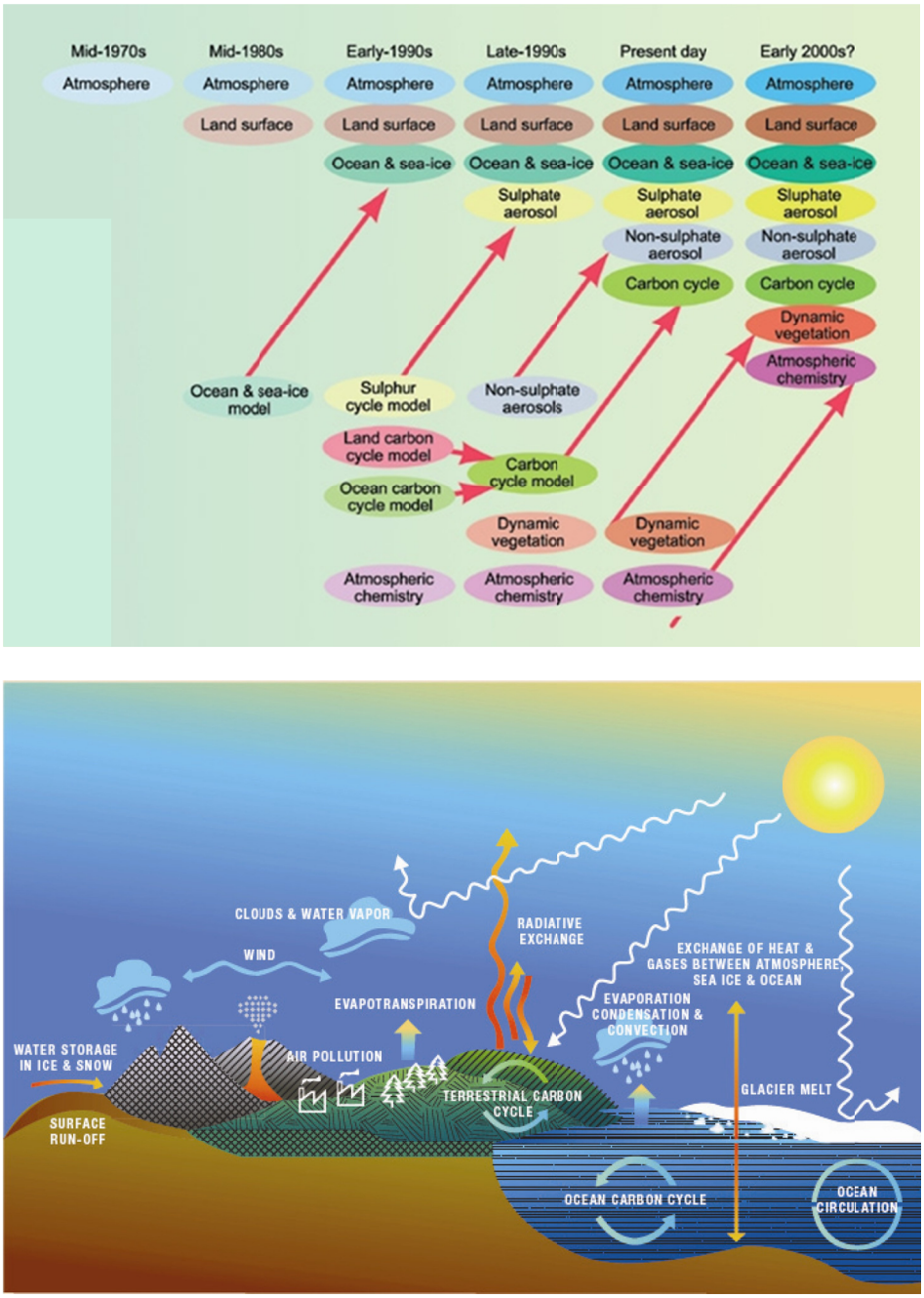


FIGURE 3. (Top) Evolution of climate models from mid-1970s to early 2000s. Climate models increase in sophistication as more elements and processes of the Earth system are integrated. Components often develop as standalone models for different processes, which are then incorporated into climate models; e.g., circa 2001, the carbon-cycle component was developed from land and ocean carbon-cycle models which were then added to existing models that already included atmosphere, land surface, ocean and sea ice, and sulfate and nonsulfate aerosol components. (Bottom) Schematic representing elements of current Earth system models—mathematical representations of the physical, chemical, and biological processes in the Earth system including those identified in the image. SOURCE: (Top) IPCC Working Group I, Third Assessment Report, 2001, http://www.globalchange.gov/browse/multimedia/climate-models-past-present-and-future; (Bottom) Marian Koshland Science Museum.

their predictive usefulness. These models are now useful for many more applications. For example, it is now possible to estimate the changing risks of extreme weather events, such as heavy precipitation, droughts, and wildfires; understanding of these changing risks is already being incorporated into planning across many sectors, from agriculture and water resource management to coastal and energy infrastructure development (see Figure 4). The emerging ability to make useful projections in turn prompts those using models to demand further improvements in the models.

Since the inception of the USGCRP, Earth system modeling has been an integral part of strategic efforts in response to its mandate (see Appendix E). Several USGCRP agencies have made significant investments to develop these capabilities. In contrast to other nations, in which a centralized approach to model development was pursued, the United States has supported multiple centers that develop and use climate models in largely independent efforts. This approach makes it possible to test different model techniques and uses (NRC, 2012a). However, at times, it has proven challenging to coordinate these efforts (NRC, 1998). These challenges were particularly apparent in the late 1990s, at which time the U.S. modeling capabilities were perceived to be lagging. To address these challenges, the Environmental Division of the White House Office of Science and Technology Policy commissioned a report authored by the USGCRP (2001a), and NOAA and the National Science Foundation (NSF) requested a second report from the National Academies in 2001 (NRC, 2001).

Building on the recommendations of these reports, multiple USGCRP agencies focused existing and/or launched efforts to rapidly improve models, and to improve linkages among their programs. For example, NSF initiated a major interagency effort in the early 2000s to link multiple smaller and larger climate modeling centers to accelerate U.S. modeling. Smaller centers focused on specific topical areas and approaches were developed for incorporating insights from their work into the models of the two large centers. NASA funded a multiagency activity focused on model interoperability and reuse, which resulted in the Earth System Modeling Framework (NRC, 2012a). To take stock of progress in improving modeling capacity, the Program's 2003 Strategic Plan commissioned Synthesis and Assessment Product 3.1, which provided an assessment of the strengths and limitations of climate models and guided future research efforts (CCSP, 2008b).

Recognizing the need for even more coordination of efforts, the USGCRP established an Interagency Group on Integrative Modeling (IGIM) in 2011. The need for the USGCRP to provide coordination at the interagency working group level was emphasized in *A National Strategy for Advancing Climate Modeling* (NRC, 2012a). The report also called for a National Climate Modeling Forum to "help bring together the nation's diverse and decentralized modeling communities," and identified the USGCRP as a natural choice for organizing such a forum. In response, the IGIM began convening an annual U.S. Climate Modeling Summit[12] (starting in 2015) to bring together participants from the leading U.S. governmental and academic modeling centers.[13] Objectives of this summit are to develop a shared understanding of research directions and implementation strategies, to identify opportunities for enhanced coordination, and to identify outreach opportunities to user communities. Given the recent increase in Earth system models in operation in the United States, continued attention is merited by the USGCRP to avoid redundancy and maximize collaboration.

USGCRP agencies have also played a role in international modeling efforts, specifically the Coupled Model Intercomparison Project (CMIP). CMIP was established in 1995 under the Working Group on Coupled Modeling of the WCRP. The model comparisons in CMIP use standardized specifications of inputs and output formats established by an international committee; an extensive suite of model outputs is

[12] See http://www.globalchange.gov/about/iwgs/igim-resources#Annual U.S. Climate Modeling Summit.

[13] Leading modeling centers include the Geophysical Fluid Dynamics Laboratory (NOAA), the Climate Forecast System (NOAA), Goddard Institute for Space Studies (NASA), Goddard Earth Observing System (NASA), the Community Earth System Model (National Center for Atmospheric Research), and the Accelerated Climate Model for Energy (DOE).

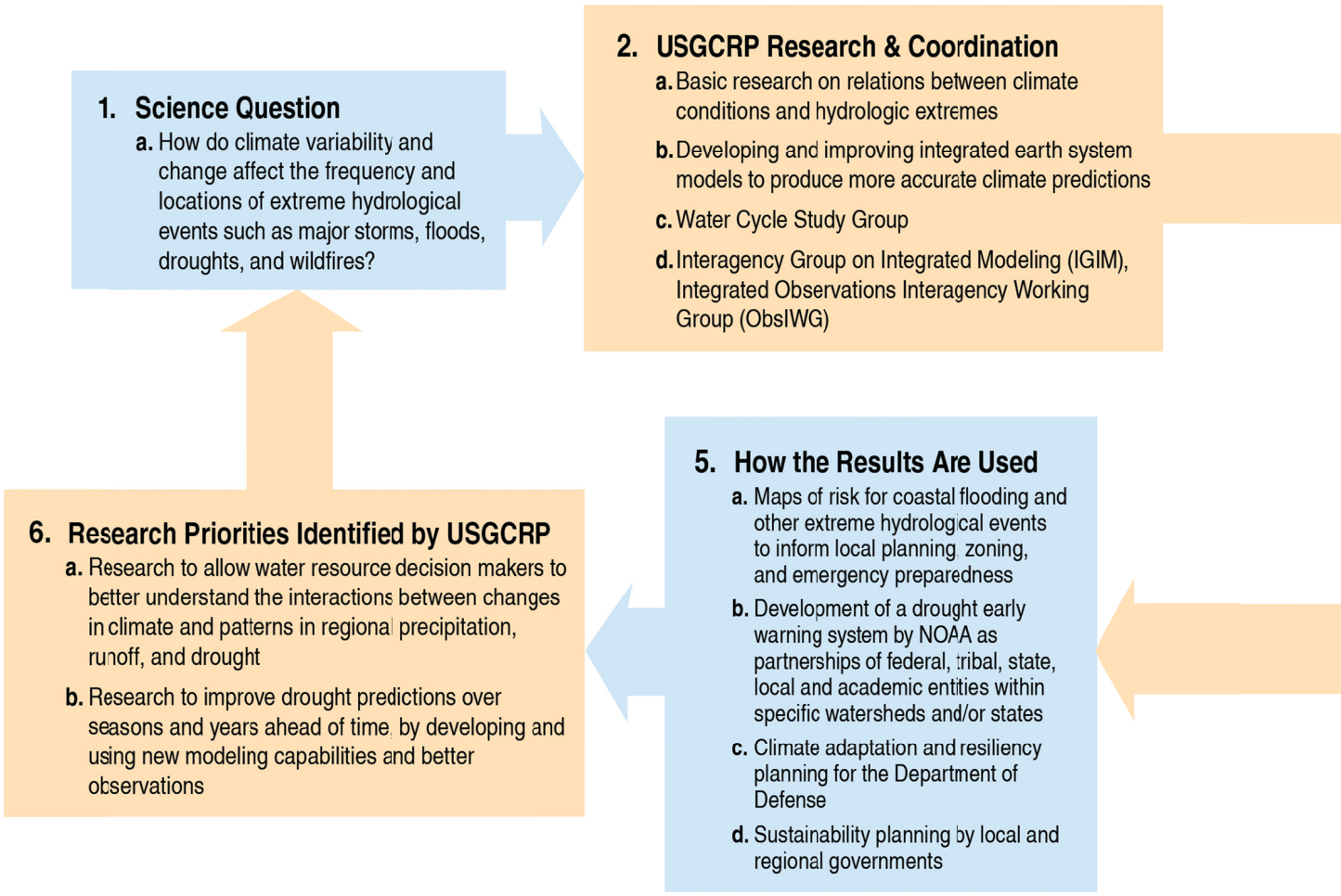


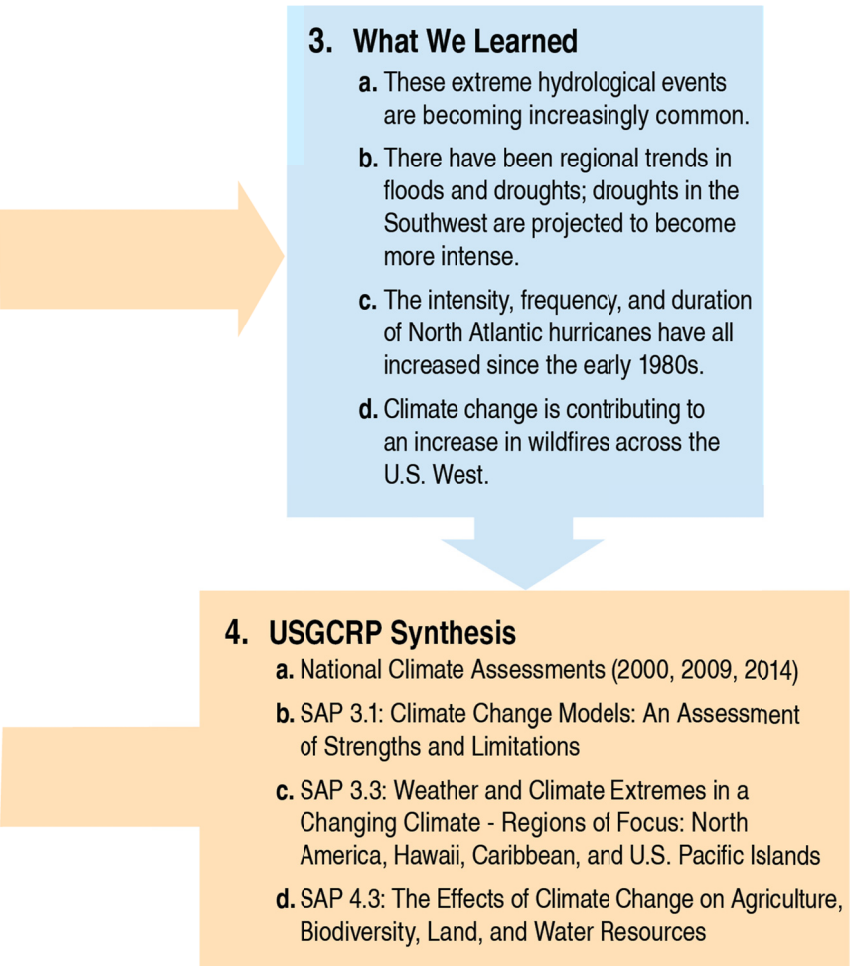
FIGURE 4. This schematic illustrates how USGCRP efforts contributed to advancing understanding of extreme events (e.g., storms, floods, and droughts) and the value of that information in stimulating a broad array of applications, including for emergency preparedness and resiliency planning. For example, addressing the question of how climate variability and change affect the frequency of droughts and other extreme hydrologic events has led to the development of a drought early warning system and guidance for emergency managers and local and regional planners. Orange boxes indicate points of specific USGCRP contributions: research and coordination, synthesis of what was learned through that process, and identification of new research priorities. Citations for selected bullets are included in Figure Notes.

