U.S. Global Change Research Program

The National Global Change Research Plan 2012-2021: A Triennial Update

January 2017

About this Document

This report was developed by the Strategic Plan Integration and Writing Teams, which report to the Subcommittee on Global Change Research and the National Science and Technology Council's Committee on the Environment, Natural Resources, and Sustainability. This report is published by the National Coordination Office for the U.S. Global Change Research Program. It meets the requirements set forth in the U.S. Global Change Research Act of 1990 (Section 102, P. L. 101–606) to provide a triennial update of the decadal National Global Change Research Plan. It does not express any regulatory policies of the United States or any of its agencies, or make any findings that could serve as predicates for regulatory action.

The official and complete version of this report is the interactive PDF, available at:
https://downloads.globalchange.gov/strategic-plan/2016/usgcrp-strategic-plan-2016.pdf

Suggested citation:

U.S. Global Change Research Program. 2017. National Global Change Research Plan 2012–2021: A Triennial Update. Washington, DC, USA.

January 2017

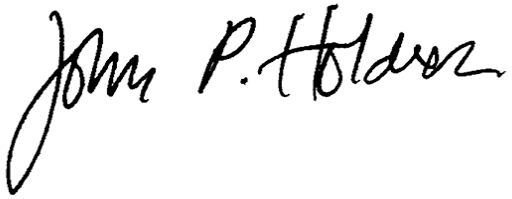
Members of the Congress:

On behalf of the National Science and Technology Council, I am pleased to transmit this *Triennial Update to The National Global Change Research Plan 2012–2021: A Strategic Plan for the U.S. Global Change Research Program* (USGCRP). USGCRP coordinates and integrates scientific research across 13 Federal agencies whose missions include understanding changes in the global environment and their implications for society. The Strategic Plan was mandated by the Global Change Research Act (GCRA) of 1990 (GCRA, P.L. 101–606), and serves as the guiding document for USGCRP through 2021. In accordance with the GCRA, the enclosed report summarizes USGCRP's progress in implementing the Strategic Plan since 2012, and refines Program priorities in response to advances and new challenges.

In this update, USGCRP's four goals remain: advance science, inform decisions, conduct sustained assessments, and communicate and educate. This update builds upon significant accomplishments in basic research, scientific assessment and the production of science for decision support, information management and sharing, and engagement and education. It also discusses progress and challenges in interagency research priority areas, such as Arctic research and resilience, methane cycling in the context of the carbon cycle, and water-cycle extremes and their impacts.

USGCRP is committed to building a knowledge base and information resources that inform human response to global change through coordinated and integrated Federal programs of research, scientific assessment and decision support, communication, and education. I appreciate the close cooperation of the participating agencies and look forward to working with members of the Congress to implement the continuation of this essential national program.

Sincerely,



Dr. John P. Holdren
Director, Office of Science and Technology Policy
Assistant to the President for Science and Technology

Subcommittee on Global Change Research

Leadership

Ann Bartuska – SGCR Chair, Department of Agriculture

Virginia Burkett – SGCR Co-Chair, Department of the Interior

Michael Kuperberg – USGCRP Executive Director, U.S. Global Change Research Program, White House Office of Science and Technology Policy

Amanda McQueen – SGCR Executive Secretary, U.S. Global Change Research Program, National Coordination Office

Executive Committee

Michael Freilich – National Aeronautics and Space Administration

Gerald Geernaert – Department of Energy

Richard Spinrad – Department of Commerce

Roger Wakimoto – National Science Foundation

Jeffrey Arnold – U.S. Army Corps of Engineers (Adjunct)

Principals

John Balbus – Department of Health and Human Services

John Furlow – U.S. Agency for International Development

Joel Clement – Department of the Interior

Pierre Comizzoli – Smithsonian Institution

Wayne Higgins – Department of Commerce

Scott Harper – Department of Defense (Acting)

William Hohenstein – Department of Agriculture

Jack Kaye – National Aeronautics and Space Administration

Dorothy Koch – Department of Energy

Andrew Miller – Environmental Protection Agency

Craig Robinson – National Science Foundation

Arthur Rypinski – Department of Transportation (Acting)

Trigg Talley – Department of State

Executive Office of the President

Afua Bruce – Executive Director, National Science and Technology Council

Tamara Dickinson – Principal Assistant Director for Energy and Environment, White House Office of Science and Technology Policy

Richard Duke – Associate Director for Energy and Climate Change, White House Council on Environmental Quality

Kei Koizumi – Assistant Director for Federal Research and Development, White House Office of Science and Technology Policy

David Reidmiller – Director, National Climate Assessment, U.S. Global Change Research Program, White House Office of Science and Technology Policy

Rachael Leonard – General Counsel, White House Office of Science and Technology Policy

Kimberly Miller – Program Examiner, White House Office of Management and Budget

Strategic Planning Integration and Writing Team

Farhan Akhtar (DOS), Jeffrey Arnold (DOD), Bob Vallario (DOE), Caitlin Simpson (NOAA), Christopher Clark (EPA), Carolyn Olson (USDA), Curt Tilmes (NASA), Christopher Weaver (EPA), Candace Major (NSF), Daniel Eleuterio (DOD), Caroline Dilworth (HHS), Frank Niepold (NOAA), Jennifer Saleem Arrigo (NOAA), Juli Trtanj (NOAA), Noor Johnson (SI), Kurt Johnson (DOI), Mike Patterson (US CLIVAR), Meredith Muth (NOAA), Michael Tanner (NOAA), Maria Uhle (NSF), David Reidmiller (DOS), Richard Eckman (NASA), Ron Sands (USDA), Shaima Nasiri (DOE), Kimberly Thigpen-Tart (HHS), Woody Turner (NASA), Nicholas Fisichelli (DOI)

National Coordination Office Contributors

Julie Morris, Strategic Planning Lead Coordinator

Bradley Akamine, David Allen, Susan Aragon-Long, Emily Cloyd, Justin Goldstein, Alexa Jay, Fred Lipschultz, Glynis Lough, Tanya Maslak, Amanda McQueen, Katie Reeves, Emily Seyller, Mark Shimamoto, Gyami Shrestha, Matthew Stephen, Robert Wolfe, Catherine Wolner, Sarah Zerbonne

Table of Contents

Table of Figures

Executive Summary

The global environment is changing rapidly as a result of human activities. Over the last half-century, population growth and urbanization, economic growth, energy production, natural resource use, and other trends have accelerated at a rate unprecedented in human history, driving profound changes in ecosystems, oceans, ice, the composition of Earth's atmosphere, and other systems that influence human life.[1] These global changes are causing climate change, ocean acidification, air and water pollution, species loss, and other impacts; and these changes pose both risks and opportunities that present complex challenges for communities, governments, and businesses across the Nation and the world.

As the impacts of global change progress, demand for information on response measures is rising. Global- change science is needed to inform adaptation actions to cope with risks created by a changing climate, and to inform mitigation actions (e.g., greenhouse gas reduction measures) to decrease the risks associated with climate change, especially over the long-term. The global-change research enterprise faces the challenge of further advancing fundamental understanding of the causes and effects of change while providing information needed for response measures of many kinds and at different scales.

Figure 1: USGCRP Member Agencies

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

The U.S. Global Change Research Program at a Glance

To help address the challenge of advancing basic scientific knowledge while informing practical action, President Ronald Reagan created—and Congress codified with the 1990 Global Change Research Act (GCRA)—the United States Global Change Research Program (USGCRP), charged with providing a scientific foundation to support the Nation's response to present and future global change. USGCRP comprises 13 Federal agencies that conduct or use

[1] Blunden, J. and D. S. Arndt, Eds., 2016: State of the Climate in 2015. *Bull. Amer. Meteor. Soc.*, 97 (8), S1–S275. Available online.

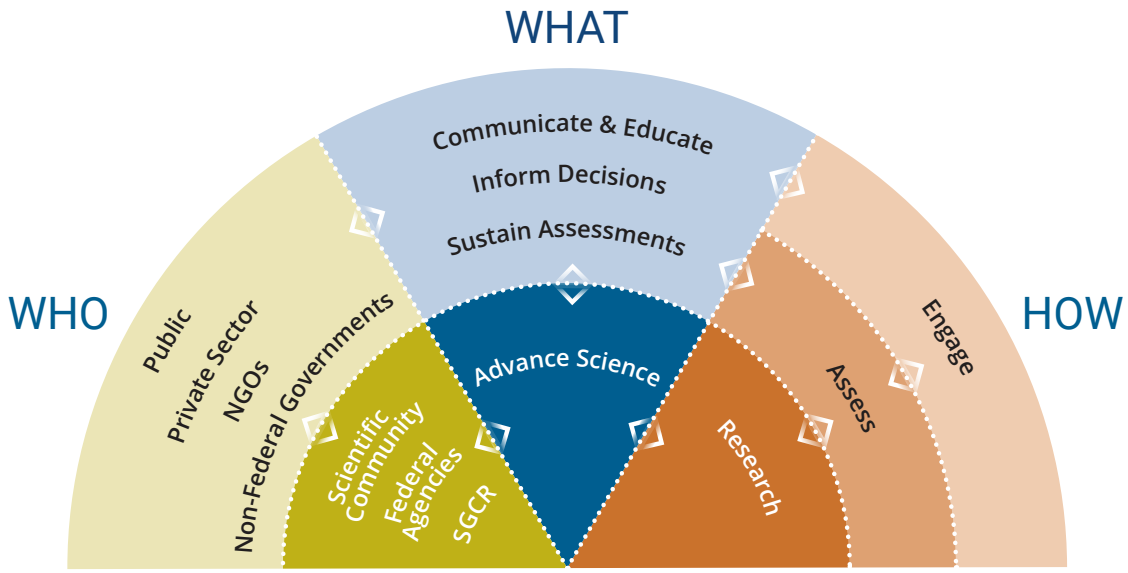
research on global change and its impacts on society (see Figure 1) and is overseen by a Principal from each member agency, constituting the Subcommittee on Global Change Research (SGCR). USGCRP's focus spans from basic research that advances understanding of the Earth system to decision support, scientific assessment, and public engagement surrounding global-change science and response measures. USGCRP's mandate under the GCRA encompasses both climate change and other global environmental changes related to, interacting with, or associated with climate—such as ocean acidification, agricultural land–use change, pollution, and natural climate variability—that have implications for economic and societal well-being. Throughout this document, "climate-related global change" is used to describe the current scope of USGCRP's mission.

Figure 2: USGCRP Vision and Mission

- **Vision:** A Nation, globally engaged and guided by science, meeting the challenges of climate and global change.
- **Mission:** To build a knowledge base that informs human responses to climate and global change through coordinated and integrated Federal programs of research, education, communication, and decision support.

As understanding of global change advances, and climate-change impacts deepen, USGCRP is increasingly in a position to support decisionmaking in a number of affected sectors by providing information on likely impacts of change, as well as societal and ecological characteristics that influence resilience under changing conditions. Within this framework, USGCRP sees its role as freely providing scientific information that can be used by others for both research and operational purposes and that builds awareness of the information provided by the Program and its potential uses. USGCRP's core scientific capabilities in Earth observations, modeling, and understanding of Earth-system processes provide the knowledge base for decision support, scientific assessment, and communication, education, and engagement goals under the 2012–2021 Strategic Plan. In carrying out its mandate, the Program engages with a range of stakeholders and global-change information producers and users, primarily

Figure 3: USGCRP Overview



From left to right: USGCRP participants and information users (WHO), USGCRP's 2012–2021 Strategic Plan goals (WHAT) and core Program capabilities that enable USGCRP to meet its goals (HOW).

through a sustained-assessment process that includes the quadrennial National Climate Assessment (NCA), and through regional science organizations of its member agencies.

Advancing Strategic Goals

As required by the GCRA, the Strategic Plan is updated triennially, reporting on progress and refining Program priorities in response to advances and new challenges (see Figure 4 for selected accomplishments under the 2012–2021 Strategic Plan). This update retains the goals of the 2012–2021 Strategic Plan and builds upon significant accomplishments in basic research, scientific assessment and the production of actionable science, information management and sharing, and engagement, discussed in detail in Chapter III. The Program's priorities, grounded in USGCRP's core scientific capabilities, are revisited annually, and adjusted as appropriate, in response to progress made and emerging challenges. Chapter II discusses progress in recent Program priority areas in Arctic Research and Resilience, Water-Cycle Extremes, and Methane Cycling within the Context of the Carbon Cycle.

Since the release of the 2012–2021 Strategic Plan, new capabilities for observing key elements of the water cycle and the response of Arctic systems to rapid warming, among other advances, are driving new understanding, extending and challenging model capabilities, and providing records of change that can be used to develop decision-support tools (Chapter III, Objective 1.3). Building on the long-term development of multi-model ensembles for North America and the data that support them, USGCRP is advancing its ability to perform and analyze seasonal climate predictions used in agriculture and water-resources management, among other sectors (Chapter III, Objective 1.4). In addition, a new national information system on extreme heat and human health led by several USGCRP member agencies uses observations, predictive capabilities, and decision tools to support preparedness in the face of temperature and water-cycle extremes (Chapter II).