NOTES:

1. **Science Question** includes an example of basic research question from the scientific community in this area.
2. **USGCRP Research and Coordination** includes examples of activities and mechanisms for research and coordination by the USGCRP.

a/b. For example, research by the National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, National Science Foundation, Department of Energy, and the Department of the Interior can be found in the USGCRP's annual reports to Congress and strategic plans (e.g., CCSP, 2002, 2008a; Subcommittee on Global Change Research, 1996; USGCRP, 2012a, 2015).

c. In 2000, the USGCRP appointed a Water Cycle Study Group, which produced A Plan for a New Science Initiative on the Global Water Cycle (WCSG, 2001).



d. For more on IGIM and ObsIWG, see http://www.globalchange.gov/about/iwgs,

3. **What We Learned** includes examples of high-level findings from the research and coordination in box 2. Citations for the work to support these statements can be found in the products included in box 4.

4. **USGCRP Synthesis** includes examples of Assessments conducted by the Program that communicate the findings to decision makers and the public.

a. Karl et al. (2009, pp. 30-38, 41-45, 57-58, 64-66, 74, 78, 97-98, 100-102); Melillo et al. (2014, pp. 63, 75-76, 86, 106-112, 159, 375-376, 442-443, 446, 482-483, 497, 507-513, 540, 594-595, 745-746); National Synthesis Assessment Team (2000, pp. 53-59, 94-97, 111, 116-127, 139, 146-161, 169, 174-183, 193, 202-210, 225-229, 253,262, 317-341, 361-364, 442-453, 472).

b. CCSP (2008b).

c. CCSP (2008c).

d. CCSP (2008e).

5. **How the Results Are Used** includes examples of the use of this information to provide benefits for the nation.

a. For example, FEMA, working with USACE, has begun to develop flood risk maps that take sea-level rise into account. Maps for New York and New Jersey can be found at http://www.globalchange.gov/browse/sea-level-rise-tool-sandy-recovery.

b. The National Integrated Drought Information System can be accessed at: https://www.drought.gov/drought/.

c. See the U.S. Department of Defense Directive 4715.21: Climate Change Adaptation and Resilience, January 14, 2016: http://www.dtic.mil/whs/directives/corres/pdf/471521p.pdf.

d. See NRC (2009a): *Informing Decisions in a Changing Climate*; Gulf Coast efforts described in USGCRP (2015).

6. **Research Priorities Identified by USGCRP** includes examples of priorities identified in USGCRP strategic plans (USGCRP, 2012b).

then archived and made publicly available for the science and applications communities. In addition to considerable national research, notably the National Climate Assessments, the output from CMIP3 and CMIP5 have been coordinated with and used in the IPCC fourth and fifth assessment reports, respectively. The Department of Energy has been instrumental in developing CMIP, including archiving, analysis, and quality control of model output, through the Program for Climate Model Diagnosis and Intercomparison at Lawrence Livermore National Laboratory. CMIP has also been supported through meetings and the annual summit convened by the USGCRP IGIM.

EXAMPLE 3: CARBON-CYCLE SCIENCE

The USGCRP agencies have played an important role in carbon-cycle research by championing strategic planning activities and by promoting and coordinating core observations and process studies. Carbon is the basis of all organic material, and carbon-cycling research has been a focus for the USGCRP because of the role this element plays as a regulator of Earth's climate and as a key factor in controlling the acidity of the global oceans. Research supported by USGCRP agencies has contributed to our understanding of these important functions, for example in understanding the rate of ocean acidification, consequences of ocean acidification for marine ecosystems and society, and the quantification of the current land carbon sink (see Box 5).

The accumulation of carbon dioxide in the atmosphere is a primary driver of climate change. Understanding the rates and causes of both carbon fluxes to the atmosphere (sources) and carbon sequestration in land and ocean ecosystems (sinks) is essential for developing policies to manage climate change. The USGCRP agencies have played an important role in research on the global carbon sink by championing strategic planning activities and by promoting and coordinating core observations and process studies. In 1998, the Carbon Cycle Interagency Working Group of the USGCRP was formally constituted to coordinate efforts that 12 U.S. government agencies and departments (currently) lead as part of the U.S. Carbon Cycle Science Program. In 1999, a plan to study the carbon cycle as it affected the United States was prepared at the request of the USGCRP (Sarmiento and Wofsy, 1999).

Today, the U.S. Carbon Cycle Science Program consists of the North American Carbon Program (NACP) and the Ocean Carbon and Biogeochemistry Program (OCBP), which is supported by USGCRP member agencies NSF and NASA, as well as by international partners. Having already absorbed ~30% of the carbon dioxide released to the atmosphere by human activities, the oceans play an important role in mitigating warming and other climate-related impacts of rising carbon dioxide levels. The OCBP has been built on a solid foundation of ocean research such as the Joint Global Ocean Flux Study, funded by NSF in the 1990s, to improve understanding of the time-varying fluxes of carbon and other life-essential elements, including nitrogen and phosphorus, both within the ocean and between the ocean and the atmosphere.

As with other aspects of globalization, the flows and transformations of carbon are complicated, and some of them affect the accuracy of models. Over the past 25 years, research, partly organized and supported through the USGCRP, has greatly increased our understanding of the processes involved. This has led to more accurate accounting of how carbon flows through ecosystems, atmosphere, land, and ocean, and has contributed to a better understanding of how changes in average global temperature affect the flows of carbon. For example, scientists now better understand the dynamics of carbon dioxide fertilization, the potential for enhanced decomposition of soil carbon as the climate warms, and the processes influencing carbon dioxide uptake in a warming ocean. Natural and human-induced disturbances, such as fire, thawing permafrost, melting sea ice, water deficits and management, and land use, have increased our understanding of geographic and ecosystem differences in carbon and their sensitivities to change and disturbance. Important components of this research are intensive, interagency coordinated field campaigns. They unite *in situ*, airborne, and satellite-based observations that bring the

BOX 5
Terrestrial Carbon Sources and Sinks

The accumulation of carbon dioxide (CO_2) in the atmosphere is a primary driver of climate change, and in order to better assess and predict change, sources and sinks of CO_2 need to be understood and quantified. A decade of research in the 1990s led to a major hypothesis that there was a large terrestrial sink for anthropogenic CO_2 in the Northern Hemisphere; much of the near-term observational work proposed in the first U.S. Carbon Cycle Science Plan was meant to test that hypothesis (Sarmiento and Wofsy, 1999).

The 2003 USGCRP strategic plan included the key research question: "What are the magnitudes and distributions of North American carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?" (CCSP, 2003). This question was motivated by a discrepancy in estimates of land carbon sources and sinks, where regional distributions of carbon sources and sinks from atmospheric and ocean data differed from the forest inventory and model estimates (IPCC, 2001). The NACP, supported by USGCRP member agencies NASA, NOAA, the Environmental Protection Agency, NSF, USGS, DOE, and the U.S. Deaprtment of Agriculture (USDA) in addition to the National Institute of Standards and Technology, was designed to tackle this important research question. The 2003 plan also included plans for a SAP on the carbon cycle (CCSP, 2003). In 2007, the U.S. Climate Change Science Program released SAP 2.2, also known as the State of the Carbon Cycle Report (or SOCCR),[14] which synthesized current knowledge and uncertainties about carbon sources and sinks in North America (CCSP, 2007). SOCCR reported on the substantial progress made in the quantification and reduction of uncertainty of the land carbon sink. The report estimated "a North American [terrestrial] sink of approximately 500 million tons of carbon per year for 2003" (CCSP, 2007). That report also estimated that the North American sink accounts for approximately 25% of the global terrestrial sink, whose total size was less certain.

One component of that sink is U.S. forests and associated wood products, which absorb and store about 200 million metric tons of carbon annually, or the equivalent of about 16% of carbon dioxide emitted by fossil fuel burning in the United States during 2011 (USGCRP, 2014). In the context of the global carbon cycle, U.S. forests account for about 10% of the annual global land carbon sink over the first decade of the 21st century. The carbon land sink is slowing the rate of the increase in atmospheric carbon dioxide and, therefore, slowing the rate of climate change.

resources of many agencies to bear on measuring the influences of human and natural processes on carbon-cycle variability and change. While the tools for conducting carbon-cycle research have become increasingly sophisticated over the past two decades, there is a need to develop additional observational capacities including those that are satellite based.

EXAMPLE 4: INTEGRATING HUMAN DIMENSIONS INTO GLOBAL CHANGE RESEARCH

The value of integrating social and behavioral sciences into global change research has become increasingly important. Economic approaches to modeling energy use are necessary but not sufficient to understand the complexities involved in projecting future climate and the potential consequences for human and natural systems. The social forces shaping land and energy use and urbanization globally are now understood to be of basic importance in developing scenarios for climate models. Designing effective responses to both disasters and ongoing stress, and designing programs to adapt to ongoing environmental change, requires understanding the behavior of individuals, organizations, and communities. Through its coordinating activities, the USGCRP has made important contributions to recognizing and expanding the interdisciplinary imperative bringing together the natural and social sciences in global change research.

[14] The Second State of the Carbon Cycle Report (SOCCR-2) is currently in production by the U.S. Carbon Cycle Science Program.

In 1990, there was already a large foundation of knowledge in the social sciences and in various fields of professional practice—including public health, development assistance, and agricultural extension—that examined the interaction of human activities and well-being with the ecosystems and climates in which people lived. While some understanding reflected global changes implicitly, there was little focus on the significant magnitude of human-induced change. The biophysical research described above has, in this respect, altered our understanding of the place of humans in the world over the past quarter-century. Humans do not just live in a world controlled by nonhuman forces; we change that world, too, for better and worse. Understanding how this happens has been a major contribution of the global change science coordinated by the USGCRP.

In 1992, the National Academies noted that social science research was essential to understanding, preparing for, and responding to global environmental change (NRC, 1992). That study reviewed knowledge, suggested a research agenda, and noted challenges the USGCRP would face in developing the appropriate social science research program as an essential companion to its natural science research program. The following year the congressional Office of Technology Assessment (OTA) concluded that adaptation research, encompassing human dimensions and economic implications, was lacking (OTA, 1993).

Although the need to integrate social science research within the Program was recommended early in its existence, there were and are obstacles to this effort. Most universities are organized primarily around disciplines, although some have also developed innovative structures to encourage interdisciplinary research and education. Most of the USGCRP agencies, as well as the national laboratories, have very few social scientists on staff, making integration difficult. Despite these and other challenges, the USGCRP has made progress, albeit uneven at times, in better integrating social sciences within the federal global change research portfolio.

The USGCRP has enabled and encouraged member agencies to support fundamental social science that can advance the understanding of the human dimensions of global change. For example, the Program coordinated the establishment of the National Science Foundation's Decision Making Under Uncertainty research centers that have supported research on decision making relevant to global change and especially on situations when outcomes of actions are uncertain, policy proposals face controversy, and the responses of the natural world to human actions are delayed and indirect (SSTF, 2013). Additionally, investments in Integrated Assessment Modeling as part of the overall USGCRP portfolio have supported the United States becoming a world leader in this field; these models link climate system processes with socioeconomic drivers of global change, allowing decision makers to explore issues such as the potential consequences of different pathways of greenhouse gas emissions and mitigation options (SSTF, 2013).

Several mission agencies within the USGCRP have made strides in delivering actionable science in support of decision making, particularly at the regional scale. Regional decision support centers were established by the DOI (Climate Science Centers), NOAA (Regional Integrated Sciences and Assessments [RISA] program and Regional Climate Centers), and USDA (Climate Hubs), each targeted at the specific responsibilities of the sponsoring agency. These centers have served as testbeds for experimentation in informing decisions, effectively providing platforms for applied human dimensions research. Indeed, the RISAs explicitly seek to include social, behavioral, economic, policy, and communications experts as part of their centers. Because of the regional focus of these centers, they have played a key role in the National Climate Assessments, often taking the lead in producing regional reports. All of this has drawn on and contributed to social science. However, work on actionable science has to be supported by parallel work to improve fundamental knowledge. Systematic efforts to improve fundamental global change social science remain a challenge.