The Third National Climate Assessment (NCA3), released in 2014, synthesized an extensive scientific literature for decision makers, focused on climate change and its impacts on people and places across the United States. NCA3 is supported by a searchable and shareable website, which has had more than one million visits to report chapters and highlights as of July 2016. NCAnet, a network of more than 180 organizations and networks from both the private and public sectors, aims to understand user interests and needs while also sharing USGCRP information widely. As part of developing a sustained-assessment process that extends beyond the quadrennial report, USGCRP develops special assessments including *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (2016), which broke new ground in quantifying the increased risks that climate changes poses to the health of all Americans, and highlighted factors that make some individuals and communities particularly vulnerable. Assessments on climate change and food security (2015) and the impacts of drought on forests and rangelands (2016) have also been released, and assessments of carbon-cycle science and climate science are underway, all of which will contribute to NCA4, planned for release in 2018. In support of the NCA3, USGCRP built the Global Change Information System (GCIS) to provide transparent and traceable linkages to the science that supports the NCA3's major findings, intended for use by both policy makers and the scientific community. This system is used with other special reports and is being further developed to support

Figure 4: USGCRP Accomplishments under the 2012–2021 Strategic Plan

- Delivery of the Third National Climate Assessment, the most comprehensive analysis to date of how climate change is affecting the United States now and how it could affect it in the future, with input from over 1000 scientists and more than one million web visits to report chapters and highlights to date
- As part of the sustained-assessment process, delivery of *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*, a significant advancement in understanding of the impacts of climate change on human health that will contribute to the Fourth National Climate Assessment
- The production of actionable science that has informed policy decisions such as the President's Climate Action Plan of 2013, and provided the science that EPA considered in its 2016 Endangerment Finding for aircraft greenhouse gas emissions under the Clean Air Act
- Coordination of sustained observational campaigns, including measuring air quality for public health (DISCOVER-AQ), investigating precipitation variability (ACAPEX/CalWater-2, PECAN), and studying key elements of variability in El Niño's impact on the United States (NOAA El Niño Rapid Response Campaign)
- Pioneering research on changing patterns of severe weather under climate change
- Led interagency reviews and author nominations for the Intergovernmental Panel on Climate Change assessment reports
- Contributions to climate-related decision-support tools, including the Climate Resilience Toolkit and the Climate Data Initiative
- Convened the first and second annual U.S. Climate Modeling Summit among the leaders of the six major U.S. modeling centers to promote collaboration and advancement in modeling the impacts of climate change.

the Program more widely. Findings from the NCA and other research also provide the underlying science called for in the President's Climate Action Plan.

Addressing Challenges

USGCRP continues to confront a number of challenges in achieving the mandate of the GCRA and the goals of the 2012–2021 Strategic Plan, addressed in detail in Chapter III. While the Program has made significant progress in developing science that can inform adaptation planning and action, the development of a unified framework for incorporating social-science methodologies and expertise into both fundamental science and decision-relevant components is among the ongoing challenges for the Program. USGCRP is also using its long-running programs, aimed at understanding the natural processes governing the behavior of greenhouse gases and other atmospheric constituents, to provide further scientific foundations for understanding mitigation options and impacts; in this effort, the Program faces many of the same challenges noted for building capacity to inform adaptation decisions.

Informing adaptation actions calls for USGCRP to translate expertise, data, tools, and model outputs into products for societal benefit as determined by end-user needs, and to work with end users to develop the capacity to use decision tools. Building the kind of governmental, non-governmental, and academic partnerships and private sector collaborations needed to fully address these challenges, and to enable the collaborators to fulfill roles that are outside of the scope of USGCRP as a knowledge provider and translator, is an ongoing effort.

On the technical side, advancements in climate model resolution and integration with societal impacts models create the need for USGCRP to ensure consistency and robustness in downscaling approaches and to provide guidance in helping decision makers access relevant, standardized information and understand uncertainties. Maintaining the long-term observations that allow scientists to monitor, understand, and model change, while also developing and deploying new observing approaches, is also an ongoing challenge.

Road Ahead

Given the relatively short time since the release of the 2012–2021 Strategic Plan, this update refreshes it and discusses how USGCRP will build on recent progress and navigate new and ongoing challenges. The next update, to be developed for release in 2019, will initiate an extensive review of Program directions, in preparation for a new decadal Strategic Plan due in 2022. The Program expects to consult with Program participants and stakeholders in developing special activities (e.g., community workshops, commissioned studies) needed to inform the 2022–2031 Strategic Plan.

Acknowledgments

This update was greatly improved by revisions made in response to public comments, and those made by the Committee to Advise USGCRP at the National Academies of Sciences, Engineering, and Medicine, as well as extensive review from within the U.S. Government.

Guide to this Document

This update to the Strategic Plan was developed by an interagency author team. It reflects USGCRP's dual mission—to both advance fundamental science and support its use by decision makers—and is written with both scientific and decision-maker audiences in mind. Readers will note that:

- Chapter III provides a more detailed look at USGCRP's goals and objectives, written for a more scientific audience. The other chapters are written for more general audiences.
- Underlined text indicates a hyperlink to more detailed organizational, scientific, or policy background information.
- USGCRP expects that readers may visit the sections that most interest them, without necessarily reading all preceding text; as a result, there is some duplication of key content across chapters so that individual chapters may stand alone.

Reflecting the collective nature of the Program, the term "USGCRP" encompasses multiple elements. This update uses USGCRP (or "Program") in reference to the collective global-change research activities of the Subcommittee on Global Change Research (SGCR), USGCRP member agencies or bureaus, and the USGCRP National Coordination Office (NCO). Subsets of the Program are referred to as: the SGCR (serving as USGCRP's board of directors); the USGCRP member agencies (in reference to activities carried out by the agencies in support of USGCRP goals); and its Interagency Working Groups and NCO (in reference to the coordination function for the Program).

Chapter I: Introduction

The United States Global Change Research Program (USGCRP) is guided by its founding legislation to advance understanding of global change and inform a national response to global-change impacts. The Global Change Research Act (GCRA) of 1990 tasks USGCRP with providing a "comprehensive and integrated United States research program to assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." USGCRP's 2012–2021 National Global Change Research Plan (henceforth, "2012–2021 Strategic Plan") envisions an increasing orientation of the Program's activities towards decision support, assessment, and engagement, while maintaining strong fundamental research capabilities.

As mandated by the GCRA, the Program's Strategic Plan is updated triennially, refining Program priorities in response to advances and new challenges. This document provides an update to the 2012–2021 Strategic Plan, highlighting areas where the Program is building on progress towards its goals, and the challenges it is navigating. Since the release of the 2012–2021 Strategic Plan, USGCRP has made significant advances in basic research, scientific assessment and the production of actionable science, information management and sharing, and engagement, and continues to address challenges to achieving its vision.

In this update, the four goals for USGCRP remain:

- **Goal 1. Advance Science:** Advance scientific knowledge of the integrated natural and human components of the Earth system
- **Goal 2. Inform Decisions:** Provide the scientific basis to inform and enable timely decisions on adaptation and mitigation
- **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
- **Goal 4. Communicate and Educate:** Advance communications and education to broaden public understanding of global change and develop the scientific workforce of the future

USGCRP's core capabilities in observations, modeling, and process research enable advances in fundamental understanding of changing human and natural systems that are affected by, or themselves affect, climate change. This knowledge base provides the scientific foundation needed to understand and respond to global change and its anticipated effects on areas including human health, energy production and distribution, water-cycle extremes, agriculture and food security, and natural and managed ecosystems, among others.

New capabilities for observing key elements of the water cycle and the response of Arctic systems to rapid warming, among other advances, are driving new understanding, extending and challenging model capabilities, and providing records of change that can be used to develop decision-support tools (Chapter III, Objective 1.3). Building on the long-term development of

multi-model ensembles for North America and the data that support them, for example, USGCRP is advancing its ability to perform and analyze seasonal climate predictions used in agriculture and water-resources management, among other sectors (Chapter III, Objective 1.4). In another example, a new national information system on extreme heat and human health, led by several USGCRP member agencies, uses observations, predictive capabilities, and decision tools to support preparedness in the face of temperature and water-cycle extremes (Chapter II).

The Third National Climate Assessment (NCA3), released in 2014, synthesized an extensive scientific literature for decision makers, focused on climate change and its impacts on people and places across the United States. NCA3 is supported by a searchable and shareable website, which has had more than 900,000 visits to report chapters and highlights as of July 2016. NCAnet, a network of more than 180 organizations and networks from both the private and public sectors, aims to understand user interests and needs while also sharing USGCRP information widely. As part of the sustained-assessment process envisioned by the 2012–2021 Strategic Plan, USGCRP developed special assessment reports on topics including climate and health, climate and food security, and drought and forests, with reports in progress for climate science, and the carbon cycle, which will contribute to NCA4, due out in 2018 (Chapter III, Goal 3). The Global Change Information System, built in support of NCA3 and future assessments, connects the NCA3's scientific findings to the underpinning research (Chapter III, Objective 1.5).

USGCRP's interaction with its stakeholders, and understanding of their needs, comes largely through two avenues: via its member agencies and through the NCA. Through these avenues, the Program has made advances in characterizing user needs for science and translating research into scientific findings that are easily accessible and understandable for users with multiple levels of understanding. Within the Federal government, USGCRP synthesizes and distills the content from Federal Agency Climate Change Adaptation Plans and incorporates their major science needs into its planning (Chapter III, Goal 2). It also includes representatives from response-oriented offices within member and non-member agencies on its interagency working groups (IWGs). Member agencies feed their stakeholders' interests and needs into the USGCRP strategic planning process, including this update and the development of annual interagency priorities, which involve the production of actionable science and informing stakeholders. USGCRP is expanding stakeholder participation in interagency efforts such as the NCA, increasing engagement with agency regional science organizations to better understand agency stakeholder needs, and expanding participation of non-R&D agencies in the Program's IWGs, among other efforts. Reaching beyond the Federal government, USGCRP is also exploring avenues for expanding public-private collaborations towards building community resilience to global-change impacts (Chapter III, Goals 2–4).

Ongoing challenges for USGCRP member agencies include the integration of social-science methodologies and insights into understanding and supporting responses to global change, improving computing capacity, and maintaining needed observational capabilities over time. For the Program collectively, broadening the Program's ability to engage with stakeholders and understand user needs remains an ongoing challenge. Strategies for addressing each of these challenges and advances made to date are discussed in Chapter III.

The 2012–2021 Strategic Plan envisions an integrated program that both advances fundamental and use-inspired science, and transitions relevant data, tools, and model outputs into products for societal benefit. Progress in meeting this vision better allows the USGCRP to serve as the integrating focal point for global-change research across and beyond the U.S. Federal landscape. This triennial update to the 2012–2021 Strategic Plan is required by the GCRA, and it encapsulates scientific advances and challenges that have emerged since the release of the Strategic Plan.

Looking ahead to the remainder of this update, Chapter II provides an overview of USGCRP's organizational structure, recent interagency focal areas, and challenges the Program is facing. Chapter III centers on the four goals of the 2012–2021 Strategic Plan, emphasizing areas of progress on which to build and strategies for navigating challenges. Chapter IV provides an updated view of USGCRP's role in international cooperation, building from guidance in the GCRA, and reflecting a rapidly changing international landscape for global-change science. Chapter V provides an update on USGCRP's strategies for implementing the remaining years of the 2012–2021 Strategic Plan. Each chapter can be read as a standalone section, entailing some repetition of introductory material. Throughout the document, hyperlinks provide access to further information on individual programs, activities, and accomplishments.

Chapter II: USGCRP Strategic Overview

USGCRP is more than three years into the implementation of its National Global Change Research Plan 2012–2021 (2012–2021 Strategic Plan). While the 2012–2021 Strategic Plan remains the current blueprint for USGCRP, the landscape has changed in some areas by virtue of significant scientific progress, changing scientific or societal needs, and/or new challenges that have emerged. This update speaks to these areas.

The Program has made significant progress towards achieving the goals of the 2012–2021 Strategic Plan. The Plan centers on advancing fundamental science, making new and existing science accessible and useful for decision making, and broadening participation in USGCRP science, assessment, and decision-support activities. USGCRP member agencies have collectively identified near-term (3–5 year) focal areas while also emphasizing a long-term commitment to core Program capabilities. USGCRP has developed approaches for assessing science that result in reports and web materials intended for use by educators, communicators, and decision makers across the Nation. Through the assessment process and other avenues, USGCRP has broadened participation in the Program both within and beyond the Federal government. These efforts help shape the evolution of USGCRP in accordance with its 2012–2021 Strategic Plan.

This chapter provides a brief overview of USGCRP—the way it functions, the changes and progress it is making, and the challenges it faces. It also provides a high-level overview of key areas of emphasis throughout the Program, described in greater detail in later chapters.