In addition, these regional centers carry out projects that help decision makers in their regions to adapt effectively to climate variability and change. For example, the Great Lakes Integrated Sciences and Assessments Center (a NOAA RISA center) worked with the Michigan Department of Health and Human

Services and with the U.S. Centers for Disease Control and Prevention to identify climate-related health risks, and to tailor climate information so that it was useful to state and local public health officials for emergency planning, especially for helping vulnerable people (the elderly, the chronically ill) deal with heat extremes (Cameron et al., 2015). The goal is to reduce the costs and deaths from heat waves such as the one that killed over 700 people in Chicago in 1995 (Kaiser et al., 2007). The Consortium for Climate Risk in the Urban Northeast supported a similar effort in New York City (Petkova et al., 2016). The Southern Climate Impacts Planning Program (SCIPP), another RISA, has provided decision makers with forecasts of summer temperatures, made several months in advance, to inform farmers, provide a reservoir data visualization tool to help water managers, and inform a mobile phone app that can assess conditions for pastures, cropland, lawns and gardens, water resources, and wildfires (SCIPP, 2016).

The USGCRP has emphasized the need for greater integration across the sciences in its strategic planning (e.g., CCSP, 2003). The 2012 strategic plan highlighted the integration of social, behavioral, and economic sciences within its discussion of goal 1: to advance scientific knowledge of the integrated natural and human components of the Earth system, which includes all physical, chemical, biological, and human components, and the interactions among them, to improve knowledge of the causes and consequences of global change. The plan also designated "informing decisions" as one of four overarching goals, along with advancing scientific understanding of global change (as mentioned above), conducting assessments, and communicating and educating (USGCRP, 2011), and emphasized the need for research both *for* and *on* decision support. The Program has been developing plans to include more social science research into more activities in pursuit of that goal (Meyer, 2012).

After it released the 2012 strategic plan, the Program put in place a Social Sciences Task Force that produced a white paper in December 2013 on the integration of social sciences to support the implementation of the strategic plan. This task force was in part motivated by the National Academies' review of the draft strategic plan (NRC, 2012b). The task force recommended an organizational structure to help implement its recommendations. In response, the Program created an interagency working group, the Social Science Coordinating Committee, that is charged with putting in place means to foster "integration of the methods, findings, and disciplinary perspectives of the social, behavioral, and economic sciences" into the Program's activities.[15]

While progress is being made, challenges remain (NASEM, 2016). Given the lack of social science expertise at most of the USGCRP agencies, they will have to actively engage the larger environmental social science community to develop research programs that effectively integrate and make use of social science. Additionally, the National Academies identified the integration of human dimensions as "the most critically underfunded" area of the USGCRP in its review of the fiscal year (FY) 1991 budget (NRC, 1990) and has continued to make similar assessments over the years. The lack of sustained data resources remain an impediment to the development of cumulative understanding in the environmental social sciences. These challenges will have to be overcome for further progress in incorporating the social sciences into the USGCRP, to provide the information the nation needs to effectively and efficiently manage current and likely consequences of global environmental changes.

This committee noted in its recent review of the draft Update to the Strategic Plan (USP; NASEM, 2016) that calling for greater integration of social science within an agenda set largely by the natural sciences, as the draft USP did, fails to recognize and build upon the disciplinary contributions from the social sciences or, even more importantly, the novel contributions that can arise from an interdisciplinary approach combining social and natural sciences. A logical next step for the Program would be a broad review of the relevant social science research, e.g., in developing understanding of vulnerabilities to the multiple stressors involved in global change, or in understanding decision making by individuals and organizations under uncertainty.

[15] http://www.globalchange.gov/about/iwgs.

COMMITTEE REFLECTIONS

Looking back over a quarter-century and four presidential administrations, the USGCRP has made notable accomplishments in its mission of scientific research to advance the national interest. Fundamental advances in knowledge have been achieved. Collection of consistent data sets, at levels of spatial resolution from global down to specific watersheds and neighborhoods, has documented a range of global environmental changes in ways that can inform American decision making. The development of sophisticated models now gives us the ability to forecast near-term risks such as drought or the track of severe storms, with an accuracy that far exceeds our capabilities in 1990. With a greater volume of useful knowledge has come a growing societal capability and demand for knowledge about risks and how to manage them that is timely and relevant to a wide range of users. For example, the ability of emergency responders to prepare for wildfire or unusual storm surges, and to place those risks in the context of their past experience, is now an operational reality. The evidence is clear that climate is changing, and this knowledge matters directly in long-range capital budgets as well as decisions about training, education, the location of homes and businesses, and national security (DOD, 2015).

The Program has also provided coordination to the efforts of a large federal research establishment. This has reduced duplication and increased efficiency. But it has done more: by finding alignments among the missions of agencies, the Program has made it possible for data collected by one agency to inform the modeling of a second agency and the operational decisions of a third. Many agency-supported programs and projects developed and evolved over time and supported data collection that continues to be an important component of the Earth Observing System. For example, the TOGA Coupled Ocean Atmosphere Response Experiment led to sustained tropical observations critical to projects on the El Niño–Southern Oscillation and to the study of the influence of climate change on natural variability. Global change is a multidisciplinary challenge, and bringing together the diverse capabilities of the federal government is an important objective that transcends the missions of individual agencies and departments; the USGCRP brings that objective within reach in ways that are economical and indispensable.

3
Assessments and Stakeholder Engagement

The Global Change Research Act (GCRA) requires the U.S. Global Change Research Program (USGCRP) to submit to Congress an assessment of the main findings of the Program regarding global change science every 4 years. The GCRA specifies that the assessment address the potential effects of global change, both human and natural, on a set of sectors and activities given observed trends and near-term (25 years) and long-term (100 years) projections. The Program prepared three National Climate Assessments (NCAs)—published in 2000, 2009, and 2014—and is in the process of preparing a fourth one. The NCAs are coordinated and produced by the USGCRP National Coordination Office. Dozens of supplementary reports have been produced by the Program and its participating agencies, often as input to the NCAs. In addition, the USGCRP helped to establish and actively participates in several international assessment processes including the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO)/United Nations Environment Programme (UNEP) Scientific Assessment of Ozone Depletion.

The purpose of an assessment is to evaluate the state of scientific knowledge (NRC, 2007). A useful assessment communicates, to a wide range of audiences and users, what research indicates about risks and potential benefits of current and projected global change. With assessments, one can appraise the efficacy of policies, measures, and programs intended to manage those risks. The assessment process also produces a host of ancillary outcomes that are more diffuse and difficult to document, including new collaborations, new research, and newly engaged stakeholders. It also can stimulate substantial involvement by agencies, which have supported the assessments by lending staff to the USGCRP, providing technical input, and leading the federal government's engagement with specific expert and stakeholder communities.

As documented in previous sections, scientific investments have led to, for example, useful and useable knowledge about changes in the frequency, intensity, and duration of some extreme weather and climate events. Knowledge summarized in assessments is being used to prepare for and reduce the human and financial costs of future events. Research on the societal impacts of hurricanes shows that forecasts are likely generating substantial benefits by saving lives, reducing the costs of evacuations, and improving supply chain management (Sutter and Ewing, 2016). In addition, evidence suggests that hurricanes can lead to substantial increases in government outlays not only for direct disaster relief but also for other forms of assistance, such as unemployment insurance and public medical payments (Deryugina, 2016), and for infrastructure improvements that can build resilience to future events. Thus, having better information about factors influencing the frequency and costs of hurricanes and cost-effective means of mitigating their impacts can provide substantial benefits not only within the affected communities but for the nation as a whole. This is just one example of the wide range of public goods benefits of investment in the scientific enterprise and of the value of the USGCRP in prioritizing and coordinating research to benefit the nation. Other examples are provided in Figures 2, 4, and 5.

HISTORY OF THE U.S. NATIONAL CLIMATE ASSESSMENTS

The process used by the USGCRP to prepare the assessments has changed over time. The main variation concerns the degree of participation by experts and stakeholders outside the federal government. The first and third NCAs were produced through a process that included extensive engagement of

university-based experts and stakeholders from different sectors (e.g., agriculture, water resources, and insurance) and regions. The second NCA involved a smaller author team asked to synthesize material from a set of more focused assessments. In all cases, the reports have been reviewed for relevance, technical accuracy, and clarity by experts, stakeholders, and federal agencies that are part of the USGCRP.[1]

The first NCA was released in 2000 and was titled "Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change"[2] (National Synthesis Assessment Team, 2000). The report was prepared with input from academic and government scientists. The assessment began with a set of workshops for stakeholders from regions and sectors to articulate their concerns. Uncertainty was framed through use of climate scenarios produced primarily using Canadian and U.K. models, although results were also drawn from U.S. modeling centers. The assessment revealed a number of national-level impacts of climate variability and change including impacts on natural ecosystems and water resources. The report combined this national-scale analysis with findings on potential impacts on different regions. Authors employed a lexicon of "uncertainty terms" to convey uncertainty and likelihood. The timing of the release of the report, at the transition from the Clinton to the George W. Bush Administration, likely reduced its impact since the incoming administration withdrew the report from government websites and did not continue the extensive process of stakeholder engagement that had been initiated.

The second NCA (NCA2) was released in 2009, titled "Global Change Impacts on the United States" (Karl et al., 2009). It was prepared by a team of approximately 30 authors using material from a set of 21 Synthesis and Assessment Products (SAPs)[3] produced by the Program (known as the Climate Change Science Program during the George W. Bush Administration), other assessments, and the research literature. In NCA2, impacts were addressed by sector (water resources, energy supply and use, transportation, agriculture, ecosystems, human health, and society) and region (seven geographical regions plus cross-cutting chapters on coasts and islands). Increased attention to adaptation was incorporated, as several SAPs analyzed available options, e.g., for ecosystems.

The third NCA (NCA3) was released in 2014 (Melillo et al., 2014), based upon wide engagement with stakeholders, researchers, and experts from business and civil society (Cloyd et al., 2016). Extensive stakeholder engagement occurred through multiple workshops convened by lead authors and other participants. More than 300 authors guided by a 60-person Federal Advisory Committee were drawn from the research and user communities, including government (federal, state, local, and tribal stakeholders), industry, and civil society. NCA3 was aimed at informing those user groups, as well as the broader public. Extensive public comments were received (more than 4,000 comments from more than 600 individuals) and a review was conducted by the National Academies (NRC, 2013b). NCA3 included a number of innovations related to engagement, scenarios, risk assessment, and communications that are described by Jacobs et al. (2016). Of particular note, the report was released through an interactive website,[4] in addition to being available for download in more traditional report formats. The USGCRP also developed the Global Change Information System,[5] a web-based resource for traceable global change data, information,

[1] In addition to public review, this committee and others of the National Academies have reviewed reports for the USGCRP, including many of the Synthesis and Assessment Products and the latest National Climate Assessment (NCA3). A list of reports for the USGCRP from the National Academies is included in Appendix E.

[2] Available at http://www.globalchange.gov/browse/reports/climate-change-impacts-united-states-potential-consequences-climate-variability-and.

[3] The SAPs were designed to meet the GCRA requirement for assessment by addressing a series of policy-relevant questions related to human and natural influences on the Earth system, the response of the climate system, impacts, and response strategies. These questions were linked with the main elements of the CCSP strategic plan. References for SAPs provided in Appendix B.

[4] See http://nca2014.globalchange.gov/.

[5] See https://data.globalchange.gov/.

and products, designed for use by scientists, decision makers, and the public, which includes fully transparent access to data in the NCA3.

Reflecting the research literature on effective communication of science for policy and decision support, the USGCRP continues to evolve its assessment program toward more varied processes and products. The Federal Advisory Committee for NCA3 produced a report with a set of recommendations for building a sustained process (Buizer et al., 2013). A new Federal Advisory Committee[6] has been established to focus on developing a more sustained assessment process with products in addition to reports to better support the wide range of users whose interests are expected to be affected by global change. The fourth assessment is being prepared through a process that is similar to that used for NCA2—a smaller core team of federal authors—but with opportunities for the public and research community to provide inputs.[7]

BOX 6
Assessing the Impact of Climate Change on Human Health

Early in its existence, the priorities of USGCRP were focused on understanding global-scale environmental processes and identifying and explaining the causes and consequences of global environmental change. The first NCA was built to tackle this scientific agenda, and informed the national dialogue already under way about coming changes and their impacts on Americans. Since then, assessing the impact of climate change on human health has been a regular activity of the Program, and the process has become more sophisticated as the science evolves.

Between 1998 and 2000, the Program conducted the first national assessment of the potential impacts of climate change on human health in the United States, which was published as a series of articles as part of a supplemental issue of the journal *Environmental Health Perspectives* (USGCRP, 2001b). That assessment identified five categories of health outcomes most likely to be affected by climate change because of their exposure-response relationship with weather and/or climate variables: temperature-related morbidity and mortality, health effects of extreme weather and climate events, air pollution–related health effects, water- and foodborne diseases, and vector- and rodent-borne diseases. The assessment concluded that the levels of uncertainty precluded any definitive statement on the magnitude and pattern of potential future change for each of these health outcomes (Patz et al., 2000).

Since then, the Program has coordinated research to support advancements in the science, including through its Interagency Working Group on Climate Change and Health, and developed products to assess the state of knowledge (e.g., CCSP, 2008d; Portier et al., 2010; USGCRP, 2016). The latest assessment concluded health impacts from anthropogenic climate change are observable and increasing nationwide, with climate-related increases in exposure to high ambient temperatures; more frequent, severe, or longer-lasting extreme events; degraded air quality; diseases transmitted through food, water, and disease vectors; and stresses to mental health and well-being (USGCRP, 2016). According to this assessment, these impacts interact with underlying health, demographic, and socioeconomic factors to exacerbate existing climate-related health threats (e.g., heat-related morbidity and mortality) and create new population health challenges (e.g., emerging vectorborne diseases). While every American is vulnerable to the health risks of additional climate change, some individuals and populations are disproportionately vulnerable, including those with low income, some communities of color, immigrant groups, indigenous people, children and pregnant women, older adults, vulnerable occupation groups, persons with disabilities, and persons with preexisting or chronic medical conditions (USGCRP, 2016).

Scientific advancements in understanding climate change impacts on human health have led to the development of the National Integrated Heat Health Information System and resources meant to guide local decision makers, emergency managers, and others on responses to excessive heat (see Figure 5).

[6] See http://sncaadvisorycommittee.noaa.gov/.
[7] For more detail, see http://www.globalchange.gov/search/Fourth%20Assessment.

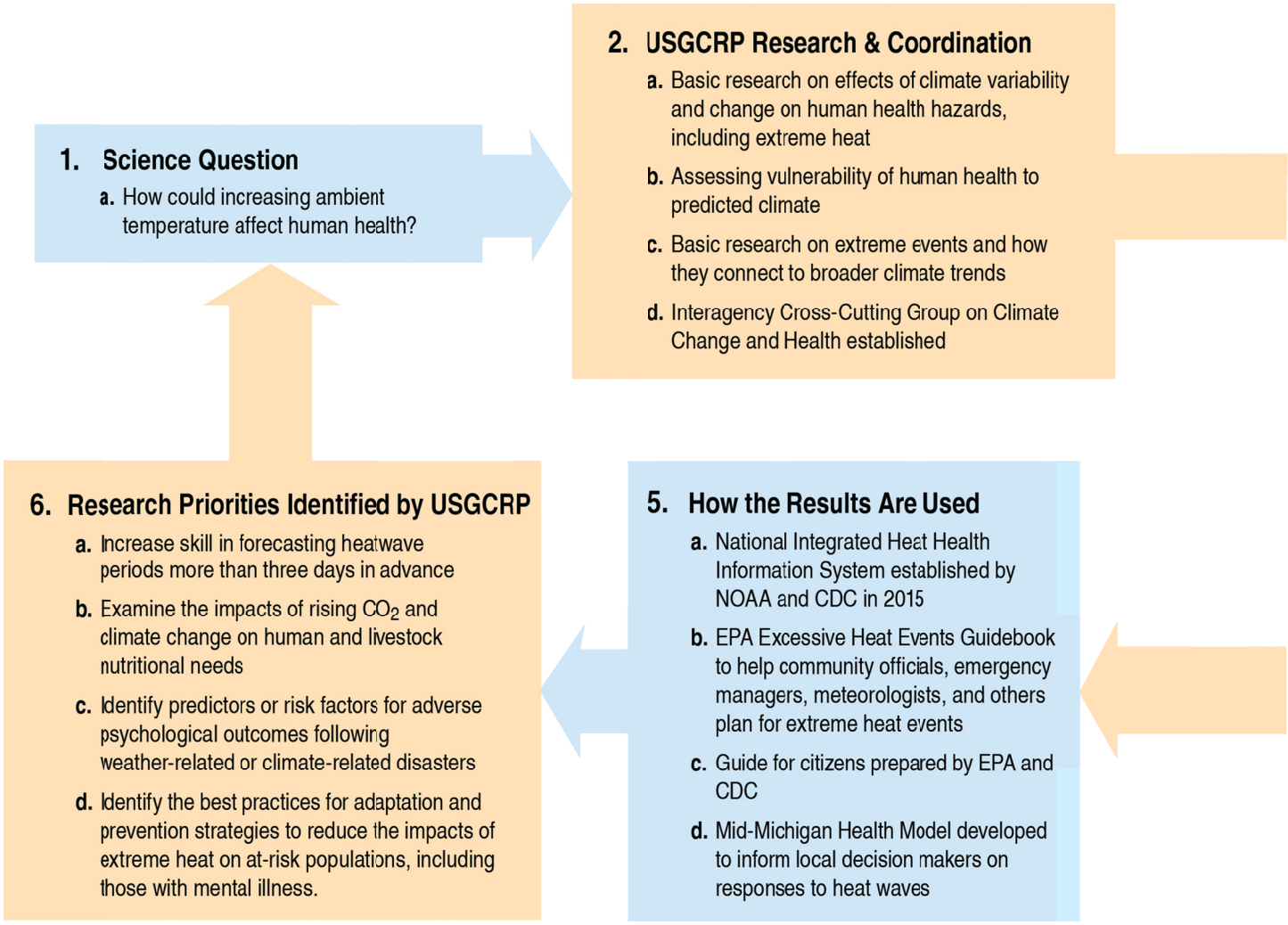


FIGURE 5. This flowchart illustrates the ways USGCRP contributes to scientific advancements in global change research and the value of that information in stimulating a broad array of applications, including for protecting and promoting human health. As an example, addressing the question of how increasing temperatures could affect human health led to tools and guidebooks designed to reduce morbidity and mortality. Orange boxes indicate points of specific USGCRP contributions: research and coordination, synthesis of what was learned through that process, and identification of new research priorities. Citations for specific bullets are included in Figure Notes.

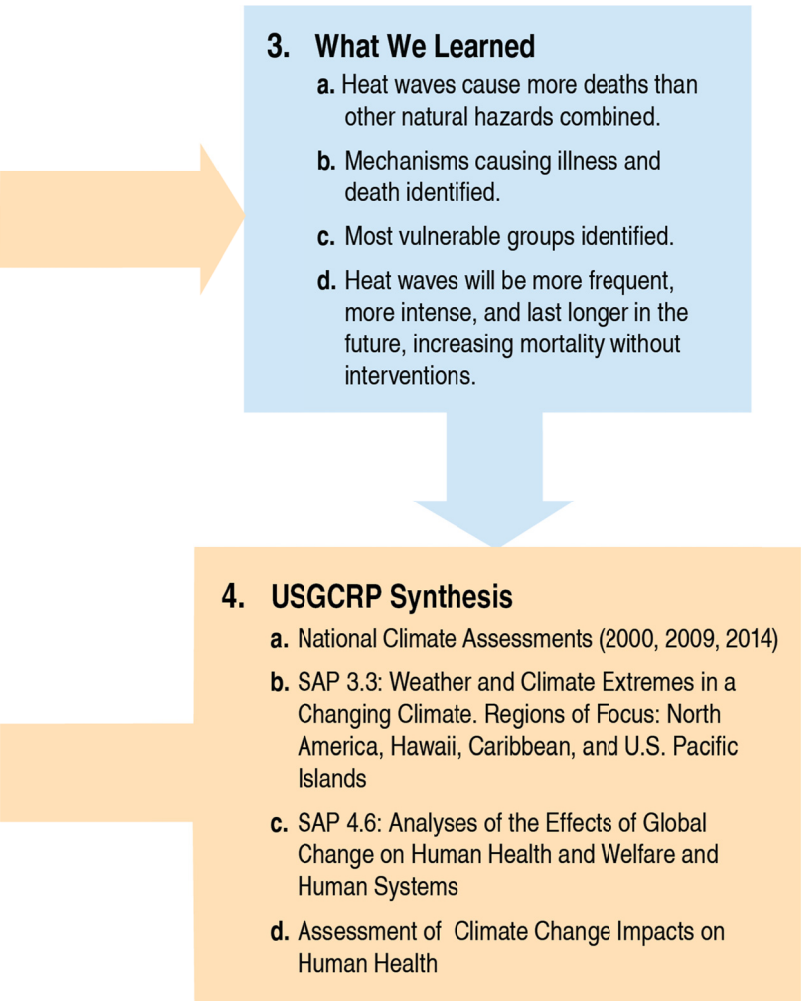
NOTES:

1. **Science Question** includes an example of basic research question from the scientific community in this area.
2. **USGCRP Research and Coordination** includes examples of activities and mechanisms for research and coordination by the USGCRP.

d. a/b/c. For example, research by the National Institutes of Health, Centers for Disease Control and Prevention (CDC), National Oceanic and Atmospheric Administration, Environmental Protection Agency (EPA), U.S. Department of Agriculture, National Aeronautics and Space Administration, and National Science Foundation can be found in the USGCRP's annual reports to Congress and strategic plans (e.g., CCSP, 2002, 2008a; Subcommittee on Global Change Research, 1996; USGCRP, 2012a, 2015). See http://www.globalchange.gov/about/iwgs for more on interagency working groups.

3. **What We Learned** includes examples of high-level findings from the research and coordination in box 2. Citations for the work to support these statements can be found in the products included in box 4.
4. **USGCRP Synthesis** includes examples of Assessments conducted by the Program that communicate the findings to decision makers and the public.

a. Karl et al. (2009, pp. 89-98); Melillo et al. (2014, pp. 220-256); National Synthesis Assessment Team (2000, pp. 102-107).



a. CCSP (2008c).
b. CCSP (2008d).
c. USGCRP (2016).

5. **How the Results Are Used** includes examples of the use of this information to provide benefits for the nation.
   a. The National Integrated Heat Health Information System can be accessed at: http://toolkit.climate.gov/nihhis/.
   b. EPA (2016).
   c. EPA and CDC (2016).
   d. See Olabisi et al. (2012).
6. **Research Priorities Identified by USGCRP** includes examples of priorities identified in USGCRP reports and strategic plans (USGCRP 2012b, 2016).

The Program's assessment products (for an example, see Box 6) are a key accomplishment of the Program and have been of demonstrable value to the nation in informing decisions at all levels of government, within the private sector, and among the public (Jacobs et al., 2016). They have also led to identification of research directions and outputs, new collaborations, and broader and deeper engagement with stakeholders, including those within the federal family, within and outside USGCRP agencies (NASEM, 2016).

CONTRIBUTIONS TO INTERNATIONAL ASSESSMENTS

The USGCRP has played a major role in establishing, providing scientific inputs for, and preparing international scientific assessments. In particular, the USGCRP and its participating agencies have made significant contributions to assessment activities convened by the WMO and UNEP, specifically the IPCC and a series of scientific assessments of ozone depletion. Other U.S. agencies have taken the lead with respect to the Global Biodiversity Assessment and its successor, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, but USGCRP research has also contributed to the knowledge base for this assessment process.

The need for international assessments grows out of experience preparing national studies of ozone depletion, which was understood to have the potential to lead to increases in UV radiation and risks of impacts to human health (e.g., skin cancers) and the environment (NRC, 2007). Governments agreed it was important to establish a shared understanding of the state of science with respect to ozone depletion, climate change, and other environmental issues that required coordinated national responses to inform international negotiations.

The IPCC was established in 1988 to assess scientific information about climate change. IPCC reports are prepared through a multistage process that includes formulation of the information request to the scientific community through preparation and approval of the outline for a given report, independent drafting of the reports by scientists, and co-production of report summaries by scientists and government representatives. All IPCC products go through several rigorous stages of expert and governmental review to ensure accuracy and relevance to information needs. The success of the process over the years has depended on its transparency—comments and responses on all drafts are compiled and available through the Secretariat—and the enthusiastic participation of thousands of scientists (IAC, 2010). IPCC assessments have provided many important inputs to the negotiations that led to the United Nations Framework Convention on Climate Change.

The United States has played a key role throughout the IPCC process as a major contributor of scientific and technical expertise and funding. U.S. participation in the intergovernmental process is coordinated through the U.S. Department of State. The USGCRP coordinates scientific and technical inputs. The United States chaired the IPCC during the Third Assessment Report. USGCRP has supported coordinating secretariats ("Technical Support Units" or TSUs) for many of the Working Groups as they prepared specific components of major assessments, special reports, and technical papers including the TSUs for the First Assessment's "Response Strategies Working Group"; Working Group II (generally focused on issues related to impacts, adaptation, and vulnerability) for the Second, Third, and Fifth Assessments; and Working Group I (climate and Earth systems science) for the Fourth Assessment. Over the decades, the USGCRP has provided travel support for hundreds of U.S. scientists to participate in lead author meetings for drafting IPCC reports; the time spent by these scientists in assessing the state of knowledge and participating in the meetings was volunteered.[8]

USGCRP agencies have also played extensive roles in leading, authoring, and reviewing international scientific state-of-understanding assessments on the stratospheric ozone layer. Since its inception in 1987, the WMO/UNEP Scientific Assessment Panel on Ozone Depletion has provided state-of-science assessments to underpin the decisions associated with the protection of the Earth's ozone layer through the United Nations Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments. The most recent assessments were in 2010 and 2014 (WMO, 2010, 2014). These assessments provided the foundation for policies to reduce and then phase out the use of ozone-depleting chemicals that were developed under the Montreal Protocol.

[8] A digital record of documents associated with U.S.-hosted Working Groups is archived at the Environmental Science and Public Policy Archives at the Harvard University Library at http://hcl.harvard.edu/collections/ipcc/.

ADVANCING THE PROCESS OF ASSESSMENT

The understanding of best practice in assessment has evolved over the life of the USGCRP, and in many respects the USGCRP has been a leader in innovating and advancing this practice. For example, it is now widely recognized that scientific information is more trusted and usable if conveyed through a sustained process and in a variety of formats, not just as reports (Brown et al., 2015; Buizer et al., 2015; USGCRP, 2016). The idea of presenting climate assessment results within a risk framework was introduced in the third NCA and the USGCRP is continuing to support efforts to advance these approaches (see Box 7).

The Program has been particularly innovative in how it has connected knowledge users and producers. For example, NCAnet[9]—a network of partner organizations—was launched in 2011 to regularly interact with stakeholders across the country. The network offers a platform for constituents to provide technical inputs to assessment processes and build national assessment capacities by hosting public meetings, advancing work on indicators, and engaging with stakeholders.

BOX 7
Framing Climate Assessments in Terms of Risk

The NCAs have increasingly used a risk-based framing to explicitly acknowledge and explore the multiple drivers of changes and impacts. Although there continues to be uncertainty about the magnitude and pattern of climate-driven events that create risks to human and natural systems, indicators such as economic losses from severe storms are consistent with an increase in climate-related risks (Smith and Katz, 2013). There is also evidence that climate change increases multiple risks to complex and interrelated ecological and human systems that may exceed the capacity of societies to manage. Hazards may be posed by phenomena such as reduced genetic diversity in crops, inconsistent crop yields, decreased productivity in fisheries, changes in the distribution of disease vectors, and the emergence of novel pathogens and pests (NRC, 2013a; Scheffers et al., 2016).