USGCRP Organizational Overview

USGCRP was established by President Ronald Reagan in 1989, and codified by Congress in the Global Change Research Act of 1990 (P.L. 101–106). The 2012–2021 Strategic Plan and this update are responsive to the GCRA directive to provide a "comprehensive and integrated United States research program to assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The 2012–2021 Strategic Plan aligns with the science and information needs identified in the President's Climate Action Plan (PCAP) released in 2013, which recognizes USGCRP's role in areas such as developing actionable climate science, assessing climate-change impacts in the United States, and providing information for decision makers. USGCRP sees significant roles for itself in providing the underlying science for areas linked to protecting the Nation's economy and natural resources in the face of climate change, both referenced in the PCAP.

Guided by the White House Office of Science and Technology Policy (OSTP), USGCRP consists of 13 Federal agencies that conduct or use research on global change and its impacts

(see Figure 5), and share knowledge and coordinate activities to advance fundamental science and its utilization in addressing the challenges of climate-related global change. The Program is directed and overseen by the Subcommittee on Global Change Research (SGCR), which is chartered under the Committee on Environment, Natural Resources and Sustainability (CENRS), a part of the National Science and Technology Council (NSTC). Much of USGCRP's work is coordinated through its interagency working groups (IWGs), which have significant participation from science- and mission-focused Federal agencies, including member and non-member agencies. The USGCRP National Coordination Office (NCO) serves as an Executive Secretariat for USGCRP, staffed by Federal detailees and contractors who facilitate and support interagency planning and coordination. The NCO is guided and overseen by the USGCRP Executive and Deputy Executive Directors, which are filled by member agency employees on detail to NSTC and OSTP.

Figure 5: USGCRP Member Agencies

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

Reflecting the collective nature of the Program, the term "USGCRP" encompasses multiple elements. This update uses USGCRP (or "Program") in reference to the collective global-change research activities of the SGCR, USGCRP member agencies or bureaus, and the NCO. Subsets of the Program are referred to as: the SGCR (serving as USGCRP's board of directors); the USGCRP member agencies (in reference to activities carried out by the agencies in support of USGCRP goals); the IWGs, and the NCO (in reference to the coordination function for the Program).

See Chapter V for more information about the Program's implementation strategy and operations.

Guiding the Program

The vision, mission, and goals outlined in the 2012–2021 Strategic Plan remain the guideposts for USGCRP. The Plan emphasizes advancing scientific understanding in key areas (Goal 1) and making that science accessible and actionable for decision making (Goals 2, 3, and 4). USGCRP's sustained-assessment activities (Goal 3) play a key role in synthesizing and translating science for decision makers and identifying science needs (Goal 2), which collectively feed back into the scientific advancement and decision-support goals. Assessment activities also provide a framework for engagement beyond the Federal family and support communication and education activities for a wide range of audiences (Goal 4).

Since the release of the 2012–2021 Strategic Plan, the SGCR has worked in consultation with the IWGs to identify scientific focal areas that build on progress towards achieving the goals of the Strategic Plan, and on the Program's core science capabilities. These areas reflect the convergence of priorities among the science agencies and their awardees, the more mission-focused agencies and their stakeholders, and the Administration. These areas also represent those where the collective work of multiple agencies is needed to advance knowledge, and where current and maturing science can be assessed and harvested for decision support and communication and education efforts, thus supporting all four goals of the Strategic Plan.

In developing these focal areas, USGCRP is also guided by the annual Office of Management and Budget (OMB)/OSTP Memo on Multi-Agency Science and Technology Priorities, which directs the USGCRP member agencies to advance the goals of the Strategic Plan as well as make progress in selected areas. These areas, along with the core science capabilities discussed below, serve as a programmatic focus for several years, evolving over time as progress is made and needs change. While building on strong interagency collaboration, progress in the focal areas may also depend on key single-agency contributions to USGCRP, such as observations.2

USGCRP FY 15, 16, and 17 Focal Areas

USGCRP is highlighting to OMB the topics below as USGCRP interagency priorities. Specific activities related to these areas are discussed in more detail in Chapter III, in relation to the goals and objectives of the Strategic Plan. More information about progress in these areas is highlighted in the call-out boxes below, and is available through USGCRP's annual report to Congress, *Our Changing Planet*. Extremes, Thresholds, and Tipping Points forms an overarching, longer-term theme for USGCRP that includes building observational and modeling capabilities and theoretical understanding. Continuing as priorities from FY 2015 and 2016, nearer-term foci within this theme include Arctic Research and Resilience and Water-Cycle Extremes. Methane Cycling within the Carbon Cycle Context is a new focal area for FY 2017. USGCRP is also highlighting achievements in core Program capabilities of predictability, integrated observations, and making science actionable and accessible. Figures 6–11 highlight selected accomplishments and activities in each of these areas, drawn from the annual *Our Changing Planet* report and other sources.

[2] USGCRP considers observations in a manner equivalent to that in the 2013 National Strategy for Civil Earth Observations, where "data" and" Earth observations" include "observations, metadata, imagery, derived products, data-processing algorithms (including computer source code and its documentation), and forecasts and analyses produced by computer models."

1. Arctic Research and Resilience. Recent observations confirm the particularly rapid pace of climate change in the Arctic, its profound impacts in the region, and its connections through feedbacks to global climate change. Global impacts include sea-level rise; amplification of planetary warming; potentially altered global weather patterns; and direct effects on the global budget of greenhouse gases, including methane. Under the auspices of the recently-established Arctic Executive Steering Committee, USGCRP is coordinating with other interagency groups (the Interagency Arctic Research Policy Committee, Subcommittee on Ocean Science and Technology, and U.S. Group on Earth Observations) to focus respective and collaborative efforts and leverage capabilities. USGCRP's efforts within this arena (see Figure 6) include advancing Arctic observations, including field campaigns; contributing to assessments of Arctic adaptation and resilience; and improving understanding of the connections between Arctic change and global climate change. Enhanced understanding of the processes governing carbon emissions in the Arctic, particularly as permafrost thaws, links USGCRP's Arctic and methane priorities. Work in this area further supports Arctic Council goals during the 2015–2017 U.S. Chairmanship.

Figure 6: Selected Arctic Research and Resilience Accomplishments and Activities

- Arctic Observations to meet Scientific and Societal Needs
- Tracing Short-lived Climate Forcers in the Arctic
- Measuring Natural Greenhouse Gas Emissions in Alaska
- Predicting Changes in Arctic Sea Ice
- Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of Alaska
- Modeling Permafrost Response to Climate Change
- Improving Predictions of Changing Arctic Ecosystems

2. Water Cycle Extremes. The water cycle, and its extremes, affect all aspects of life on Earth, including food availability, infrastructure durability, human health and energy production. This research area addresses knowledge gaps that limit the ability to understand and predict the interplay between climate change and water-cycle extremes. It includes an emphasis on improving water-cycle projections and predictions; understanding impacts of water-cycle changes and extremes on various sectors; advancing integrated models of the water cycle, including sectoral interdependencies; and developing tools for stakeholder use (see Figure 7). In support of the PCAP, this priority will provide new knowledge that can be used for drought and flood preparedness and longer-term resilience strategies.

Figure 7: Selected Water-Cycle Extremes Accomplishments and Activities

- La Niña and the Greening of the Southern Hemisphere
- Mapping Fallowed Farmland During Drought
- Building Capacity Among Water Resources Managers
- Drought Research to Support Management and Preparedness
- Understanding Atmospheric Rivers and West Coast Precipitation
- Focusing on the California Drought
- Successfully Predicting the Large 2015/2016 El Niño
- Building Regional Collaboration for Drought Resilience

3. Methane Cycling within the Carbon Cycle Context (New for FY 2017). Increased atmospheric concentrations of carbon-based greenhouse gases are the main driver of climate change. Methane is a potent greenhouse gas and the second most prevalent emitted by human activities, with large natural and anthropogenic sources. Its shorter atmospheric lifetime relative to carbon dioxide means that steps to mitigate methane emissions could have a relatively rapid impact. Building on its carbon cycle research program (see Figure 8), in support of the PCAP Strategy to Reduce Methane Emissions and in consultation with the interagency group on Methane Measurement Science and Technology convened by OSTP, USGCRP will initiate an FY 2017 interagency priority centered around methane. It will include strengthening capabilities to monitor natural and anthropogenic methane fluxes; improving understanding of processes governing significant methane emission sources; and improving models and predictions of the carbon/methane cycle.

Figure 8: Selected Accomplishments and Activities in Carbon Cycle Science

- Tracking Earth's Carbon Budget with Global Observations
- Natural and Human Emissions in the Tropical Canopy
- Soil Carbon Storage: A Big Role for Microorganisms
- Carbon Community Collaboration
- Measuring Natural Greenhouse Gas Emissions in Alaska
- Carbon Cycle Science for a Changing World
- A Global Carbon Atlas for Educators, Policymakers, and the Public
- AMAP Assessment 2015: Methane as an Arctic Climate Forcer
- Assessments of Carbon Storage and Greenhouse Gas Flux: Ecosystems of the Great Plains, Western U.S. and Eastern U.S.

USGCRP Core Capabilities

USGCRP's ability to identify and make progress on emerging science needs—for society and for research—critically depends on the ongoing development of core capabilities that support the breadth of the Program. Deployed through interagency cooperation and single-agency activities, core capabilities provide critical knowledge and methodologies to the Program and the member agencies. These capabilities are summarized below and discussed in greater detail in Chapter III.

1. Integrated Observations. Observations are at the heart of USGCRP's ability to understand climate-related global change and its impacts (see Figure 9). The responsibility for maintaining and advancing Earth system observations is spread across numerous agencies, and it is through the collective sum of these observations that scientists are able to develop, model, and test their understanding of Earth system processes; provide predictions and projections of future conditions; and assess confidence in these predictions and projections. USGCRP agencies work together to bring cohesion to observational approaches across the Program, including collaborative field campaigns; science development using new observing capabilities; and long-term planning and development of observations-based indicators of climate change for decision makers. In FY 2017, emphasis will be placed on the integration and harmonization of heterogeneous observational records (e.g., satellite and

non-satellite data) with model outputs, to more comprehensively utilize the full capacity of USGCRP agency observing systems. In addition, the USGCRP Observations Interagency Working Group will be focusing attention on Observing System Simulation Experiments for climate in the near future.

Figure 9: Selected Accomplishments and Activities in Integrated Observations

- Monitoring the State of the Global Climate
- Tracking Earth's Carbon Budget with Global Observations
- Observations to Improve Climate Models
- Evaluating U.S. Earth Observations
- Two Cutting Edge Missions to Measure Global Change
- Strengthening Global Observations of Biodiversity
- Extending Climate Records Beyond Instrumental Measurements
- Tracking Climate Change with Indicators
- Measuring Change at Sea
- Connecting the Remote Ocean to Global Climate
- Studying Northern-Ecosystems Response to a Changing Climate
- Monitoring Urban Emissions Hotspots

2. Predictability and Integrative Modeling. This core capability addresses knowledge gaps that are common to both climate prediction and climate-change impact modeling (see Figure 10). The intent is to improve the ability to accurately assess and increase confidence in projections/predictions of climate variability and change at finer geographic (10–50 km) scales, and time scales ranging from intra-seasonal to multi-decadal. It also includes the development of a common set of methodologies to provide probabilistic information on climate change and events important to decision making. In FY 2017, new efforts will be made to improve accuracy and confidence in global climate predictions and projections and to develop a new class of finer resolution assessment capabilities that combine aspects of natural and human system models, based on a combination of Integrated Assessment Models and Impact, Adaptation, and Vulnerability models, in the context of Regional Earth System Models.

Figure 10: Selected Accomplishments and Activities in Predictability and Integrative Modeling

- Building Synergy in the U.S. Modeling Community
- Tropical Cyclones in a Warming World
- Modeling Thunderstorm Clouds for Better Regional Climate Predictions
- Seasonal Prediction System from Research to Operations
- DYNAMO: Linking Models and Observations to Predict Near-Term Climate
- Modeling Climate Impacts on Agriculture and Adaptation by the Agro-Economy
- Improving Climate Predictability
- Modeling Ice Sheets and Sea-Level Rise

3. Actionable and Accessible Science. Assessments, including National Climate Assessments (NCAs), are a key element of USGCRP's programming in this arena (see Figure 11). FY 2017 will see a full ramp-up in preparation for NCA4, due out in 2018. In addition to leading the development of the quadrennial NCA report, USGCRP will support work in areas including climate scenarios and projections, the economic impacts of climate change, development of risk-based framing, and expansion of the Global Change Information System. As part of its focus on a sustained-assessment process (see Chapter III, Goal 3), USGCRP and its member agencies released assessment reports on climate change and human health (2016, see Figure 12), the effects of drought on forests and rangelands (2016), and food security (2015). The Program is developing assessments of the carbon cycle and the state of climate science, all of which will feed into NCA4. More broadly, USGCRP works to strengthen the scientific basis for decision making and to enhance the accessibility and utility of data and tools for decision support and risk management (e.g., via assessment of Federal Agency Climate Change Adaptation Plans, through the NCA, and through agency engagement with stakeholders). Co-production of actionable knowledge with entities such as state and tribal governments and regional consortia that work closely with stakeholders remains an important emphasis, as discussed under Goal 3. The Program also has continuing emphases on providing information to stakeholders on high impact extremes, incorporating citizen science into USGCRP programming, and supporting climate literacy across the Federal Government and for the public.

Figure 11: Selected Accomplishments and Activities in Actionable and Accessible Science

- Adaptive Action Plan for Fish, Wildlife and Plants in a Changing Climate
- Supporting Resilience Water Resources and Utilities
- From Space to Village: Satellite Data for Decisions in the Developing World
- Regional Science Networks for Climate-Smart Decision Making
- Empowering States and Communities with Climate Science
- The National Climate Assessment in Review: Frameworks for Evaluation
- Scenarios of Change for Sustained Assessment
- Teaching Climate Where We Live
- Crowdsourcing Climate: Citizen Science and the National Climate Assessment
- Connecting with Public Health Communities of Practice
- Data on Scales Needed by Resource Managers
- Providing Drought Information to Farmers
- Reducing the Health Risks of Extreme Heat

Figure 12: Climate Change and Human Health

Since the release of the 2012–2021 Strategic Plan, USGCRP has made substantial advancements on understanding the human health risks from climate change, and has become a center for knowledge sharing among Federal health communities considering the risks of climate change. To expand engagement within and beyond the Federal Government, USGCRP agencies supported a number of outreach events focused on climate and health. In support of the President's Climate Action Plan, USGCRP:

- Released the report, The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, breaking new ground in quantifying the increased health risks that climate changes poses, and highlighting factors that make some individuals and communities particularly vulnerable
- Released the Metadata Access Tool for Climate and Health and coordinated the health input for the U.S. Climate Resilience Toolkit and Climate Data Initiative
- Supported the development of the National Integrated Heat Health Information System, which focuses on preparing communities for impacts from rising temperatures and extreme heat events

Meeting Challenges

USGCRP has made significant progress since the release of the 2012–2021 Strategic Plan, as discussed in Chapter I and noted above. USGCRP is the only interagency group focused on advancing the fundamental research of global climate change and its impacts, and on using that knowledge to help identify emerging climate-related societal issues. The scope of the Program spans a continuum from fundamental research to decision support, which is represented by the capabilities of its member agencies. Guided by the 2012–2022 Strategic Plan, USGCRP is committed to improving its ability to provide decision makers with actionable information. There are considerable challenges in navigating this landscape, discussed briefly here and in greater detail in Chapter III.

Figure 13: Broadening USGCRP Participation

Since the release of the 2012–2021 Strategic Plan, Areas of progress in broadening engagement and participation in USGCRP include:

- Strong engagement processes for NCA3 and 4
- Cooperation with groups such as Resilience AmeriCorps, Climate Action Champions, and the Interagency Forum on Climate Impacts and Adaptation
- USGCRP support for continuing private-public collaborations on climate resilience (See Figure 22)
- Support for FEMA Climate Resilience Exercises
- 20 non-member agencies participate in USGCRP IWGs
- Broad consortium building around efforts such as the OSTP-led Climate Education and Literacy Initiative

While USGCRP has made significant progress in developing science that can inform adaptation planning and action, the Program's role in generating science for informing mitigation decisions has been less well defined. Chapter III, Objective 1.2 outlines next steps in this area.

The demand for increasingly fine-scale climate information creates a need for rigorous and robust approaches to downscaling climate models and for providing guidance in the use of downscaled products. USGCRP is working systematically to improve regional- and finer-scale models (see Chapter III, Objective 1.4), and is participating in a pilot private-public collaboration involving the use of climate information to support urban adaptation planning at regional,

state, and municipal scales (see Figure 22). Through collaborations like this, USGCRP is exploring avenues for supporting the provision of climate information across the country at regional and finer scales and attuned to the full range of end-user needs, which is beyond the scope and capacity of USGCRP and its member agencies alone.

The Program also continues working to define and implement key elements of its role in connecting science providers and science users, and its relationships with other organizations that aim to do the same (see examples in Figure 13). In doing so, the Program incorporates input from the NCA3 Development and Advisory Committee's Sustained Climate Assessment Special Report (especially Recommendation 1) and the National Academies report on Broadening Participation in the U.S. Global Change Research Program.

The Program has been successful in integrating the social, behavioral, and economic sciences into specific activities within USGCRP (see Chapter III, Goal 2), but it is still challenging to develop a broader program that combines the social and natural sciences, where appropriate, to better understand how humans drive and respond to global change.

Sustaining critical observations for long time series, while also developing systems to observe needed new variables, is an ongoing challenge, discussed further in Chapter III.

Looking ahead to the remainder of this update, Chapter III centers on the four goals of the 2012–2021 Strategic Plan, emphasizing areas of progress on which to build and challenges to navigate. Chapter IV provides an updated view of USGCRP's role in international cooperation, building from guidance in the GCRA, and reflecting a rapidly changing international landscape for global-change science. Chapter V provides an update on USGCRP's strategies for implementing the remaining years of the 2012–2021 Strategic Plan. Each chapter can be read as a standalone section, entailing some repetition of introductory material.

Chapter III: USGCRP Goals and Objectives

This chapter and the following one are structured into three main sections. Within a given goal, the "Maintaining Directions" section highlights foundational approaches from the 2012–2021 Strategic Plan that the Program has maintained. The "Building on Progress" section identifies areas over the next few years where USGCRP expects to shift focus, accelerate progress or capitalize on opportunities for integration that build on progress under the Strategic Plan, or are called for by changes in the science and policy landscape. Finally, the "Navigating Challenges" section notes areas where the pace of progress or even some of the objectives of the 2012–2021 Strategic Plan are challenging because of scientific gaps, lack of capacity, or other constraints.

Goal 1: Advance Science

Goal 1, Advance Science, is the central pillar for USGCRP. Program capabilities, outlined in the objectives below (see Figure 14), can be oriented or reoriented towards emerging scientific and societal imperatives, such as the interagency priorities discussed in Chapter II (p. 15–22). These capabilities are foundational to developing science that supports adaptation and mitigation decisions (Goal 2). Scientific advancements from Goal 1 also form the basis for USGCRP assessments that synthesize and translate science for decision makers (Goal 3); provide the basis for communication, engagement, and education efforts (Goal 4); and identify future research needs. The Advance Science goal underpins and supports Goals 2, 3, and 4, which in turn inform science planning and priorities. From providing a deeper understanding of extreme events or changes in the Arctic, to providing leadership on evaluating the applicability of climate models and downscaling approaches for decision makers, the USGCRP interagency teams work to align agency efforts to advance collective scientific goals.

Figure 14: Goal 1. Advance Science

Advance scientific knowledge of the integrated natural and human components of the Earth system.

- **Objective 1.1. Earth System Understanding:** Advance fundamental understanding of the physical, chemical, biological, and human components of the Earth system, and the interactions among them, to improve knowledge of the causes and consequences of global change
- **Objective 1.2. Science for Adaptation and Mitigation:** Advance understanding of the vulnerability and resilience of integrated human-natural systems and enhance the usability of scientific knowledge in supporting responses to global change
- **Objective 1.3. Integrated Observations:** Advance capabilities to observe the physical, chemical, biological, and human components of the Earth system over multiple space and time scales to gain fundamental scientific understanding and monitor important variations and trends
- **Objective 1.4. Integrated Modeling:** Improve and develop advanced models that integrate across the physical, chemical, biological, and human components of the Earth system, including the feedbacks among them, to represent more comprehensively and predict more realistically global change processes
- **Objective 1.5. Information Management and Sharing:** Advance the capability to collect, store, access, visualize, and share data and information about the integrated Earth system, the vulnerabilities of integrated human-natural systems to global change, and the responses to these vulnerabilities

The objectives of Goal 1 jointly advance fundamental scientific knowledge of the integrated natural and human components of the Earth system, and provide essential science needed to reduce vulnerability to global change through increased resilience and managed risk. Although discussed individually for clarity and to reflect the depth of work across USGCRP, scientific progress requires linkages across the objectives. Within these linkages, several common themes emerge. For instance, there is increasingly deep interplay among observations (Objective 1.3), process research (Objective 1.1), and modeling (Objective 1.4) at multiple spatial and temporal scales, on topics such as the dramatic decline of Arctic sea-ice extent, or the need to better understand aspects of known climate variability, such as global surface temperatures. The scientific community is capitalizing on improved observational systems and more readily accessible and customizable datasets to drive rapid progress in fundamental understanding. These efforts are leading to improvements in Earth System Models (ESMs) and increasing insight into future changes.

Another common theme is integration across the traditional boundaries between research communities working on different aspects of ESMs. Internationally, the Coupled Model Intercomparison Project (CMIP) produced a standardized experimental protocol for studying the output of coupled ocean-atmosphere general circulation models (GCMs), enabling more rigorous evaluation of climate model performance. As an outgrowth of CMIP, new Model Intercomparison Projects (MIPs) are addressing critical topics such as how potential greenhouse gas emissions pathways affect climate extremes, regional sea-level rise, water availability, and biospheric feedbacks, and how these effects will influence mitigation and adaptation options. The MIPs provide an expanded capacity for rapid analysis of models, development of new projections, exploration of uncertainties, and generation of policy-relevant scenarios, breaking down barriers across research, impact, and adaptation communities. The USGCRP community is deeply engaged with CMIP and other MIPs; such participation brings the challenge of managing the proliferation of modeling activities and using new knowledge (see Objective 1.4) gained in the process to support useable science (Goals 2, 3 and 4).

USGCRP is adapting to the increased demand from Federal agencies and other entities for information relevant to preventing and managing the impacts of climate-related global change. A continuing priority is science to inform mitigation and adaptation efforts, including carbon cycle-based understanding of greenhouse gas sources and sinks; characterization of future conditions, emissions drivers and scenarios, and uncertainties; evaluation of adaptive capacity; and the science of decision support and evaluation. Effective engagement of social scientists and integration of social-science methodologies remains a challenge, discussed in further detail in Objective 1.2.

Interagency coordination surrounding improvements to data management practices and the development of the Global Change Information System continue to support both basic science and decision support through enhanced data discoverability, usability, and interoperability. USGCRP has formed a new working group to foster coordination in this crucial area. Challenges remain in encouraging best practices in data management across agencies and externally-funded scientists (see Objective 1.5).

Objective 1.1: Earth System Understanding

Maintaining Directions

USGCRP advances scientific understanding of the changing Earth system by considering natural, and increasingly, societal, drivers and their interdependencies as part of one integrated research effort. These drivers interact at various spatial and temporal scales and involve departures from recent trends in historical climate conditions, a condition described scientifically as "non-stationarity." This objective, and the following one on science for adaptation and mitigation, focus on scientific insight from process research and experimentation, which draws from USGCRP investments in areas such as observations (Objective 1.3), modeling (Objective 1.4), and data management and utilization (Objective 1.5). Due to the international nature of global-change science, USGCRP will continue to coordinate with related and complementary international scientific programs, discussed in more detail in Chapter IV.

Building on Progress

USGCRP is making progress across the objectives outlined in the 2012–2021 Strategic Plan, as directed by OMB and OSTP in their annual Science and Technology Priorities Memos. As discussed in Chapter II, priority areas are extremes, thresholds and tipping points (currently with a topical focus on water-cycle extremes and the Arctic), and methane cycling in the context of the larger carbon cycle. For each area, the section below discusses fundamental research needed for overall progress, as well as research that is more targeted to societally relevant topics.

Extremes, Thresholds, and Tipping Points: Topical Areas

This topic is a USGCRP interagency priority for fiscal years 2014–2017, reflecting the need to characterize the impacts of a changing climate that is creating current and likely future conditions outside the scope of those within which our industrial society developed. Changing patterns of extreme events, such as increasing drought in specific regions or higher storm surges and more frequent coastal flooding, are already occurring. Looking ahead, gradual climate change could give way to abrupt change when thresholds in the climate system are reached—for example, the possibility that greenhouse gas-induced warming will accelerate the release of additional greenhouse gases from thawing permafrost, which would further accelerate warming. A tipping point could occur when such change becomes irreversible—for example, if warming of the oceans and atmosphere caused the collapse of the West Antarctic Ice Sheet—generating much greater sea-level rise than is currently projected.

USGCRP approaches this priority through nearer-term (3–5 year) emphasis on topical areas of Arctic change and water-cycle extremes (see Chapter II). The Program also emphasizes longer-term research necessary to address the broader array of potential climate extremes, thresholds, and tipping points. Central to progress in this area is the need for improving observations, modeling, and understanding of the interplay between natural climate variability and climate change associated with human activities. The potential for complex feedbacks within and between different parts of human and natural systems, with the potential for crossing thresholds, is a focus for USGCRP. Such complexity is a significant source of uncertainty in characterizing a range of possible future conditions, known as scenarios of change.