Risk is determined by the interplay of several factors: the severity of events, the exposure of human and natural systems, and the vulnerability of these systems, including susceptibility to harm and the effectiveness of coping, response, and recovery (NRC, 2013a). Attention to only one of these factors will not reduce risk to the maximum extent possible. Because global change research is rapidly evolving, for any given issue, relevant information will likely be incomplete, placing a premium on rigorous and ongoing assessment processes that can cogently characterize scientific confidence/uncertainty in light of the information needs of users.

Past climate assessments summarized available knowledge about climate change in terms of potential changes in key climate variables. NCA3 took a step toward evaluating impacts in a risk framework. Authors were asked to consider key risks in their chapters, and to evaluate the likelihood and consequences of these risks in ways relevant to decision making. A number of the chapters offered narrative accounts linking potential changes in climatic variables to effects on some of the socioeconomic and ecological systems that directly affect users, including cascading risks and risks that cross sectors; a few specifically evaluated likelihood and consequence based on the scenarios recommended for use in the assessment.

As part of the preparation for the fourth NCA, the USGCRP asked the National Academies to hold a workshop to consider ways to gather insights from scientists and practitioners with expertise in climate science and impacts, risk characterization and communication, and management of climate risks in various U.S. regions and sectors. Workshop participants focused on three main challenges: characterizing climate risks in terms of their implications for people and ecosystems; conveying risk information in ways that are clear, accurate, useful, and accessible; and identifying the connections across regions and sectors that are critical for understanding risks. Among other things, the discussion underlined the value of engaging expertise from across the sciences and the user communities and the need to focus on decision-critical hazards, including low-probability, high-impact conditions (NASEM, 2016).

[9] See http://ncanet.usgcrp.gov/.

While the assessment process has demonstrated the value of robust basic research to produce decision-relevant findings, more broadly, the sustained assessment process is beginning to demonstrate the capacity of a user-led approach to provide guidance to the research community on what needs to be learned as the consequences of global change emerge and people and institutions respond. The ongoing interaction between researchers and those who make use of scientific understanding aids in identifying priorities for future research while it helps build trust in the science. These processes also have the advantage of linking agencies, offices, and programs whose mission is primarily research with those whose mission is managing resources or providing other forms of public service. The collaboration of agencies with different missions in assessments led by the USGCRP facilitates mutual understanding of the state of the science and of user needs across agencies.

Use-inspired research is an innovation that is emergent in critical ways, and the idea that research agendas should be informed by users remains an aspiration to a degree. It is a goal that is in tension with the longstanding role of scientists in setting the agenda of research. The scientific community has an essential role to play, because discoveries and insights flowing from a scientific perspective identified the phenomena of global change long before they began to be felt in practical affairs, a pattern that is likely to continue because the global environment is now on a trajectory unlike that of the past. Finding the appropriate balance between applied research and scientific discovery is a recurrent challenge, and the USGCRP continues to play a critical role in the evolution of this balance, reflecting the essential need to generate scientific knowledge, but also to place this knowledge in the service of the nation.

4
Building on the Accomplishments of the USGCRP for the Next 25 Years

The first 25 years of the U.S. Global Change Research Program (USGCRP) were marked by impressive advances in understanding of global change, by unprecedented efforts to observe and document change in the natural and built environments, and by major improvements in bringing scientific knowledge to bear in decision making. Several highlights of these accomplishments are described in this report, and many more could have been featured.

Looking forward, the Program should build on this legacy to be ready to address the challenges and needs emerging today and over the next few decades. Over the past three decades, the USGCRP and the research community supported by its member agencies focused on detecting the signal of climate change against a background of natural variability, and then analyzing how and when more significant impacts might become manifest. Based on that research, we can expect the impacts of climate change will be increasingly apparent. As a result, the Program will need to strengthen the knowledge base for protecting the nation's interests in the face of accelerating global environmental changes, and to work with users to provide timely warning to citizens, businesses, and governments at all levels.

SUSTAINING, EXPANDING, AND COORDINATING OBSERVATIONS

The current global observing system has been implemented by USGCRP agencies, a process that has benefited from the formal and informal coordination of the Program. The data and information from these observation systems form the foundation for global change science, both in the United States and globally. The USGCRP has a critical responsibility to ensure their continuity, while also looking to expand the observational archive to address new scientific questions and users' needs. The coordinating role of the USGCRP will become more important, as a greater diversity of observations becomes available and needed. For example, coordinating observations from more diverse platforms and sources, including those operated by other nations, by the private sector, or by disciplines not typically associated with climate science, will present new challenges as well as opportunities.

Sustaining and expanding Earth observations are at the core of our ability to enhance scientific understanding of our interconnected planetary system and in developing and providing information products for decision makers. Earth system modeling is complicated, and the process understanding of atmosphere-ocean-land-ice interactions that needs to be discovered and incorporated into models requires an increasingly diverse set of satellite and *in situ* observations. The United States has benefited greatly from the investment that has been made to date in Earth observations, including enhanced forecasts of weather extremes and climate variability impacts, as needed by cities and communities to develop plans for climate adaptation. Almost every sector of our economy, national security, and the sustainability of ecosystem services that are provided to humanity depend on the understanding and use of integrated global Earth observations (both satellite based and *in situ*). The USGCRP has been the critical coordination group for planning this observation system and must remain a core responsibility.

USE-INSPIRED RESEARCH

Global environmental changes, including climate, are transforming the conditions of human life and the ecosystems on which we depend. Global change research has much to contribute—to identifying vulnerabilities and threats, to evaluating alternative policies and programs, and to informing the judgments and decisions of individuals, organizations, and institutions, including national governments. As with much research, the returns from the investments in global change science are largely public goods (see Figures 2, 4, and 5 for examples), making it a responsibility of government to support that research. Users of this research include decision makers, such as farmers coping with drought, governments planning for sea-level rise, and scientific groups using data, models, and assessments in their investigations of global change.

To increase the return to the nation on investments in global change research, the committee supports use-inspired research within the Program (Clark et al., 2016; Stokes, 1997). This research entails engagement with a wide spectrum of users, so as to produce research that informs decision making, and leverage the value of discovery-driven research, including long-term observations of the Earth system. For example, given the dependence on ecosystems, use-inspired research is critical for natural resource management, for example in informing the use of forest thinning as a management tool to prevent massive wildfires. Use-inspired research requires the fluent integration of knowledge from the social and biophysical sciences, a synthesis that remains more of an aspiration than an achieved reality. The wide uptake of the third National Climate Assessment (NCA3) suggests, however, that a clear articulation of the state of knowledge contributes to the continuing dialogue on climate change and its potential hazards, benefits, and solutions. This is a hopeful sign, as well as a significant accomplishment of the Program.

The committee believes there are opportunities for use-inspired research to make further significant contributions to the work of the USGCRP and its member agencies as part of the current strategic plan, for example by synthesizing the data now being collected into indicators of vulnerability for specific regions (Janetos and Kenney, 2015). A broad analysis identifying some potential vulnerability indicators was prepared by a working group during the process of developing NCA3 (Kenney et al., 2016). Kennel et al. (2016) suggested that indicators can be grouped into leading and lagging sets. Testing whether a set of indicators can provide reliable warning of abrupt changes in specific locales may be an attainable objective in the next 5 years.

INTERNATIONAL PARTICIPATION

In global change science, U.S. government agencies make a major contribution to the necessarily global enterprise of research, data development, and analysis. The effectiveness of U.S. efforts is enhanced by dialogue and coordination with other nations, catalyzing scientific understanding while reducing duplication of efforts. The USGCRP, with its unique overview of diverse U.S. climate research activities, plays an important role in this process in three useful areas: joint research, global observation, and international assessment.

The collection and analysis of data on Earth processes, which are crucial to understanding current and potential future change, are international tasks. Efficient use of resources demands effective collaboration among the nations able to carry out this work. To this end, the USGCRP supports global observation and data management through participation in the Group on Earth Observations. This group coordinates investments in Earth system observation and facilitates access to the information through its Global Earth Observation System of Systems. These data also are crucial for detecting current impacts and projecting future risks under a range of climate and development pathways, and for assessing the potential for adaptation and mitigation policies and programs to increase the resilience of communities and regions no matter what the future holds.

The USGCRP is a point of contact for U.S. participation in international assessment activities in global change. For example, it participates in recruiting, coordinating, and supporting U.S. chapter authors and reviewers for the reports of the Intergovernmental Panel on Climate Change (IPCC). The USGCRP manages the review process for national and international assessments, including coordination of thorough review by U.S. agencies to ensure the accuracy and robustness of scientific findings. The USGCRP maintains a Review Portal for hosting and coordinating U.S. national reviews of international assessments and other reports.

The need for effective coordination of U.S. agencies with international activities seems likely to increase in the future. In addition to its 6th Assessment Report, just getting under way, the IPCC is organizing three special reports. The United Nations Framework Convention on Climate Change (UNFCCC) requested by 2018 a report on the impacts of global warming of 1.5°C, and commitments were made on two other special reports: one on oceans and the cryosphere and another on desertification, land degradation, land management, food security, and greenhouse gas fluxes. The United States has much to offer these activities, and much to learn from such global assessments, but coordination is needed to help ensure that its best scientists are involved.

In addition, terms of the Paris Agreement (adopted by consensus December 12, 2015, at the 21st Conference of the Parties of the UNFCCC) likely will place additional demands on U.S. agencies, creating an even greater need for coordination. For example, under Article 11 of the Agreement, developed country parties should "enhance support for capacity-building actions in developing country parties." This obligation covers adaptation and mitigation, thus spanning the capacities of several U.S. agencies. Article 8 of the Paris Agreement incorporates the *Warsaw International Mechanism for Loss and Damage Associated with Climate Change Impacts* (COP19, November 2013). The Warsaw text commits the parties to efforts that enhance understanding of climate-related phenomena that is needed to support action to compensate or otherwise aid damaged parties. Meeting this objective involves resolving challenging scientific issues related to the attribution of specific climatic events, and of understanding the extent to which underlying vulnerabilities contributed to impacts; these cut across the capabilities of U.S. agencies involved in climate research.

Although details of implementation of these provisions is being worked out in ongoing negotiations among parties to the Paris Agreement, the United States may respond to these calls for action with contributions from U.S. agency programs. The salient research questions will require fundamental science and long-term observations to gain satisfactory answers, requiring decades of collaborative global effort.

MEETING A DIVERSITY OF NEEDS

Addressing the problems of global environmental change will require advances in fundamental scientific knowledge and application of that knowledge to decision making at all levels of government and by nongovernmental organizations, the private sector, and households. This diversity of information needs is reflected in the diversity of missions of the agencies that participate in the USGCRP. Some are primarily research agencies dedicated to advancing science in the public interest. Some consider global change and climate change in the context of particular missions, whether to promote agricultural productivity, to manage the nation's public lands and fisheries, or to identify meteorological hazards. Many support research to inform resource management and other decisions. A special advantage of the USGCRP is that it facilitates dialogue across these agencies and allows the varied missions to inform each other (NASEM, 2016). The coordination function of the Program is most obvious in *Our Changing Planet*, the strategic plans, the NCAs, and other summaries of knowledge and activities. In addition, the ongoing dialogue across the USGCRP facilitates mutual understanding and sharing of knowledge and resources. For example, it allows research-focused agencies to be aware of the information needs of action-focused

agencies. Conversely, it helps action-focused agencies to understand the strengths and limits of current science and what is likely to emerge from research over time.

CLOSING STATEMENT

Through interagency partnerships and collaborations with leading experts, the USGCRP has worked successfully since its inception to advance global change science and improve understanding of how global change affects society today and how it could affect society in the future. As we look to the coming decades, the impacts of climate change and other global changes will be increasingly apparent. In the nation's interest, the USGCRP should continue to pursue two primary value-added activities: (1) strategic planning and coordination of global change research activities across federal agencies and (2) high-level synthesis of global change research results and sharing them with decision makers and the American public. To achieve its goal of providing science for the people of the United States and the world, it is essential that the USGCRP continue to build a balanced program that includes long-term observations of the Earth system, discovery-driven research, and use-inspired research that supports future decision making, mitigation, and adaptation efforts at local, regional, and global scales.

In 1989, the Committee on Earth Sciences stated the following as the fundamental rationale for the U.S. Global Change Research Program:

> "In the coming decades, global change may well represent the most significant societal, environmental, and economic challenges facing this Nation and the world. The national goal of developing a predictive understanding of global change is, in its truest sense, science in the service of mankind" (CES, 1989).

Despite major advancements in our understanding of, observations of, and ability to model and predict global change, much remains to be done, making this rationale as true today as it was a generation ago.

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Acronyms

AR6	6th Assessment Report
CCSP	U.S. Climate Change Science Program
CCTP	Climate Change Technology Program
CDC	U.S. Centers for Disease Control and Prevention
CEES	Committee on Earth and Environmental Sciences
DMUU	Decision Making Under Uncertainty
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
EOS	Earth Observing System
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GCRA	Global Change Research Act
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GLISA	Great Lakes Integrated Sciences and Assessments Center
IAM	Integrated Assessment Modeling
IGIM	Interagency Group on Integrative Modeling
IHDP	International Human Dimensions Program
IPCC	Intergovernmental Panel on Climate Change
IWGCCH	Interagency Working Group on Climate Change and Health
IWG	interagency working group
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCA	National Climate Assessment
NGO	nongovernmental organization
NIH	National Institutes of Health
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSTC	National Science and Technology Council
ObsIWG	Integrated Observations Interagency Working Group
OCBP	Ocean Carbon and Biogeochemistry Program
OCP	*Our Changing Planet*
OTA	Office of Technology Assessment
RISA	Regional Integrated Sciences and Assessments
SAP	Synthesis and Assessment Product
SCIPP	Southern Climate Impacts Planning Program
SOCCR	State of the Carbon Cycle Report
TAO	Tropical Atmosphere Ocean
TOGA	Tropical Ocean-Global Atmosphere

UNFCCC	United Nations Framework Convention on Climate Change
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
USP	Update to the Strategic Plan
WCRP	World Climate Research Program
WOCE	World Ocean Circulation Experiment

Appendix A
Global Change Research Act of 1990

Public Law 101-606 [S. 169]; November 16, 1990
104 Stat. 3096-3104

An Act to require the establishment of a United States Global Change Research Program aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment, to promote discussions toward international protocols in global change research, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "Global Change Research Act of 1990".