Water-Cycle Research. The U.S. droughts of 2012–2015 and subsequent research related to climate trends on decadal time scales are helping drive USGCRP research on the dynamics of water-cycle extremes and related interactions among the land surface, oceans, and atmosphere. In contrast, excessively heavy precipitation has been trending upward across much of the U.S. and many other parts of the world over the past few decades. The need for information on a changing water cycle led to a USGCRP interagency priority focused on both wet and dry extremes in the water cycle in the face of a changing climate, with an emphasis on the process-based understanding, observations, and modeling that improve forecasting of the water cycle. This priority includes topics such as changing precipitation patterns; integrating groundwater recharge storage capacity and withdrawals into projections of water availability; improving projections of drought and flood risk, including on the decadal scale and via incorporating changes in extreme event probability from past historical averages; and extending regional multi-model capabilities to improve projections. This research will incorporate and integrate results from the recently launched Global Precipitation Measurement mission (satellite observations), Deep Argo deployment (*in situ* ocean data), improved customized river basin flow projections and improved meteorological reanalyses (model data), and the National Water Information System (*in situ* surface and groundwater data).

These initiatives are providing new, higher-resolution scientific insights into atmospheric processes and water-cycle dynamics on larger spatial scales and at new locations and heights/depths. For example, a new understanding of the ocean's influence on North American climate is being derived from improved understanding of variability in El Niño events and the range of their effects on precipitation. Similarly, recent research highlights the strong influence of moisture-laden atmospheric currents known as atmospheric rivers on West Coast precipitation patterns. Understanding the thermodynamics associated with the causes of changes in extreme precipitation events at local, regional, and global scales is of fundamental importance, both practically and theoretically. Guided by the Committee on the Environment and Natural Resources, and Sustainability (CENRS), there is coordinated effort to understand, model, and manage the climate-related aspects of the interconnected food-water-energy system, which incorporates natural, social, and human-built components. Within this larger collaboration, USGCRP provides critical insight into the nature and likely impacts of a changing climate on these systems.

Clouds, Aerosols, and Aerosol-Cloud Interactions. Uncertainties in the proper representation of clouds, aerosols, and aerosol-cloud interactions in climate models lead to known biases in the water cycle and in radiative energy balance, in both seasonal and annual mean climate forecasts. Recent concerted multi-agency observational efforts (e.g., the CalWater 2 and ARM Cloud-Aerosol-Precipitation Experiment field campaigns and the Cloud-Aerosol Transport System) aim to improve understanding of cloud and aerosol processes. Modeling efforts will focus on incorporating improved process-level knowledge into climate models to evaluate the impacts on climate scenario projections. Knowledge gained from these recent observational efforts will be applied to other cloud regimes that have strong climate feedbacks and are poorly represented in climate models, such as those in the Arctic and Southern Ocean. Research in this domain also provides insights relevant to proposed climate intervention pathways, such as solar radiation management (i.e., potential future efforts to reduce the amount of solar radiation that reaches the Earth's surface, or the amount that the Earth's surface reflects).

Rapid Arctic Change. There is a growing awareness of the rapid changes occurring in the Arctic. In addition to uncovering the impacts of climate change within the Arctic region itself, ongoing "attribution science" research (see "Attribution" section, p. 27–28) is investigating the role that changing Arctic conditions have in global climate and in various extreme weather events elsewhere. In concert with international science programs, such as the World Climate Research Programme, USGCRP will continue to improve understanding in a variety of topics. These include physical and chemical changes in permafrost, sea and land ice, and oceans; rates of ice loss; feedback between permafrost processes and the carbon cycle; and aerosols and clouds and their impacts on the surface energy budget, including feedbacks to ice and snow cover. Coupled interactions between the Arctic Ocean and the Northern Pacific and Atlantic oceans will be further explored to investigate their impacts on Arctic systems and feedbacks to regional and global climate. Via its Arctic priority, USGCRP will continue to emphasize these physical processes while also deepening investigations into ecosystem and socioeconomic responses. The U.S. chairmanship of the Arctic Council (May 2015-April 2017) provides an opportunity to leverage the Program's efforts to enhance observational capacity (including that gained through Traditional Environmental Knowledge/Indigenous Knowledge) and integrate the new findings into models at all scales to support appropriate adaptation and mitigation actions (see Objective 1.2). Under the auspices of the Arctic Executive Steering Committee, USGCRP works closely with its sibling CENRS subcommittees, the Interagency Arctic Research Policy Committee, and the Subcommittee on Ocean Science and Technology, to coordinate science addressing critical Arctic issues.

The Impact of Antarctic Ice-Sheet Loss on Sea-Level Rise. The possible demise of the West Antarctic Ice Sheet (WAIS) is a potential tipping point that could have significant global-scale impacts well past 2100. The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5, 2013) and the 2015 National Academies of Sciences, Engineering, and Medicine report *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research* highlighted dynamical ice loss from the marine-based WAIS and resultant sea-level rise as a key research challenge and a top priority, respectively. A recent modeling study projected sea-level rise of more than one meter by 2100 and more than 15 meters by 2500 from WAIS loss, far higher than IPCC AR5 scenarios. The study was a big step forward in ice-sheet modeling as it incorporated both atmospheric and ocean drivers of ice-sheet change and was validated by hindcasting sea-level rise events driven by WAIS loss during the last interglacial and the Pliocene. Supported by USGCRP member agencies, many national research programs will continue to focus observational and modeling research on the instability of the WAIS and the associated sea-level rise implications.

Extremes, Thresholds, and Tipping Points: Underlying Capabilities

Using Long-Term Data Records to Understand Climate Variability. Seamless integration, validation, and interpretation of paleoclimate data (data on ancient climates collected from proxy records extending beyond the instrumental record), together with data from the instrumental record are important research areas. The combination of the two different types of records are critical for research into the longer-term record of climate non-stationarity, nonlinearities, and natural variability. Stitching together high-quality, high-resolution, and long time series (from decades to millions of years), from both active observing systems and paleoclimate information (e.g., from ice cores, corals, tree rings, stalactites and stalagmites, and marine and

lake sediments), offers great potential for robust analyses of climate variability and change at global, regional, and local spatial scales. Such records can include very high temporal resolution (hourly) data from instrumental observing systems to lower temporal resolution (annual to centennial or greater) data from the paleoclimate record. Together, they can constrain variability in key features of the global climate, such as continental-scale temperature and hydroclimate variability; the cryosphere; carbon dioxide forcing of surface temperature change; manifestations of major climate variations such as the El Niño-Southern Oscillation; and the ocean's overturning circulation.

Rigorously combining long-term datasets that may have been collected with different sampling frequency or geographic distribution is an ongoing research activity for USGCRP. The knowledge to be gleaned from new methodologies and extended records is essential to distinguishing the signatures of anthropogenic influences from natural variability. It also helps define the baseline from which trends in extreme events can be distinguished. Looking ahead, study of geologic episodes, such as the Last Glacial Maximum, Little Ice Age, and Medieval Warm Period, will improve understanding of how the climate system responds to a wide range of forcings, with opportunities to revolutionize the understanding of how the ocean, atmosphere, and land surface are linked in modulating the Earth's carbon cycle. Syntheses of large regional and global datasets are now possible. Further integration of these datasets with models (see Objective 1.4), and novel applications of numerical techniques, will help to focus new data collection on key areas of uncertainty. Conversely, new data are helping to improve and challenge model simulations. In sum, these long-term datasets help scientists understand the timescales of climate variability and sensitivity of the climate system to internal and external forcings. Building on progress in this area requires strong coordination among member agencies that support dataset development across observing systems, including paleoclimate data. Research on seamless integration of datasets is paramount to building on these advances (see Objective 1.5).

Attribution. A key intersection between Earth system understanding and actionable science lies in further advancing understanding of the extent to which current and future climate change is associated with human-caused drivers (e.g., energy use, land use and land-cover change) that are perturbing natural variability and changing the baseline climate with which human societies and natural ecosystems have evolved. For example, examining human versus natural contributions to changing patterns of extreme weather can improve understanding of the potential consequences of mitigation efforts on future extreme events (e.g., their probabilities, geographic distribution, intensity, and return intervals). USGCRP continues to build on advances in, and growth of, research on the respective influences for climate phenomena affecting society, such as the 2013 floods in Boulder, Colorado; the 2013 Australian heat wave; the 2013–2014 United Kingdom floods; Typhoon Haiyan and Superstorm Sandy; and the 2012–2015 droughts in California and the central United States. Approaches to isolating the anthropogenic signal from natural climate variability—termed "attribution science"—are rapidly developing, as documented by the recently released National Academy of Sciences, Engineering, and Medicine report *Attribution of Extreme Weather Events in the Context of Climate Change*. These approaches rely on increased mechanistic understanding grounded in the observational and modeling capabilities foundational to USGCRP's core mission. USGCRP will continue to build this capacity, which leads to a greater ability to inform decisions based on improved clarity about future risks.

Decadal Climate Variability. Although not itself an extreme, threshold, or tipping point, understanding changes in the rate of global warming is a high-priority issue against which thresholds are identified. The relative roles of anthropogenic climate change and natural variability have spurred numerous studies supported by USGCRP agencies examining the global energy balance and evaluating alternative mechanisms (e.g., teleconnections including the El Niño-Southern Oscillation, internal ocean thermodynamics and variability, volcanic activity, land-use and land-cover change, or aerosol radiative effects) that could be responsible for decadal-scale variations that depart from the long-term anthropogenic climate-change trend. Ascertaining the various components of heat storage on the planet is an ongoing challenge being debated within the scientific community. Additionally, limitations in observational methodology and analysis methods are barriers to understanding the uncertainty in global estimates of change. USGCRP will continue to promote the systematic evaluation of time-series analyses and process-based interpretation of decadal and multi-decadal changes in the context of the long-term trends. The Program will also promote further evaluation (through observations and modeling) of the impacts of various natural and anthropogenic internal and external factors affecting the climate system. Such research informs USGCRP efforts regarding the impacts of temporal and spatial scales on models of the global climate system.

The Carbon and Methane Cycles

The natural and anthropogenic processes governing the methane cycle are the focus of another USGCRP priority area (see Chapter II). This focus builds on USGCRP's long-time focus on understanding the carbon cycle and its interaction with climate change, which forms the context for the methane priority. Methane, the second most important greenhouse gas emitted by human activities, has a far higher global warming potential than carbon dioxide on a per unit basis. It has large natural as well as anthropogenic sources. Its shorter atmospheric lifetime relative to carbon dioxide means that steps to mitigate methane emissions could have a relatively rapid impact. USGCRP will commence an FY 2017 interagency priority that includes strengthening capabilities to monitor natural and anthropogenic methane fluxes; improving understanding of processes governing significant methane emission sources; and improving models and predictions of the carbon/methane cycle.

Carbon Cycle Advances. Many advances in the sciences of biodiversity and biogeochemical cycles, including the carbon cycle, have been catalyzed by interdisciplinary USGCRP collaborations. For instance, since its establishment in 2005 as a core element of USGCRP, the North American Carbon Program community has promoted integrated research on the impact of multiple greenhouse gases on carbon and other global biogeochemical cycles. This includes, for example, Coastal CARbon Synthesis (CCARS) activities in the coastal and Great Lakes regions of North America, and air-sea carbon dioxide flux syntheses for the Arctic and the Gulf of Mexico. The contribution of urban areas to regional carbon cycles is also emerging as an important research area for USGCRP, conveying with it information that may be used by non-USGCRP agencies in mitigating urban emissions.

The degree to which the carbon and hydrologic cycles are tied together is being shown through the effects of new energy developments on water requirements. Recent comparisons of multiple models for the exchange of carbon between land and the atmosphere use improved empirical data to better represent terrestrial processes below ground, and are allowing improved

quantification of terrestrial carbon sequestration rates and biogeochemical cycling. The notion of a "boundless" carbon cycle, with land-margin ecosystems providing a critical link in the lateral transport of carbon from land to ocean, is advancing, including research on "blue carbon" ecosystems (mangroves, salt marshes, and seagrasses) that contain significant carbon stocks and sequestration potential but are experiencing severe degradation from increased urbanization and other global-change drivers. Progress in theoretical understanding, observational technologies and networks, and modeling capabilities is leading to improved measurements and estimates of carbon sources, sinks, and dynamics nationally and globally—an area in which USGCRP will continue to focus attention, including the effective stewardship, accessibility, and archiving of these critical data. This work on the larger carbon cycle underlies the USGCRP interagency priority on methane cycling (see Chapter II, p. 15–22).

Methane Cycling. Methane is a potent greenhouse gas with a relatively short residence time in the atmosphere (~12 years, in comparison to carbon dioxide's much longer average residence time. Since methane is a short-lived climate pollutant, steps to reduce methane emissions could have a relatively rapid impact. USGCRP has developed methane cycling as an interagency priority area, starting in FY 2017 (see Chapter II, p. 15–22). In planning and implementing this priority, USGCRP is working closely with the Office of Science and Technology Policy (OSTP)-convened interagency group on Methane Measurement Science and Technology. This group includes a number of USGCRP member agencies, and will have an anthropogenic emissions measurement orientation. USGCRP will retain its basic research orientation, with greater focus on methane emissions fluxes from natural and managed ecosystems, including agroecosystems. USGCRP's methane priority builds from the long-term results of its agency investments in fundamental carbon cycle research. Objectives for this priority include: understanding processes governing natural and anthropogenic methane emissions; improving estimates and predictions of methane emissions, inventories, radiative forcing and attribution; improving and utilizing climate models to simulate methane sources and sinks; and evaluating and characterizing anthropogenic methane emissions. The Program is fostering the combination of newly available and continuing data streams produced from local-, regional-, and global-scale measurements and observational platforms (including airborne platforms, flux towers, and global satellite-based carbon dioxide measurement capabilities) across land, air, water, and ecosystem interfaces, and their integration into the evolving suite of global biogeochemical models. A key aspect of this effort will be in the Arctic, where warming temperatures are leading to permafrost thawing and could cause large-scale methane release to the atmosphere. Utilizing data from recently-completed or initiated airborne platforms (e.g., DISCOVER-AQ and CARVE), in conjunction with *in situ* studies (e.g., NGEE-Arctic, NGEE-Tropics, ABoVE) and climate projections, potential future emissions of methane from soils and sediments will be studied further (e.g., rice agricultural fields, peatlands, and coastal ecosystems).

Ecological Modeling and Biodiversity. USGCRP is making significant progress in integrating ecological and carbon-climate models. Increasingly, non-satellite information goes beyond species information to include genetic data, and its integration with ecological models is promoting the relatively new field of landscape genetics as a partner to information on species occurrence and population ecology. Improved remote sensing capabilities capture observations of ecological traits and other aspects of phylogeny, enabling greater characterization of the components of ecosystems and how they are processing energy and elements. Because plant

species differ in timing of leaf-out, peak photosynthetic activity, and tissue decomposability, among other traits, capturing this fine-scale information on the ground and assimilating it into dynamic models allows for better cross-disciplinary integration between ecological models and carbon-climate models. Drawing from the parallel developments of improved observation networks across spatial scales, bioinformatics tools that link cross-scale observations, and recent theoretical understanding captured in models, USGCRP will work to build testable ecological forecasts. Researchers can now assemble predictions of the impacts on ecosystems, species, and populations resulting from changes in climate; human land, water, and energy use; and other drivers. The last three years have seen an acceleration of this trend, as well as the advent of new satellite and other remote sensors (e.g., UASs, camera traps, sound recordings, enhanced tracking/tagging devices, and environmental DNA). The ability to integrate observations across scales is leading to predictions that will underlie USGCRP's increasing ability to assess regional to local impacts of a changing climate on living systems, and vice versa.

Navigating Challenges

Making progress in areas such as climate sensitivity, feedbacks, water cycle and extremes remains a constant challenge for the Program, but USGCRP also faces challenges related to specific applications of these global-scale behaviors. The surge in demand for a wider variety of climate data at very fine spatial resolutions (e.g., city scales and smaller) and short timescales exceeds the resolution of current scientific understanding. This challenge is especially pertinent for regional and more local projections of precipitation and many types of climate extremes, where GCMs fail to adequately characterize the potential range of probability. With a focus on high-resolution data and model output, research will continue in quantifying uncertainty across multiple time and distance scales, to advance USGCRP's capabilities in responding to this surge of user demand.

Identification of the appropriate scales that allow for robust integration and analysis across disciplines is a challenge to which the Program must continue to pay attention. For example, social science and biological studies are often conducted on the scale of communities or institutions, while General Circulation and Earth System models are developed at global and regional scales. Similarly, hydrogeological and hydrometeorological models and events are often studied at much finer scales than those used in water-cycle models. Use of downscaled climate models provides one avenue to address this challenge, but metrics of reliability are required. USGCRP is also attempting to tackle the challenge of providing information at user-appropriate scales through the exploration of various model-observations experiments and MIPs (e.g., Obs4MIP, AgMIP) that explicitly bring together models and observations on a common scale. Upscaling or generalizing of social-science findings for integration with climate understanding at larger scales may also be necessary. This broad research area cuts across all of the objectives in the Advance Science Goal, and affects science utilization for informing decisions (Goal 2). Related to the question of scale is the research challenge of how to represent heterogeneity in models (e.g., in soils, riparian vegetation and geology, use patterns, storm infrastructure). Such heterogeneity may not be meaningful when averaged over global or regional scales, but may be very important at more local scales relevant for decision making.

Objective 1.2: Science for Adaptation and Mitigation

USGCRP sees a complete continuum from its basic global-change science, through climate impacts and vulnerabilities, to translation and provision of this information and knowledge needed to inform responses to climate change, such as adaptation and mitigation. USGCRP's longstanding philosophy is that its work is policy relevant but also policy neutral, which applies here to science for informing adaptation and mitigation. The science needed to inform decisions builds from USGCRP's core capabilities, discussed in other Goal 1 objectives, in observations, regional- and global-scale modeling, decision-scale scenario development, and increasing understanding of the carbon cycle (including natural and anthropogenic sources and sinks) and its interaction with the climate system. This section focuses on related underlying science needs; Goal 2 focuses on science translation and tool development for decision makers, building on the scientific advances discussed in this section.

In the context of climate-related global change, science that can inform adaptation enables adjustments in natural or human systems to a new or changing environment, allowing either beneficial opportunities or helping to moderate negative effects. The USGCRP 2012–2021 Strategic Plan defines mitigation as intervention to reduce the sources or enhance the sinks of greenhouse gases and other climate warming agents. In this arena, USGCRP research focuses on understanding the climate impacts of different emission scenarios as well as the science that underpins carbon sinks and natural system carbon-reduction approaches. To the extent that different scenarios lead to different outcomes, USGCRP is committed to working with policy makers to enable them to most effectively understand the implications of different mitigation (and thus emission) pathways. For decision support relative to mitigation, modeling capabilities are a critical need. Note that mitigation approaches that include the development or evaluation of engineering technologies or devices for energy generation, tailpipe or power plant emissions control, or active/direct carbon capture are outside the scope of USGCRP. However, USGCRP will maintain awareness of evolving technology as it impacts science needs and boundary conditions for climate models.

Maintaining Directions

USGCRP reaffirms the commitment made in the 2012–2021 Strategic Plan to advance use-inspired science to inform adaptation and mitigation decisions, and to enhance understanding of the vulnerability of social, ecological, and human-natural systems to climate-related global change. To better understand likely future conditions to which response will be necessary, USGCRP will continue its research on (1) national-to-local-scale consequences of gradual global change (e.g., increasing temperatures, changing water availability, agricultural shifts, sea-level change); (2) similar scale consequences of changing patterns of extreme weather events (e.g., drought, floods, heat waves, storms); and (3) the potential impacts and consequences of rapid, large-scale global change (e.g., permafrost loss, sea-ice and glacial melt).

Building on Progress

USGCRP will continue its work to better inform adaptation and mitigation options and strategies to improve understanding of their potential effects, including risks, benefits, synergies, and co-benefits. Through its longstanding scientific programs, USGCRP will continue providing

the underlying science for areas such as drought, heavy precipitation and flooding, which also support the President's Climate Action Plan. Such efforts will draw on observing and modeling capabilities discussed under Objectives 1.3 and 1.4, and indicators of change intended for use by decision makers (see Goal 3). Such science will also contribute to science needs identified in Federal Agency Climate Change Adaptation Plans, such as science needs for water-resource management (see Chapter II, p. 15–22).

Science to Inform Adaptation Decisions

In addition to its ongoing work to observe and project near- and longer-term climate change to which society will need to adapt, USGCRP research will include the areas outlined below.

Models for Decision Making. Decision makers often need climate change information in a regional context. While general circulation models provide foresight into future climate conditions, they do not account for this more localized context. A range of statistical and dynamical modeling techniques have been developed, collectively termed "downscaling," to bridge the gap between processes and scales simulated by global models and information needs for finer-scale changes. The USGCRP member agencies are providing leadership to the rapidly expanding effort in downscaling by fostering research evaluating the efficacy of these techniques and clarifying best practices for choosing appropriate datasets. They are also working to develop robust regional climate models that evaluate spatial scales down to a kilometer and temporal scales from intraseasonal to decadal (see Objective 1.4 and Chapter II).

USGCRP will continue, and accelerate, its focus on enhancing Integrated Assessment Models (IAMs) and Impact, Adaptation and Vulnerability Models (IAVs), and fostering their integration. These modeling approaches explicitly couple human and natural components of the Earth system, and can incorporate adaptation actions and their consequences. A community workshop framed a USGCRP roadmap for this effort (see Figure 15), which will use the IAM and IAV approaches together in the context of technology models for specific sectors and regional Earth

Figure 15: Developing a Coordinated Framework for Modeling the Interactions of Human and Environmental Systems

On May 24–26, 2016, USGCRP's Interagency Group on Integrated Modeling hosted a workshop to chart a path forward to make major advances in modeling the impacts of climate change, including the feedbacks of specific types of impacts on how quickly climate change will occur on the regional level. More than 50 participants from the Federal government, academia, national laboratories and private organizations participated, with discussions centered on approaches and options for a new modeling framework that combines different types of models, that include climate prediction systems, and risks and resiliency associated with water, energy, and other types of infrastructure. The group explored a new type of modeling design for eight different use cases in the areas of concentrated and connected infrastructure in a variety of geographic regions, and in particular for conditions when drought introduces variability and stresses involving water supply, land use, and demographic change.

For each use case, the participants explored user information needs, data requirements, appropriate model complexity and coupling approaches, modeling capabilities and gaps, and decision-support requirements. The workshop will inform interagency collaboration to further develop the framework, and explore common areas of interest on these and other use case and research topics.

System Models (e.g., for regional water cycles). This is a long-term challenge in building both modeling capacity and cooperation across distinct communities. The long-term focus of these efforts includes the ability to model multi-sector impacts and their economic and biophysical consequences; system and cascading system vulnerabilities; tradeoffs in complex dynamic systems; and implications and uncertainties for decision options. These advances will aim to better support assessments, scenario planning, and in general the co-production of usable information about future global-change risks.

Scenarios to Inform Planning. USGCRP is also focusing efforts on developing scenarios for possible future climate conditions and their impacts. Scenarios examine "if-then" situations, such as how global temperatures will rise over time if atmospheric carbon dioxide concentrations rise by a given amount. They can also be used to create "if-then" estimates of conditions such as future sea-level rise or changes in land use under specified rates and levels of temperature rise. These scenarios do not invoke the full complexity of climate models, but rather use a set of well-based assumptions to describe a family of possible future conditions. USGCRP is working to foster scenarios of the interaction of human population dynamics under climate change or plausible upper bounds for future sea-level rise and climate extremes that are not well captured by GCMs. Additional scenario needs include improved economic scenarios (e.g., avoided costs) and additional appropriate valuation metrics for planning and, ultimately, evaluation of adaptation actions.

Science Capabilities to Strengthen Decision Support

USGCRP will continue building on the observing and modeling capabilities discussed above to provide projections of key values such as sea-level rise; temperature and precipitation scenarios, changing trends in severe weather; and vulnerabilities of and impacts on social and ecological systems, at different scales of decision making. Easy access to agency and USGCRP indicators of change, intended for decision makers, will be an important element.

Regional Science Organizations. Research into the types of information people need, and how they use it in making decisions about responding to climate change, falls within USGCRP's purview. USGCRP will strengthen its interactions with the regional science organizations of its member agencies, which are often at the forefront of understanding regional needs—developing and using science for regional or local adaptation decisions. Research efforts that will be supported by USGCRP include understanding adaptive capacity and its governing factors, and developing methods for both prospective and retrospective evaluation of the efficacy of adaptation actions. Ongoing efforts include a focus on topics such as individual and institutional decision making under uncertainty.

Social-Science Research for Decision Support. Social-sciences research linked to climate-related global change is an important aspect of science for decision support. Through its Social Sciences Coordinating Committee (see Figure 16), USGCRP is convening Federal social scientists, and interacting with academic social scientists, to better define and address social-science research needs as they link to climate-related global change. The Coordinating Committee will host a meeting in 2016 with professional societies, aimed at identifying opportunities for integrating social and climate sciences, as well as obstacles. The latter include bridging the differences in scale between climate and social science, and the relative scarcity of datasets that

combine physical and social data in consistent and coherent ways. The USGCRP interagency priorities on Arctic Research and Resilience and Water-Cycle Extremes (see Chapter II, p. 15–22) include topics such as vulnerability and risk assessment, making them targeted opportunities for integrating the social sciences through agency activities and academic research.

Research areas of interest include adaptive learning, characterization of adaptive capacity of human-natural systems, and the role of social networks in collective decision making. Continuing areas of emphasis include economic research on responses to different economic stimuli and climate scenarios, and climate responses to different economic stimuli.

Figure 16: USGCRP and Social Sciences

USGCRP activities linking social sciences and global change include:

- Workshop on integrating Impacts, Adaptation, and Vulnerability and Integrated Assessment Models
- Framework for incorporating social sciences in NCA4
- March 2017 workshop with the social-science research community to identify actions that the USGCRP and its member agencies could take to enhance the effectiveness of Federal climate change activities
- Agency solicitations including social-science components in areas such as sustainability, food-energy-water systems, anticipating decision tipping points, and assessing the costs and benefits of action versus inaction in adapting to climate change

Science to Inform Mitigation Decisions

In December of 2015 in Paris under the United Nations Framework Convention on Climate Change, 195 countries adopted the first-ever agreement to commit all nations to some form of greenhouse gas emissions reduction or related goal (i.e., Nationally Determined Contribution, or NDC). The U.S. NDC is a 26 to 28% reduction in greenhouse gas emissions below 2005 levels, by 2025. The Agreement also contains the objectives of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." Furthermore, countries should "aim to reach global peaking of greenhouse gas emissions as soon as possible."