SECTION 2. DEFINITIONS.

As used in this Act, the term—

1. "Committee" means the Committee on Earth and Environmental Sciences established under section 102;
2. "Council" means the Federal Coordinating Council on Science, Engineering, and Technology;
3. "Global change" means changes in the global environment (including alterations in climate, land productivity, oceans or other water resources, atmospheric chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life;
4. "Global change research" means study, monitoring, assessment, prediction, and information management activities to describe and understand—
    A. The interactive physical, chemical, and biological processes that regulate the total Earth system;
    B. The unique environment that the Earth provides for life;
    C. Changes that are occurring in the Earth system; and
    D. The manner in which such system, environment, and changes are influenced by human actions;
5. "Plan" means the National Global Change Research Plan developed under section 104, or any revision thereof; and
6. "Program" means the United States Global Change Research Program established under section 103.

TITLE I—UNITED STATES GLOBAL CHANGE RESEARCH PROGRAM

SEC. 101. FINDINGS AND PURPOSE.

(a) FINDINGS—The Congress makes the following findings:

1. Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few human generations.

Such human-induced changes, in conjunction with natural fluctuations, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being.

3. The release of chlorofluorocarbons and other stratospheric ozone-depleting substances is rapidly reducing the ability of the atmosphere to screen out harmful ultraviolet radiation, which could adversely affect human health and ecological systems.
4. Development of effective policies to abate, mitigate, and cope with global change will rely on greatly improved scientific understanding of global environmental processes and on our ability to distinguish human-induced from natural global change.
5. New developments in interdisciplinary Earth sciences, global observing systems, and computing technology make possible significant advances in the scientific understanding and prediction of these global changes and their effects.
6. Although significant Federal global change research efforts are underway, an effective Federal research program will require efficient interagency coordination, and coordination with the research activities of State, private, and international entities.

(b) PURPOSE—The purpose of this title is to provide for development and coordination of a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change.

SEC. 102. COMMITTEE ON EARTH AND ENVIRONMENTAL SCIENCES.

(a) ESTABLISHMENT—The President, through the Council, shall establish a Committee on Earth and Environmental Sciences. The Committee shall carry out Council functions under section 401 of the National Science and Technology Policy, Organization, and Priorities Act of 1976 (42 U.S.C. 6651) relating to global change research, for the purpose of increasing the overall effectiveness and productivity of Federal global change research efforts.

(b) MEMBERSHIP—The Committee shall consist of at least one representative from—

1. The National Science Foundation;
2. The National Aeronautics and Space Administration;
3. The National Oceanic and Atmospheric Administration of the Department of Commerce;
4. The Environmental Protection Agency;
5. The Department of Energy;
6. The Department of State;
7. The Department of Defense;
8. The Department of the Interior;
9. The Department of Agriculture;
10. The Department of Transportation;
11. The Office of Management and Budget;
12. The Office of Science and Technology Policy;
13. The Council on Environmental Quality;
14. The National Institute of Environmental Health Sciences of the National Institutes of Health; and
15. Such other agencies and departments of the United States as the President or the Chairman of the Council considers appropriate.

Such representatives shall be high-ranking officials of their agency or department, wherever possible the head of the portion of that agency or department that is most relevant to the purpose of the title described in section 101(b).

(c) CHAIRPERSON—The Chairman of the Council, in consultation with the Committee, biennially shall select one of the Committee members to serve as Chairperson. The Chairperson shall be knowledgeable and experienced with regard to the administration of scientific research programs, and shall be a representative of an agency that contributes substantially, in terms of scientific research capability and budget, to the Program.
(d) SUPPORT PERSONNEL—An Executive Secretary shall be appointed by the Chairperson of the Committee, with the approval of the Committee. The Executive Secretary shall be a permanent employee of one of the agencies or departments represented on the Committee, and shall remain in the employ of such agency or department. The Chairman of the Council shall have the authority to make personnel decisions regarding any employees detailed to the Council for purposes of working on business of the Committee pursuant to section 401 of the National Science and Technology Policy, Organization, and Priorities Act of 1976 (42 U.S.C. 6651).
(e) FUNCTIONS RELATIVE TO GLOBAL CHANGE—The Council, through the Committee, shall be responsible for planning and coordinating the Program. In carrying out this responsibility, the Committee shall—

1. Serve as the forum for developing the Plan and for overseeing its implementation;
2. Improve cooperation among Federal agencies and departments with respect to global change research activities;
3. Provide budgetary advice as specified in section 105;
4. Work with academic, State, industry, and other groups conducting global change research, to provide for periodic public and peer review of the Program;
5. Cooperate with the Secretary of State in—
    A. Providing representation at international meetings and conferences on global change research in which the United States participates; and
    B. Coordinating the Federal activities of the United States with programs of other nations and with international global change research activities such as the International Geosphere-Biosphere Program.
6. Consult with actual and potential users of the results of the Program to ensure that such results are useful in developing national and international policy responses to global change; and
7. Report at least annually to the President and the Congress, through the Chairman of the Council, on Federal global change research priorities, policies, and programs.

SEC. 103. UNITED STATES GLOBAL CHANGE RESEARCH PROGRAM.

The President shall establish an interagency United States Global Change Research Program to improve understanding of global change. The Program shall be implemented by the Plan developed under section 104.

SEC. 104. NATIONAL GLOBAL CHANGE RESEARCH PLAN.

(a) IN GENERAL—The Chairman of the Council, through the Committee, shall develop a National Global Change Research Plan for implementation of the Program. The Plan shall contain recommendations for national global change research. The Chairman of the Council shall submit the Plan to the Congress within one year after the date of enactment of this title, and a revised Plan shall be submitted at least once every three years thereafter.
(b) CONTENTS OF THE PLAN—The Plan shall—

1. Establish, for the 10-year period beginning in the year the Plan is submitted, the goals and priorities for Federal global change research which most effectively advance scientific understanding of global change and provide usable information on which to base policy decisions relating to global change;

2. Describe specific activities, including research activities, data collection and data analysis requirements, predictive modeling, participation in international research efforts, and information management, required to achieve such goals and priorities;
3. Identify and address, as appropriate, relevant programs and activities of the Federal agencies and departments represented on the Committee that contribute to the Program;
4. Set forth the role of each Federal agency and department in implementing the Plan;
5. Consider and utilize, as appropriate, reports and studies conducted by Federal agencies and departments, the National Research Council, or other entities;
6. Make recommendations for the coordination of the global change research activities of the United States with such activities of other nations and international organizations, including—
    A. A description of the extent and nature of necessary international cooperation;
    B. The development by the Committee, in consultation when appropriate with the National Space Council, of proposals for cooperation on major capital projects;
    C. Bilateral and multilateral proposals for improving worldwide access to scientific data and information; and
    D. Methods for improving participation in international global change research by developing nations; and
7. Estimate, to the extent practicable, Federal funding for global change research activities to be conducted under the Plan.

(c) RESEARCH ELEMENTS—The Plan shall provide for, but not be limited to, the following research elements:

1. Global measurements, establishing worldwide observations necessary to understand the physical, chemical, and biological processes responsible for changes in the Earth system on all relevant spatial and time scales.
2. Documentation of global change, including the development of mechanisms for recording changes that will actually occur in the Earth system over the coming decades.
3. Studies of earlier changes in the Earth system, using evidence from the geological and fossil record.
4. Predictions, using quantitative models of the Earth system to identify and simulate global environmental processes and trends, and the regional implications of such processes and trends.
5. Focused research initiatives to understand the nature of and interaction among physical, chemical, biological, and social processes related to global change.

(d) INFORMATION MANAGEMENT—The Plan shall provide recommendations for collaboration within the Federal Government and among nations to—

1. Establish, develop, and maintain information bases, including necessary management systems which will promote consistent, efficient, and compatible transfer and use of data;
2. Create globally accessible formats for data collected by various international sources; and
3. Combine and interpret data from various sources to produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change.

(e) NATIONAL RESEARCH COUNCIL EVALUATION—The Chairman of the Council shall enter into an agreement with the National Research Council under which the National Research Council shall—

1. Evaluate the scientific content of the Plan; and
2. Provide information and advice obtained from United States and international sources, and recommended priorities for future global change research.

(f) PUBLIC PARTICIPATION—In developing the Plan, the Committee shall consult with academic, State, industry, and environmental groups and representatives. Not later than 90 days before the Chairman of the Council submits the Plan, or any revision thereof, to the Congress, a summary of the proposed Plan shall be published in the Federal Register for a public comment period of not less than 60 days.

SEC. 105. BUDGET COORDINATION.

(a) COMMITTEE GUIDANCE—The Committee shall each year provide general guidance to each Federal agency or department participating in the Program with respect to the preparation of requests for appropriations for activities related to the Program.

(b) SUBMISSION OF REPORTS WITH AGENCY APPROPRIATIONS REQUESTS—

1. Working in conjunction with the Committee, each Federal agency or department involved in global change research shall include with its annual request for appropriations submitted to the President under section 1108 of title 31, United States Code, a report which—
    A. Identifies each element of the proposed global change research activities of the agency or department;
    B. specifies whether each element (i) contributes directly to the Program or (ii) contributes indirectly but in important ways to the Program; and
    C. states the portion of its request for appropriations allocated to each element of the Program.
2. Each agency or department that submits a report under paragraph (1) shall submit such report simultaneously to the Committee.

(c) CONSIDERATION IN PRESIDENT'S BUDGET—

1. The President shall, in a timely fashion, provide the Committee with an opportunity to review and comment on the budget estimate of each agency and department involved in global change research in the context of the Plan.
2. The President shall identify in each annual budget submitted to the Congress under section 1105 of title 31, United States Code, those items in each agency's or department's annual budget which are elements of the Program.

SEC. 106. SCIENTIFIC ASSESSMENT.

On a periodic basis (not less frequently than every 4 years), the Council, through the Committee, shall prepare and submit to the President and the Congress an assessment which—

1. integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;
2. analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
3. analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

SEC. 107. ANNUAL REPORT.

(a) GENERAL.—Each year at the time of submission to the Congress of the President's budget, the Chairman of the Council shall submit to the Congress a report on the activities conducted by the Committee pursuant to this title, including—

1. a summary of the achievements of the Program during the period covered by the report and of priorities for future global change research;
2. an analysis of the progress made toward achieving the goals of the Plan;
3. expenditures required by each agency or department for carrying out its portion of the Program, including—
    A. the amounts spent during the fiscal year most recently ended;
    B. the amounts expected to be spent during the current fiscal year; and
    C. the amounts requested for the fiscal year for which the budget is being submitted.

(b) RECOMMENDATIONS.—The report required by subsection (b) shall include recommendations by the President concerning—

1. changes in agency or department roles needed to improve implementation of the Plan; and
2. additional legislation which may be required to achieve the purposes of this title.

SEC. 108. RELATION TO OTHER AUTHORITIES.

(a) NATIONAL CLIMATE PROGRAM RESEARCH ACTIVITIES.—The President, the Chairman of the Council, and the Secretary of Commerce shall ensure that relevant research activities of the National Climate Program, established by the National Climate Program Act (15 U.S.C. 2901 et seq.), are considered in developing national global change research efforts.

(b) AVAILABILITY OF RESEARCH FINDINGS.—The President, the Chairman of the Council, and the heads of the agencies and departments represented on the Committee, shall ensure that the research findings of the Committee, and of Federal agencies and departments, are available to—

1. the Environmental Protection Agency for use in the formulation of a coordinated national policy on global climate change pursuant to section 1103 of the Global Climate Protection Act of 1987 (15 U.S.C. 2901 note); and
2. all Federal agencies and departments for use in the formulation of coordinated national policies for responding to human-induced and natural processes of global change pursuant to other statutory responsibilities and obligations.

(c) EFFECT ON FEDERAL RESPONSE ACTIONS.—Nothing in this title shall be construed, interpreted, or applied to preclude or delay the planning or implementation of any Federal action designed, in whole or in part, to address the threats of stratospheric ozone depletion or global climate change.

Appendix B
Statement of Task

COMMITTEE TO ADVISE THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

An expert committee will provide ongoing and focused advice to the U.S. Global Change Research Program (USGCRP). The committee will be broadly constituted to bring expertise in all the areas addressed by the multiagency, multidimensional USGCRP and will be supported by expertise housed in many units across the National Research Council. The committee will, over time, organize ongoing discussions, take on specific tasks, and issue reports.

In its role as a single entry source of contact to the National Research Council and source of strategic discussion with appropriate experts, the Committee to Advise the U.S. Global Change Research Program will

1. Provide ongoing, integrated advice to the USGCRP on broad, program-wide issues when requested. This began with a review of the 2011 USGCRP Strategic Plan and will include other tasks such as a review of the National Climate Assessment (NCA) and evaluation of USGCRP progress toward its Strategic Plan objectives.
2. Provide a forum for informal interaction between the USGCRP and the relevant scientific communities.
3. Provide a forum for exchange of experience and insights for integrating across science communities and improving linkages between officials of the Program and the science communities.
4. Improve the internal coordination across existing and future NRC entities related to global change (including coordination across NAS, NAE, and IOM).
5. Help identify issues of importance for the global change research community. This implies a proactive role that goes beyond simply responding to requests from the USGCRP.
6. Interact with and help USGCRP with its international activities, such as shaping the future of relevant international global environmental change programs.
7. In addition to producing NRC reports as tasked, the committee may help develop other work requests and ensure that they are conducted by the appropriate NRC units in a collaborative fashion.