The implications of the Paris Agreement for USGCRP are still under discussion at OSTP, the Department of State, and among the SGCR members. The Program will continue to evaluate the implications of different emission pathways in terms of near-term and long-term risks such that both adaptation and mitigation decisions are properly informed by this research. USGCRP will also continue to contribute, as appropriate, to the reporting requirements on climate action (e.g., mitigation, adaptation, capacity building abroad, etc.), the details of which are still an area of active negotiation. The U.S. Government's implementation of policies supporting Paris Agreement objectives will continue to be undertaken by agencies both inside and outside of USGCRP.

Models for Mitigation Science. The discussions above on modeling and science for decision support apply equally to adaptation and mitigation decisions. In terms of mitigation, USGCRP will expand efforts to assess what levels of broad-scale mitigation are necessary to avoid a range of adverse outcomes in the United States. Key needs here are clear assessments of the extent to which risks can be avoided or managed over longer time frames, by nearer-term mitigation actions. Another desired outcome is the identification of risks that are unlikely to be avoided in the short-term by immediate mitigation actions and would, therefore, require

adaptation responses. Other outcomes include evaluation of the potential need for additional emissions mitigation as a consequence of natural releases of greenhouse gases and albedo change due to climate change, and assessing the implications, in terms of adverse impacts avoided, of expected greenhouse gas reductions from a range of significant mitigation levels. NCA4 will include an assessment of emerging model results and their implications for mitigation, together with an analysis of research needs emerging from the assessment.

Carbon Cycle Research. Core collaborative scientific research arms of USGCRP, such as the North American Carbon Program, are augmenting interactions among physical scientists, economists, and decision makers, significantly advancing the science for mitigation. Consequent innovations in technologies, research and monitoring networks, and theoretical approaches to understanding the dynamics of greenhouse gases will further facilitate the applicability and transferability of carbon cycle science—enabling enhanced coordination and communication among researchers, decision makers, and data managers across the United States, North America, and the world. For instance, USGCRP's U.S. Carbon Cycle Science Program collaborated with the European Union Coordination Action on Carbon Observation Systems to establish the mean carbon balance and change over the period 1990–2009 for all continents and ocean basins (Regional Carbon Cycle Assessment and Processes activity with the Global Carbon Project). Such collaborative development and utilization of advanced remote (e.g., satellite, LiDAR) and *in situ* observations and modeling of atmospheric carbon dioxide, methane and other greenhouse gases is improving understanding of U.S. and global emissions across natural and built environments, for scientists and decision makers.

These approaches are also used to investigate natural and human-assisted sequestration of carbon in biological (e.g., soil, forests, coastal wetlands) reservoirs, and the resultant capacity for long-term carbon removal from the atmosphere. In general, improved process knowledge with respect to carbon cycling on land, in water, and in human systems is needed, including an improved understanding of how carbon moves through and is transformed within these systems, how to keep carbon within these systems for the long-term, and how to quantify "lateral flux" losses. For example, there is a rising recognition that carbon in coastal ecosystems, as well as other biological landscapes and oceans, needs to be better understood. There is limited data availability and data quality for coastal carbon distribution, properties, and processes. Coastal wetland processes, which are key drivers of land-ocean carbon exchanges, will need to be further investigated. In addition, urban areas are responsible for up to 76% of humans' carbon dioxide emissions, but much uncertainty remains regarding how these urban contributions are regionally distributed and connected with rural emissions.

The integrated scientific understanding of natural and human-induced mitigation across land, water and human systems—incorporating carbon cycle dynamics, carbon sequestration, and associated human interactions—is gaining momentum via research coordination undertaken by the U.S. Carbon Cycle Science Program, under the auspices of USGCRP. Examples include the Science Plan for Carbon Cycle Research in North American Coastal Waters, released by the North American Carbon Program and the Ocean Carbon & Biogeochemistry Program, ongoing interagency research funding activities, the ongoing development of the Second State of the Carbon Cycle Report and collaborative science facilitation on pertinent topics such as on soil carbon vulnerability and resilience.

Methane Cycling. The science framing for USGCRP's methane priority is discussed under Objective 1.1. In planning and implementing this priority, USGCRP is working closely with the Office of Science and Technology Policy (OSTP)-convened interagency group on Methane Measurement Science and Technology. This group includes a number of USGCRP member agencies, and will have an emissions measurement orientation while USGCRP retains its basic research orientation. The USGCRP methane priority does include an emphasis on enhancing estimates and projections of methane emissions, inventories, radiative forcing and attribution, and evaluating and characterizing anthropogenic methane emissions, all with implications for informing mitigation strategies. As noted above, USGCRP modeling capabilities will be used to evaluate the potential climate effects of mitigation trajectories, including for methane.

Urban Opportunities for Science for Mitigation. Dense populations, community-wide planning, and large collective carbon footprints in and from urban communities make them a natural focus for mitigation actions. Rising interagency and private sector focus is driving research on reducing emissions from natural and engineered infrastructure while simultaneously increasing resilience to natural disasters and future climate change via place-based, large-scale adaptation measures. The USGCRP agencies, in cooperation with the Executive Office of the President, have initiated efforts to improve estimates, observations, and projections of carbon emissions and stocks. Multiple areas of improvement are needed including better quantifying and understanding underlying carbon cycle processes and sequestration at the urban scale, and translating these into global-scale anthropogenic flux estimates within a truly integrated research sphere that includes the natural, social, and engineering sciences. Viewing urban areas as whole systems is vital to informing decisions that build preparedness and resilience. USGCRP is catalyzing such efforts through its working groups and their coordination with related Federal efforts. Examples include extending carbon cycle science and advancing measurement approaches to determine urban carbon stocks, research using urban test beds to develop and integrate fine-scale air sampling and greenhouse gas measurements with models, and interdisciplinary research into the dynamic interactions between humans and natural ecosystems in urban settings.

Navigating Challenges

Challenges to Inform Adaptation

The rapid growth in user demand for climate data at high spatial (e.g., city scale) and temporal resolution often challenges the scientific community's ability to provide robust and rigorously-downscaled information. Indeed, the climate community lacks consensus on how to consistently evaluate across GCMs and downscaling approaches for applicability and uncertainty when used for decision making. Providing users of USGCRP science with guidelines and recommendations for use of climate data is a major challenge. USGCRP includes this research challenge in its plan for enhancing core capabilities in modeling and prediction (see Chapter II, p. 15–22). As noted above, the Program will also support the development of less complex models and scenarios for decision making. With a focus on high-resolution data, research will continue in quantifying uncertainty across multiple temporal and spatial scales, to help decision makers understand the limits to the models and datasets.

Drawing from agency programs that quantify uncertainty across multiple time and distance scales and work to improve uncertainty estimates for different models, USGCRP working groups will aim to provide a more cohesive overview of model uncertainties and their implications for decision making. Along with its coarser-scale global models, the Program will continue to develop finer-scale products such as downscaled climate projections, water quantity forecasts, land-use change model outputs, and make it available via a range of approaches such as toolkits with reliable information about their applicability to a variety of temporal and spatial scales, including major river basins. USGCRP will provide guidance in the use of select high-resolution products (Goal 2). Educational and communication efforts (Goal 4) will emphasize the scientific meaning of "uncertainty" in their use.

A number of USGCRP research areas—such as understanding the interplay of multiple stressors (natural and human) and the potential impacts of climate system tipping points on social systems—require closer integration of social, natural, and engineering sciences. Although member agencies do provide funding opportunities for human dimensions of global change, systematic incorporation of the social sciences into appropriate parts of USGCRP research remains a challenge. Although some progress is being made (see Figure 16), continuing progress in this area is important to the Program, which will continue to work with the National Academies of Sciences, Engineering and Medicine and the member agencies to identify high-priority areas of global-change science as opportunities for longer-term integration of natural and social systems. These areas will aim to incorporate research from the growing cadre of trans-disciplinary early-career scientists interested in working at this interface.

Informing adaptation actions remains a very challenging research area, given the long response time of the climate system to perturbation. USGCRP, with its Social Sciences Coordinating Committee and Adaptation Science Working Group, will work to strengthen its portfolio in decision-support science. Research may include the development of a decision-support framework to inform adaptation decisions and evaluate adaptive capacity, decision-support tools and adaptation activities. This critical information will help provide a means to assess the progress and potential effectiveness of adaptation measures.

Challenges to Inform Mitigation

For mitigation, the Program will need to strengthen its interactions with Governmental programs outside of USGCRP, such that the Program's science and capabilities inform their work in areas like policy development and mitigation technologies. The Program will work to identify research needed to understand interactions between mitigation activities and the underlying processes of Earth system behavior. The monitoring, reporting, and verification of emissions, conducted by agencies to evaluate the impacts of mitigation approaches can be enhanced through spatial and temporal precision across multiple geographic scales within and beyond the United States. Multiple data streams (e.g., satellites, inventories, societal indicators, process models) can be included and harmonized to optimally constrain estimates of carbon fluxes on land, in oceans, and connecting surface waters. National and international cooperation using observational and modeling platforms will assist USGCRP in addressing and informing the implications of different mitigation pathways.

USGCRP's research program provides insight into the science needed to understand potential pathways for climate intervention or geoengineering and the possible consequences of any such measures, both intended and unintended. The SGCR considered since the 2012–2021 Strategic Plan how to develop its research stance with respect to climate intervention. The Program's evolution is informed by the National Research Council reports *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration* and *Climate Intervention: Reflecting Sunlight to Cool Earth*, which noted the importance of laying a science and governance foundation that would allow potential future experiments to be conducted in ethical and responsible ways. They highlighted a role for USGCRP in coordinating research, particularly in the area of carbon removal and storage. While climate intervention cannot substitute for reducing greenhouse gas emissions and adapting to the changes in climate that occur, some types of deliberative climate intervention may someday be one of a portfolio of tools used in managing climate change. The need to understand the possibilities, limitations, and potential side effects of climate intervention becomes all the more apparent with the recognition that other countries or the private sector may decide to conduct intervention experiments independently from the U.S. Government.

An immediate next step for USGCRP is defining the scale and scope of observations and modeling capabilities necessary to detect the signal of any future field experiments above baseline conditions and natural variability, and to evaluate their consequences. Such research would also define the smallest scale of intervention experiments that would yield meaningful scientific understanding. USGCRP will use its scientific understanding of natural processes, such as natural carbon sequestration or dynamics of atmospheric particulates, to inform potential pathways for carbon removal and albedo modification. Approaches would include evaluating the capabilities of current models to represent any proposed climate intervention measure and to evaluate its implications over time, using natural events as intervention analogs (such as volcanic eruptions that inject large particulate loads into the atmosphere), and laboratory experiments.

Objective 1.3: Integrated Observations

Maintaining Directions

Integrated observations are a core capability for USGCRP (see Chapter II, p. 15–22) and are foundational to all aspects of the Program. The Program reaffirms the importance of sustaining and strengthening integrated observations of the natural and human systems involved in climate-related global change. Observations are essential to advancing integrated Earth system science and for undertaking and evaluating risk management and response. The Program promotes the deployment of observations at various spatial and temporal scales through remote sensing, *in situ* networks, and combinations thereof, including via field campaigns. Such integrated observations also contribute to global-change monitoring and assessment efforts of national and international significance. USGCRP will continue to advance the observational goals of the 2012–2021 Strategic Plan, including in the areas highlighted below. It should also be noted that many observations critical to USGCRP research are conducted by parts of agencies that are not formally part of USGCRP.

Building on Progress

New observational assets and the advances in temporal, geographic, and vertical coverage they provide will enable the Program to build on recent progress, answer more science questions, and pose new ones. Recently launched and planned U.S. Earth science satellite missions will fill some of the observational gaps identified in the 2012–2021 Strategic Plan, providing key observations of the global distributions of atmospheric carbon dioxide, ocean salinity, precipitation, and soil moisture. The improvement *in situ* observations will address needs for more comprehensive and higher-quality sampling, complement and validate satellite information, constrain and validate models, and provide insight into critical processes leading to improved modeling and prediction capabilities. (Note that, except in a few areas, critical *in situ* capabilities are deteriorating, as discussed under "Navigating Challenges" below). Improvements will also facilitate more complete global sampling to validate satellite measurements in locations such as deep oceans and the poles, which can be more difficult to cover with traditional remote sensing methods.