REPORT ON THE USGCRP SCIENCE AND RESEARCH ACCOMPLISHMENTS BASED ON THE PROGRAM'S ASSESSMENTS: STATEMENT OF TASK

The Committee to Advise the U.S. Global Change Research Program will produce a short consensus report that provides a broad-brush review of the outputs of the U.S. Global Change Research Program (USGCRP) since its inception, focused on its assessments, which are the product of the USGCRP multiagency confederation. The report may include discussions of how the Program has evolved and transformed over time and how information is generated and distributed, as well as identifying areas of effort and/or mechanisms that have been most successful for the Program, and challenges faced by the Program, including gaps or disconnects in the Program's output in response to its major areas of effort.

The report will be based on public documents only, and it is not intended to be an in-depth evaluation or review of this ambitious and dynamic interagency program.

The committee will draw upon (~30) reports produced by the Program ("Program outputs") for this task, primarily focused on the assessments, the most prominent of which should be the three National Climate Assessments (NCA-1, -2, and -3), but also include the CCSP Synthesis and Assessment Products, and the most recent assessments on human health and food security. The strategic plans and the annual budgetary *Our Changing Planet* documents help serve to provide context for the assessments. The committee will commission background research to be done by an external consultant to help inform the committee's writing of this short report.

On the basis of the reports described above, the committee's report should address:

- In the context of the Program's mission and mandates and as reflected in the Program's outputs, what are the most significant and consequential science and research accomplishments of USGCRP?
- What lessons should be learned from these accomplishments with respect to future Program planning?

Appendix C
List of USGCRP Products

STRATEGIC PLANS

Committee on Earth Sciences. 1989. Our Changing Planet: A U.S. Strategy for Global Change Research. Federal Coordinating Council for Science, Engineering, and Technology. Available at https://www.carboncyclescience.us/sites/default/files/documents/2013/ocp1990-strategy.pdf.

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Appendix E
Table of USGCRP Strategic Planning Goals and Objectives

	GCRA ELEMENTS (P.L. 101-606)	1989 Strategic Plan (CES, 1989)	2003 Strategic Plan (CCSP, 2003)	2012 Strategic Plan (USGCRP, 2012b)
Understanding	Studies of earlier changes in the Earth system, using evidence from the geological and fossil record. (§104(c)(3)) Focused research initiatives to understand the nature of and interaction among physical, chemical, biological, and social processes related to global change. (§104(c)(5))	Integrating priority 2: Conduct a program of focused studies to improved our understanding of the physical, geological, chemical, biological, and social processes that influence Earth system processes and trends on global and regional scales.	Goal 1: Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change. Goal 2: Improve quantification of the forces bringing about changes in the Earth's climate and related systems. Goal 4: Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes. Approach 1: Scientific Research. Plan, sponsor, and conduct research on changes in climate and related systems	Goal 1: Advance Science: Advance scientific knowledge of the integrated natural and human components of the Earth system.
Specific Science Elements		Science priorities: • Climate and Hydrologic Systems • Biogeochemical Dynamics • Ecological Systems and Dynamics • Earth System History • Human Interactions • Solid Earth Processes • Solar Influences	Research elements: • Atmospheric Composition • Climate Variability and Change • Water Cycle • Land-Use/Land-Cover Change • Carbon Cycle • Ecosystems • Human Contributions and Responses to Environmental Change	Objective 1.1: Earth System Understanding • Climate Change and Global Change • Integration of the Biological Sciences • Integration of the Social, Behavioral, and Economic Sciences • Multiple Space and Time Scales, Natural Variability, and Extremes • Complexity, Thresholds, and Tipping Points Objective 1.2: Science for Adaptation and Mitigation • Understanding Vulnerability to Global Change • Science to Support Regional and Sectoral Responses • Science to Support Global-Scale Responses • Tools and Approaches for Iterative Risk Management
Predicting	Predictions, using quantitative models of the Earth system to identify and simulate global environmental processes and trends, and the regional implications of such processes and trends. (§104(c)(4))	Integrating priority 3: Develop integrated conceptual and predictive Earth system models.	Goal 3: Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future.	Objective 1.4: Integrated Modeling • Model Complexity • Model Interpretation, Conceptual Modeling, and Hierarchies of Model Complexity • Integrated Modeling of Complex Systems Dynamics and Decision Support

Monitoring	Global measurements, establishing worldwide observations necessary to understand the physical, chemical, and biological processes responsible for changes in the Earth system on all relevant spatial and time scales. (§104(c)(1)) Documentation of global change, including the development of mechanisms for recording changes that will actually occur in the Earth system over the coming decades. (§104(c)(2))	Integrating priority 1: Establish an integrated, comprehensive long-term program of documenting the Earth system on a global scale through • Observational programs • Data management systems	Approach 2: Observations. Enhance observations and data management systems to generate a comprehensive set of variables needed for climate-related research	Objective 1.3: Integrated Observations • Sustaining and Integrating Earth System Observational Capacity • Integrating Socioeconomic and Ecological Measurements • Integrating Observations and Modeling Objective 1.5: Information Management and Sharing • Integrated and Centralized Data Access • Integrated Knowledge for Stakeholders and Decision Makers
Assessing	Integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings (§106(1)) Analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity (§106(2)) Analyzes current trends in global change, both human induced and natural, and projects major trends for the subsequent 25 to 100 years. (§106(3))		Goal 5: Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.	Goal 3: Conduct Sustained Assessments. Build sustained assessment capacity that improves the Nation's ability to understand, anticipate, and respond to global change impacts and vulnerabilities. Objective 3.1: Scientific Integration Objective 3.2: Ongoing Capacity Objective 3.3: Inform Responses Objective 3.4: Evaluate Progress

	GCRA ELEMENTS (P.L. 101-606)	1989 Strategic Plan (CES, 1989)	2003 Strategic Plan (CCSP, 2003)	2012 Strategic Plan (USGCRP, 2012b)
Informing Decisions	Combine and interpret data from various sources to produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change. (§104(d)(3))		Approach 3: Decision Support. Develop improved science-based resources to aid decision making	Goal 2: Inform Decisions. Provide the scientific basis to inform and enable timely decisions on adaptation and mitigation. Objective 2.1: Inform Adaptation Decisions Objective 2.2: Inform Mitigation Decisions Objective 2.3: Enhance Global Change Information
Communicating and Educating			Approach 4: Communications. Communicate results to domestic and international scientific and stakeholder communities, stressing openness and transparency.	Goal 4: Communicate and Educate: Advance communications and education to broaden public understanding of global change and develop the scientific workforce of the future. Objective 4.1: Strengthen Communication and Education Research Objective 4.2: Reach Diverse Audiences Objective 4.3: Increase Engagement Objective 4.4: Cultivate Scientific Workforce

Appendix F
Committee Member Biographies

Warren M. Washington (NAE, Chair) is a Senior Scientist at the National Center for Atmospheric Research (NCAR). He has published more than 150 papers in professional journals and co-authored the book *An Introduction to Three-Dimensional Climate Modeling*. He has served on the National Science Board (chair, 2002-2006), the National Oceanic and Atmospheric Administration (NOAA) Science Advisory Board, the President's National Advisory Committee on Oceans and Atmosphere, several panels of the National Research Council, and the Secretary of Energy's Advisory Board, among others. Washington areas of research are in the development and use of climate models for climate change studies. He has also served as president of the American Meteorological Society (AMS) and a member of the AAAS Board of Directors. He is a member of the National Academy of Engineering, the American Philosophical Society, and the American Academy of Arts and Sciences. He has received many awards, including the Le Verrier Medal of the Societe Meteorologique de France, the National Weather Service Modernization Award, and the AMS Dr. Charles Anderson Award. He has honorary degrees from Oregon State University and Bates College, University of Massachusetts, Amherst. In 2010 he was awarded the National Medal of Science by President Obama.

Kai N. Lee (Vice-Chair) is the Rosenburg Professor of Environmental Studies, emeritus, at Williams College. He retired in 2015 from the David and Lucile Packard Foundation, where he led the science program for 8 years. He taught at Williams College from 1991 to 2007 and he directed the Center for Environmental Studies from 1991 to 1998 and 2001 to 2002. He also taught from 1973 to 1991 at the University of Washington in Seattle. He is the author of *Compass and Gyroscope* (1993) and coauthor of *Our Common Journey* (NRC, 1999b) and *Humans in the Landscape* (2012). He is a National Associate of the National Research Council (NRC). He was a member of the National Academies Roundtable on Science and Technology and served as vice-chair of the National Academies panel that wrote *Informing Decisions in a Changing Climate* (2009). Earlier, he had been a White House Fellow and represented the state of Washington as a member of the Northwest Power Planning Council. He was appointed in 2009 to the Science Advisory Board of the Environmental Protection Agency (EPA). He holds a Ph.D. in physics from Princeton University and an A.B., magna cum laude in physics, from Columbia University.

Doug Arent is Executive Director of the Joint Institute for Strategic Energy Analysis at the National Renewable Energy Laboratory (NREL). He specializes in strategic planning and financial analysis competencies, clean energy technologies and energy and water issues, and international and governmental policies. In addition to his NREL responsibilities, Arent is Sr. Visiting Fellow at the Center for Strategic and International Studies. Arent was recently appointed as a Coordinating Lead Author for the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). He is a member of the Policy Subcommittee of the National Petroleum Council Study on Prudent Development of North America Natural Gas and Oil Resources, and the American Academy of Arts and Sciences Steering Committee on Social Science and the Alternative Energy Future. Arent served from 2008 to 2010 on the National Academy of Sciences Panel on Limiting the Magnitude of Future Climate Change. Arent is a Member of the Keystone Energy Board and is on the Advisory Board of E+Co, a public purpose investment company that supports sustainable development across the globe. He served on the Executive Council of the U.S. Association of Energy Economists from 2008 to 2010. Prior to coming to his current position, Arent was Director of the Strategic Energy Analysis Center at NREL from 2006 to 2010. Prior to joining NREL, he was

a management consultant to clean energy companies, providing strategy, development, and market counsel. Dr. Arent has a Ph.D. from Princeton University, and an M.B.A. from Regis University.

Susan K. Avery took office as President and Director of the Woods Hole Oceanographic Institute in 2008. She holds a master's in physics and a doctorate in atmospheric science from the University of Illinois. Avery was on the faculty of the University of Colorado at Boulder from 1982 to 2008, most recently holding the academic rank of Professor of Electrical and Computer Engineering. Her research interests include studies of atmospheric circulation and precipitation, climate variability and water resources, and the development of new radar techniques and instruments for remote sensing. She also has a keen interest in scientific literacy and the role of science in public policy. She is the author or co-author of more than 80 peer-reviewed articles. A fellow of CIRES since 1982, Avery became its director in 1994. In that role, she facilitated new interdisciplinary research efforts spanning the geosciences and including the social and biological sciences. She spearheaded a reorganization of the institute and helped establish a thriving K-12 outreach program and a Center for Science and Technology Policy Research. She also worked with NOAA and the Climate Change Science Program to help formulate a national strategic science plan for climate research. Recently she served on two NRC panels: One produced a decadal plan for earth science and applications from space, and the other provided strategic guidance for the atmospheric sciences at the National Science Foundation. Avery is a fellow of the Institute of Electrical and Electronics Engineers, of the American Association for the Advancement of Science, and of the American Meteorological Society, for which she also served as president. She is a past chair of the board of trustees of the University Corporation for Atmospheric Research.

Arrietta Chakos is a public policy advisor on urban resilience, working on community resilience strategies and multisectoral engagement. Her work with the Association of Bay Area Governments focuses on disaster and climate resilience planning with 101 cities and 9 counties in the San Francisco Bay Area. The regional program focuses on development of common resilience policies and implementation measures sponsored by the Federal Emergency Management Agency and the 100 Resilient Cities Initiative launched by the Rockefeller Foundation. She is a member of the Resilience Roundtable at the National Academy of Sciences and chairs the Housner Fellow committee at the Earthquake Engineering Research Institute. Ms. Chakos served as research director at the Harvard Kennedy School's Acting in Time Advance Recovery Project. She worked extensively in local government to direct innovative risk mitigation initiatives, intergovernmental coordination, and multi-institutional negotiations at the City of Berkeley, California.

Peter Daszak, President of EcoHealth Alliance, is a leader in the field of conservation medicine and a respected disease ecologist. EcoHealth Alliance is a global organization dedicated to innovative conservation science linking ecology and the health of humans and wildlife. EcoHealth Alliance's mission is to provide scientists and educators with support for grassroots conservation efforts in 20 high-biodiversity countries in North America, Asia, Africa, and Latin America. Nine years ago Dr. Daszak became the Executive Director of EcoHealth Alliance's Consortium for Conservation Medicine (CCM), a collaborative think-tank of institutions including Johns Hopkins Bloomberg School of Public Health, the University of Pittsburgh Graduate School of Public Health, the University of Wisconsin-Madison Nelson Institute for Environmental Studies, Tufts Cummings School of Veterinary Medicine Center for Conservation Medicine, and the U.S. Geological Survey (USGS) National Wildlife Health Center. The CCM is the first formal interinstitutional partnership to link conservation and disease ecology. Dr. Daszak's research has been instrumental in revealing and predicting the impacts of emerging diseases on wildlife, livestock, and human populations. He is originally from Britain, where he earned a B.Sc. in zoology and a Ph.D. in parasitology.

Thomas Dietz is Professor of Sociology, Environmental Science and Policy, and Animal Studies at Michigan State University, where he was founding director of the Environmental Science and Policy Program. His current research examines the human driving forces of environmental change, environmental values, and the interplay between science and democracy in environmental issues. He is a Fellow of the American Association for the Advancement of Science, and has been awarded the Sustainability Science Award of the Ecological Society of America, the Distinguished Contribution Award of the American Sociological Association Section on Environment, Technology and Society. He has served on numerous National Academies' panels and committees and chaired the Committee on the Human Dimensions of Global Change and the Panel on Public Participation in Environmental Assessment and Decision Making. He holds a bachelor of general studies degree from Kent State and a Ph.D. in ecology from the University of California at Davis.

Kristie L. Ebi is a professor in the Department of Global Health and in the Department of Environmental and Occupational Health Sciences, University of Washington; a guest professor at Umea University, Sweden; and consulting professor at Stanford University and George Washington University. She conducts research on the impacts of and adaptation to climate change, including on extreme events, thermal stress, foodborne safety and security, waterborne diseases, and vectorborne diseases. Her work focuses on understanding sources of vulnerability and designing adaptation policies and measures to reduce the risks of climate change in a multistressor environment. She has worked on assessing vulnerability and implementing adaptation measures in Central America, Europe, Africa, Asia, the Pacific, and the United States. She is co-chair with Tom Kram (PBL, The Netherlands) of the International Committee on New Integrated Climate Change Assessment Scenarios, facilitating development of new climate change scenarios. She was Executive Director of the IPCC Working Group II Technical Support Unit from 2009 to 2012. She was a coordinating lead author or lead author for the human health assessment for two U.S. national assessments, the IPCC Fourth Assessment Report, the Millennium Ecosystem Assessment, and the International Assessment of Agricultural Science and Technology for Development. Dr. Ebi's scientific training includes an M.S. in toxicology and a Ph.D. and a Master of Public Health in epidemiology, and postgraduate research at the London School of Hygiene and Tropical Medicine. She edited fours books on aspects of climate change and published more than 150 papers.

Baruch Fischhoff (IOM) is Howard Heinz University Professor in the Departments of Social and Decision Sciences and of Engineering and Public Policy at Carnegie Mellon University, where he heads the decision sciences major. A graduate of the Detroit Public Schools, he holds a B.S. in mathematics and psychology from Wayne State University and an M.A. and Ph.D. in psychology from the Hebrew University of Jerusalem. He is a member of the Institute of Medicine of the National Academies and is a past president of the Society for Judgment and Decision Making and of the Society for Risk Analysis. He chaired the Food and Drug Administration Risk Communication Advisory Committee and the National Research Council Committee on Behavioral and Social Science Research to Improve Intelligence Analysis for National Security. He has been a member of the Eugene, Oregon Commission on the Rights of Women, the Department of Homeland Security Science and Technology Advisory Committee, and the Environmental Protection Agency Scientific Advisory Board, where he chaired the Homeland Security Advisory Committee. He has written or edited several books: *Acceptable Risk* (1981), *A Two-State Solution in the Middle East: Prospects and Possibilities* (1993), *Preference Elicitation* (1999), *Risk Communication: The Mental Models Approach* (2001), *Intelligence Analysis: Behavioral and Social Science Foundations* (2011), *Risk: A Very Short Introduction* (2011), *Communicating Risks and Benefits: An Evidence-Based User's Guide* (2011), *Judgment and Decision Making* (2011), *Risk Analysis and Human Behavior* (2011), and *Counting Civilian Casualties* (2013).

Nancy B. Grimm studies the interaction of climate variation and change, human activities, and ecosystems. Her long-term research focuses on how disturbances (such as flooding or drying) affect the structure and processes of desert streams, how chemical elements move through and cycle within both desert streams and cities, and how stormwater infrastructure affects water and material movement across an urban landscape. A professor in the School of Life Sciences at Arizona State University, Grimm is director of the Central Arizona–Phoenix LTER program—an interdisciplinary study of urban social-ecological system sustainability by ecologists, engineers, and physical and social scientists. She is co-director of a new Sustainability Research Network focused on resilience of cities and their infrastructure to weather-related extreme events (UREx SRN). She was president and is a fellow of the Ecological Society of America (ESA), is a fellow of the American Association for the Advancement of Science, and was a lead author for the second and third National Climate Assessments.

Henry D. Jacoby is the William F. Pounds Professor of Management (emeritus) in the Sloan School of Management and former co-director of the Joint Program on the Science and Policy of Global Change, both at the Massachusetts Institute of Technology (MIT). His work has focused on the integration of the natural and social sciences and policy analysis in application to the threat of global climate change. Previously, he served on the faculties of the Department of Economics and the Kennedy School of Government, both at Harvard University. He has also served as director of the Harvard Environmental Systems Program, director of the MIT Center for Energy and Environmental Policy Research, associate director of the MIT Energy Laboratory, and chair of the MIT faculty. He has an undergraduate degree in mechanical engineering from the University of Texas at Austin and a Ph.D. in economics from Harvard University.

Anthony Janetos is the director of the Joint Global Change Research Institute, a joint venture between the Pacific Northwest National Laboratory and the University of Maryland. Prior to this position, he served as vice president of the H. John Heinz III Center for Science, Economics, and the Environment. Dr. Janetos also directed the center's Global Change program. Before coming to The Heinz Center, he served as vice president for science and research at the World Resources Institute and senior scientist for the Land-Cover and Land-Use Change Program in the National Aeronautics and Space Administration's (NASA's) Office of Earth Science. He was also program scientist for NASA's Landsat 7 mission. He has had many years of experience in managing scientific research programs on a variety of ecological and environmental topics, including air pollution effects on forests, climate change impacts, land-use change, ecosystem modeling, and the global carbon cycle. He was a co-chair of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change, and an author of the IPCC Special Report on Land-Use Change and Forestry, the Fourth Assessment Report of IPCC, the Millennium Ecosystem Assessment, and the Global Biodiversity Assessment. Dr. Janetos recently served on the NRC Committee for the Decadal Survey for Earth Sciences and Applications from Space, and has been a member of several other NRC committees, including the NRC Committee for Review of the U.S. Climate Change Science Program Strategic Plan, the Committee on Review of Scientific Research Programs at the Smithsonian Institution (2002), and the Committee on Ecological Indicators for the Nation.

Jerry M. Melillo (NAS) is a Distinguished Scientist and Director Emeritus at The Ecosystems Center of the Marine Biological Laboratory in Woods Hole, Massachusetts, and a professor of biology at Brown University. Dr. Melillo specializes in understanding the impacts of human activities on the biogeochemistry of ecological systems from local to global scales, using a combination of field studies and simulation modeling. In 1996 and 1997, he served as the Associate Director for Environment in the U.S. President's Office of Science and Technology Policy. Dr. Melillo has completed terms as the president of the Ecological Society of America and of the Scientific Committee on Problems of the Environment (SCOPE),

an international environmental assessment body headquartered in Paris. He is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society. Dr. Melillo has published more than 250 peer-reviewed articles. Between 1998 and 2009 he co-led two assessments for the U.S. Global Change Research Program on the impacts of climate change on the United States, the first published in 2000 and the second published in 2009. Dr. Melillo chaired the independent federal advisory committee that oversaw the design and production of the U.S. Global Change Research Program's Third National Climate Assessment that was released in 2014.

Richard H. Moss is senior research scientist with the Joint Global Change Research Institute at the University of Maryland, visiting senior research scientist at the Earth Systems Science Interdisciplinary Center, and senior fellow with the World Wildlife Fund (WWF). He has served as director of the Office of the U.S. Global Change Research Program/Climate Change Science Program (2000-2006), vice president and managing director for Climate Change at WWF (2007-2009), and senior director of the U.N. Foundation Energy and Climate Program (2006-2007). He also directed the Technical Support Unit of the IPCC impacts, adaptation, and mitigation working group (1993-1999) and served on the faculty of Princeton University (1989-1991). He was a coordinating lead author of *Confronting Climate Change and Realizing the Potential of Energy Efficiency*, led preparation of the U.S. government's 10-year climate change research plan, and has been a lead author and editor of a number of IPCC Assessments, Special Reports, and Technical Papers. Moss remains active in the IPCC and currently co-chairs the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis. He serves on the U.S. National Academy of Science's standing committee on the "human dimensions" of global environmental change and the editorial board of *Climatic Change*. He was named a fellow of the American Association for the Advancement of Science (AAAS) in 2006, a Distinguished Associate of the U.S. Department of Energy in 2004, and a fellow of the Aldo Leopold Leadership Program in 2001. He received an M.P.A. and Ph.D. from Princeton University (public and international affairs) and his B.A. from Carleton College in Northfield, Minnesota. Moss' research interests include development and use of scenarios, characterization and communication of uncertainty, and quantitative indicators of adaptive capacity and vulnerability to climate change.

Ian Roy Noble has spent 10 years with lead responsibility for the World Bank's activities in adaptation to climate change. He has also worked with the Carbon Finance Unit on emissions reductions through reduced deforestation and forest degradation. Before coming to the Bank in 2002 he was Professor of Global Change Research at the Australian National University. He has had senior roles in the IPCC process and in international cooperative research on climate change as part of the International Geosphere Biosphere Program including chairing the Global Change and Terrestrial Ecosystems for some years. An ecologist by training, he holds a Ph.D. from the University of Adelaide, and his research interests cover animal behavior, vegetation and biodiversity management, ecosystem modeling, expert systems, and the science-policy interface. In 1999 he was elected as Fellow of the Australian Academy of Technological Sciences and Engineering.

Margo Oge served the EPA for more than 30 years from 1980 to September 2012. She is widely recognized as having been a key architect of the EPA's efforts to reduce air pollution and greenhouse gas emissions. During her recent 18-year tenure as director of the Office of Transportation and Air Quality, Ms. Oge led the EPA's first ever national greenhouse gas (GHG) emission standards for cars and heavy-duty trucks to double fuel efficiency by 2025, reduce GHG emissions by 50%, and save consumers $1.7 trillion at the pump. In parallel, she also helped to establish the renewable fuels standard, which will significantly increase the volume of biofuels in our nation's fuel supply. These new rules are viewed as some of the most significant steps forward in improving the sustainability of the U.S. transportation sector. Ms. Oge

earned her master's degree in engineering from the University of Massachusetts, Lowell. She also attended George Washington University and the John F. Kennedy School of Government at Harvard University.

Kathleen Segerson is a professor of economics at the University of Connecticut. She was the head of the Department of Economics from 2001 to 2005. Dr. Segerson specializes in natural resource economics and, in particular, the economics of environmental regulation. She is currently a member of both the Chartered Executive Board of the Environmental Protection Agency's Science Advisory Board, and the Vice Chair of the Advisory Board's Committee on Valuing the Protection of Ecological Services and Systems. She was a member of the U.S. General Accounting Office's Expert Panel on Climate Change Economics from 2007 to 2008 and frequently serves on external review committees for the U.S. Department of Agriculture. She has also served on three National Research Council study committees: the Committee on Assessing and Valuing the Services of Aquatic and Related Terrestrial Ecosystems (2002-2004), the Committee on the Causes and Management of Coastal Eutrophication (1998-2000), and the Committee on Improving Principles and Guidelines for Waste Resources Planning by the U.S. Army Corps of Engineers (2008 to the present). In 2008, she was named a Fellow by both the American Agricultural Economics Association and the Association of Environmental and Resource Economists. Dr. Segerson earned a Ph.D. from Cornell University in 1984.

Kathleen J. Tierney is a professor of sociology and Director of the Natural Hazards Research and Applications Information Center at the University of Colorado. The Hazards Center is housed in the Institute of Behavioral Science, where Professor Tierney holds a joint appointment. Dr. Tierney's research focuses on the social dimensions of hazards and disasters, including natural, technological, and human-induced extreme events. With collaborators Michael Lindell and Ronald Perry, she recently published *Facing the Unexpected: Disaster Preparedness and Response in the United States* (Joseph Henry Press, 2001). This influential compilation presents a wealth of information derived from theory and research on disasters over the past 25 years. Among Dr. Tierney's current and recent research projects are studies on the organizational response to the September 11, 2001, World Trade Center disaster, risk perception and risk communication, the use of new technologies in disaster management, and the impacts of disasters on businesses.

Charles J. Vörösmarty's research centers on human-environment interactions. He has led several teams that have executed interdisciplinary studies using earth system models depicting the northeastern United States, developed and analyzed databases of reservoir construction worldwide and how they generate downstream coastal zone risks, and assessed global threats to human water security and aquatic biodiversity. Dr. Vörösmarty routinely provides scientific guidance to a variety of U.S. and international water consortia. He was a founding member and from 2004 to 2014 served as co-chair of the Global Water System Project and more recently helped to design its follow-on, the Sustainable Water Future Programme. In 2015-2016 he served as Scientific Co-Chair of the Arctic Futures Initiative of the Arctic Council and International Institute of Applied Systems Analysis. He has served on a broad array of national panels, including the U.S. Arctic Research Commission (appointed by Presidents Bush and Obama), the NASA Earth Science Subcommittee, the National Research Council Committee on Hydrologic Science (as chair), the NRC Review Committee on the U.S. Global Change Research Program, and the National Science Foundation's Arctic System Science Program Committee. He is spearheading efforts to develop global-scale indicators of water stress and has been working with chief U.N. delegates who are negotiating the Sustainable Development Goals on water. Recent work is aimed at introducing quantifiable metrics on corporate environmental performance into investment decisions made by the private sector within the impact investing domain.

Brian L. Zuckerman is a Research Staff Member at the IDA Science and Technology Policy Institute (STPI). Dr. Zuckerman's areas of emphasis at STPI are in the areas of program evaluation and scientometrics, where his work focuses on federal research and development program performance and agency-wide research portfolios. Dr. Zuckerman has also analyzed federal research and development data systems and statistical data collection programs. Before joining STPI, he was a principal at C-STPS, LLC, and at the Center for Science and Technology Policy of Abt Associates, Inc. He is a co-chair of the Research, Technology, and Development Topical Interest Group of the American Evaluation Association. Dr. Zuckerman holds a B.A. in chemistry from Harvard College and a Ph.D. in technology, management, and policy from the Massachusetts Institute of Technology.