Figure 17: Observational Field Campaigns

USGCRP's coordinated multi-agency field campaigns bring together different observing assets (e.g., satellites, airborne platforms, ships, mobile labs, fixed *in situ* systems) to understand major climate-change processes using shared observations, datasets, and models. Some recent examples include:

- Monitoring the warming of Arctic ocean waters and their effect on the stability of the Greenland ice sheet (OMG)
- Understanding cloud processes linked to aerosols and atmospheric rivers, especially how they impact precipitation in the Western United States (CalWater-2/ACAPEX)
- Improving the use of satellites and models to measure pollutants at various heights in the atmosphere, for public health and environmental benefit (DISCOVER-AQ)

Integrated satellite and non-satellite datasets offer great promise, but are institutionally and disciplinarily challenging. For example, the longer records of paleoclimate data and the shorter records of satellite observing systems (see Objective 1.1) are largely interpreted by scientists who have deep expertise in one but not both observational approaches, making robust record integration a research area in its own right. Multi-agency field campaigns (see Figure 17) aim to accelerate progress in topics like natural climate variability and teleconnections; cloud and aerosol processes; coupled ocean-atmosphere processes; and carbon cycle processes. By their very nature, field campaigns tend to be local and temporary, while other ground-based assets may be global and deployed over long time periods. Effective communication pathways between scientists engaged in short-term field campaigns and those using sustained large-scale observing system programs/networks will be critical to sharing information on observing system requirements across diverse spatial and temporal scales and frequencies. For instance, USGCRP will build upon emerging and existing long-term *in situ* research to further advance comprehensive observations of ecosystem processes, changes, and interactions with human and natural systems.

Autonomous Platforms. Advances in autonomous platforms, such as Unmanned Aerial Systems (UAS) and Autonomous Underwater Vehicles (AUVs), and their sensors are opening up new observational and scientific opportunities. Observing system planning should include evaluation of new technologies, including miniaturized sensors, to identify opportunities to

augment current capabilities or inform their redesign, and to take advantage of more economically feasible approaches. As an example, current and emerging AUV technology, such as Deep Argo floats and deep-sea gliders, is enabling wide-ranging ocean observations at depths below 2000m, advancing understanding of ocean-atmosphere interactions. In addition, there have been recent demonstrations of the utility of UAS platforms, including rotorcraft and small fixed-wing aircraft for making routine atmospheric and terrestrial observations, with large fixed-wing aircraft being used for long-duration (24-hour) flights. Despite the growth in opportunities resulting from the proliferation of UAS, there are significant operating hurdles for them due to operational restrictions. It is not yet clear whether it will become easier or more difficult to operate UAS for scientific purposes.

Small Satellites. Recent advances in sensor and spacecraft technologies make it feasible to obtain key measurements from small, low-cost satellite missions. CubeSats, a type of nanosatellite, represent a low-cost pathway for space-based research, and their small size and weight allow them to "ride-share" with already-planned launches. USGCRP agencies are supporting CubeSat development (including as an educational opportunity) and have incorporated them in about 50 launches, with more planned. For example, NASA is planning to deploy a constellation composed of eight nanosat observatories to measure hurricane surface winds, and will use sounding instruments mounted on twelve CubeSats flying in formation to study the development of tropical cyclones through a multi-agency science program.

Integrated Observations and Models. Integrating observational data and model outputs is allowing the development of new information products. USGCRP agencies are supporting improved finer-scale, gridded reanalysis products incorporating atmosphere and ocean data are enabling investigations of climate variability and change. For example, MERRA-2 is a long-term global reanalysis, assimilating space-based observations of aerosols to represent their interplay with other physical processes in the climate system, while the NCEP/NCAR Reanalysis represents the state of the Earth's atmosphere, incorporating observations and numerical weather prediction model output from 1948 to the present. Various improvements in reanalysis techniques (e.g., the representation of inter-annual variability of the atmospheric state, or advances in the quality of stratospheric wind fields) enable analyses at finer scales using new observations and data assimilation approaches. Ongoing efforts are needed to evaluate the strengths and limitations of these reanalyses and to identify opportunities to make improvements. Moving forward, USGRCP will expand reanalyses to include land, ice, and biogeochemistry datasets. USGCRP will advance a strategy for integrated Earth system analyses to obtain optimal state estimates of the full Earth system to study interaction among its different components, and to assess the ability of fully coupled approaches to provide more internally consistent estimates. Furthermore, the emergence of current and planned global observational capabilities (such as the IceSat-2 (ice, cloud, and land elevation), Landsat 8, and Orbiting Carbon Observatory 2 satellites), when combined with existing observations and models, will enable new land, groundwater, ice, and carbon synthesis datasets to improve monitoring of drought and changes in land and sea-ice, and carbon budget tracking.

Identifying Gaps in the Climate Observing System. Advancing scientists' ability to address clearly articulated, testable scientific hypotheses is central to the country's ability to plan for, and respond to, the impacts of climate-related global change. Doing so will require advances in observational capabilities and improved integration of existing capabilities. This includes bridging

gaps between, for example, *in situ* and remotely sensed observations, and between models and observations. The opportunity exists to study, modify, and apply approaches that identify and evaluate observational requirements for addressing particular climate and global-change scientific-societal questions, particularly in USGCRP priority areas such as water-cycle extremes, perturbations to the global methane cycle, and climatological and ecological tipping points in the Arctic. Such approaches would identify key questions within the topic areas, measurements essential to answering the questions, and the observing system characteristics (e.g., sensor distribution, measurement frequency, precision, and duration) needed for robust answers.

Leveraging International and National Partnerships. USGCRP and its member agencies will continue to leverage numerous bilateral and multilateral international partnerships (see Chapter IV for more specific information on international partnerships), providing highly productive avenues for coordination and cooperation on both satellite and non-satellite observations. These partnerships reap the research benefits of global networks with relatively small USGCRP investments. Partnerships, including joint field campaigns, are important components in furthering observing systems worldwide. With increased data-sharing amongst nations for observing assets such as satellite systems or ocean observing networks, the United States gains access to vastly improved data sources. Discussions with the Arctic nations during the current U.S. chairmanship of the Arctic Council aim to foster Arctic observational capabilities, and strengthen existing partnerships, such as Argo, to support their expanded roles. USGCRP also works closely with other groups under the Committee on Environment, Natural Resources and Sustainability, such as the U.S. Group on Earth Observations, Subcommittee on Ocean Science and Technology, and the Interagency Arctic Research Policy Committee, to ensure coordinated observations in research areas such as the ocean's role in climate and change in the Arctic.

Lastly, there is a particular need to continue U.S. leadership in ocean and cryosphere observations since these are inherently global yet particularly important to U.S. climate observations.

Navigating Challenges

The U.S. climate observing system faces significant challenges. Many of the observation systems essential to understanding the physical climate system are aging or have reached the end of their designed life expectancies. Often, these climate-quality observations are made by research satellites, which have finite lifetimes and typically have no planned U.S. follow-ons. These include systematic measurements of aerosols, for which the lack of a follow-on could result in a gap in crucial data streams. Some polar wind measurements and surface wind observations are also at risk due to the deteriorating quality of surface wind monitoring stations. The continuity of profile ozone observations (vertical ozone distribution) is needed to understand its long-term change in response to reductions in ozone-destroying substances mandated by the Montreal Protocol. Atmospheric limb sounding of the lower stratosphere, which provides global coverage of vertically resolved information on many key atmospheric constituents important to climate studies, also faces a potential gap. Precipitation observation systems, which are important for understanding climate drivers and impacts, are key for all nine GEOSS Societal Benefit Areas. The U.S. stream-gauge network is another crucial, near-term risk in the continuity of essential observations. The network was developed for other purposes (e.g., flood monitoring, water use), but is essential for climate observations. Additionally,

the USGCRP agencies are utilizing existing observation capabilities of many types for periods longer than for which they have been designed.

Sustaining critical observations is a persistent challenge for the Program, which is using strategies including those below to partially address the problem. The USGCRP agencies are participating in a number of studies aimed at identifying critical observing needs and gaps. These include the forthcoming National Academies' second decadal survey of Earth Observations, which aims to: assess progress in addressing the major scientific and application challenges outlined in the 2007 Earth Science Decadal Survey; develop a prioritized list of high-level science and application objectives; and recommend approaches to facilitate the development of a robust, resilient, and appropriately balanced U.S. program of Earth observations from space. The agencies are also working with the U.S. Group on Earth Observations on its second Earth Observations Assessment. The assessment will evaluate current U.S. Government non-classified observing systems to foster coordination and maximize scientific and societal benefit, and therefore inform future mission design and scope, taking into account data management implications (see Objective 1.5). The USGCRP Integrated Observations Interagency Working Group enhances awareness of extant, nascent, and upcoming observing capabilities, including in selected topical areas, such as for methane observing. The Program will both contribute to the prioritization efforts and incorporate their results into its science planning and prioritization.

Collaboration opportunities for observations exist with defense agencies, the private sector, international entities, and non-governmental organizations. Such collaborations have both strengths and limitations, but overall represent an opportunity for enhancing observational capabilities. The Program is in the beginning stages of exploring such collaborations for increased observational capacity and efficiency, as well as for data sharing. Public-private collaborations offer the opportunity to leverage resources toward common goals, via sharing of data and expertise. They also carry the risk that a private partner may decide to terminate an observing program for business reasons; any specific actions with non-governmental partners would need careful consideration with regard to benefits, recognizing the need for continuity in measurements.

Observations and data management are inextricably linked. A major challenge for the future is in overcoming differences in data and metadata standards for existing data, and fostering adoption of consistent standards for new data. Expanding upon and sharing best practices in current USGCRP agency data management and data sharing activities, and enabling access to currently restricted data, is one avenue for addressing this challenge (see Objective 1.5). Additionally, there are multiple portals that provide data in many formats and different spatial and temporal resolutions, designed to best meet original user needs. Coordinating across the portals in cost-effective ways that meet wider user needs remains a challenge. Potential leveraging opportunities of various kinds are possible, including for measurements of precipitation, winds, clouds, ozone and its precursors, greenhouse gases, soil moisture, and ocean acidity.

Using Earth observations to address societal needs both enhances the relevance of the observations and improves society's resilience to changes in the Earth system. To more fully realize this goal, the efforts of USGCRP agencies to collect, store, and deliver observational data in ways that meet both societal and scientific user needs must be expanded. USGCRP provides an effective venue to systematically engage end users in a sustained and structured way to obtain requirements that inform Earth observations system development and operation.

In addition, USGCRP must determine how best to integrate or otherwise connect with socio-economic, demographic, and other non-traditional data sources needed to understand the emerging societal challenges. In particular, the climate and health community is poised to tackle this challenge by working closely with its academic, user, and observation communities to institutionalize a process for regularly collecting and communicating observational requirements for health needs. In addition, observations relevant to vulnerable communities and necessary for environmental justice are often missing, and efforts need to be enhanced to collect these data and observations. Citizen science can help to systematically collect and analyze data and plays a growing role in scientific endeavors. A catalog of Federal involvement in citizen science efforts is available at www.citizenscience.gov.

Objective 1.4: Integrated Modeling

Maintaining Directions

USGCRP's work in predictability and integrative modeling is a core capability, i.e., essential for the success of the USGCRP thematic priorities (see Chapter II, p. 15–22), and the Program as a whole. A goal for the USGCRP modeling enterprise is to further improve projections, extending to spatial scales as fine as 10-50 km, and time frames shorter than growing seasons, to complement the decadal to centennial scales normally used by the climate community. With this expansion of time scales, decision making for a wider range of societal challenges will be possible. Another component of this core area is the more active development of a new class of assessment capabilities, based on a combination of Integrated Assessment Models and Impact, Adaptation, and Vulnerability models at regional scales (see Objective 1.2, Models for Decision Makers).

Sustaining the scientific emphasis on improving all scales of models relies heavily on participation across the modeling community (e.g., modelers working on processes including weather, energy, air quality, hydrology, agriculture, etc.) to maximize collaboration, co-develop models, and coordinate integrated research, traditional roles that USGCRP will continue to play. USGCRP continues to foster deeper exploration of the nexus between multiple factors that impact decision making, such as the tradeoffs among energy, water, and agriculture. Such model development and validation requires strong integration between observational sciences, improved science understanding, and enhanced knowledge management, which the Program will continue to foster.

Building on Progress

USGCRP will continue to advance the objectives of 2012–2021 Strategic Plan in this area. Some specific areas for capacity building, highlighted below, better position the Program to address priority areas such as extremes, thresholds, and tipping points. USGCRP's annual Climate Modeling Summit provides an important new venue for making coordinated progress (see Figure 18).

Spatial Resolution. Increased computational capabilities permit continuing improvements in the spatial resolution in global models. These, in turn, allow incorporation of new, finer-scale physics and geographic features. Incorporation of smaller scale processes, such as

atmospheric turbulence and deep convection, to improve model realism, is now on the verge of permitting better representation of extreme weather, which will improve capacity to understand and project extreme events. This will be an important area for USGCRP in the future. Improving model representation of the interactions between geographic features such as mountains, coastlines, or water bodies and the atmosphere is critical to skillful projecting of important phenomena, and will allow exploration of the potential of these dynamic projections to support decision makers at more local scales. USGCRP is already working across its Interagency Working Groups to plan how best to capitalize on these and other improvements that will allow for rigorous regional and local models and to develop evaluation techniques for them, along with the more available statistical downscaling products, to better understand their utility for decision makers.

Figure 18: USGCRP's Climate Modeling Summit

As recommended in a recent National Research Council report, USGCRP has convened the first two annual meetings of the six modeling centers supported by the USGCRP agencies. The Summits have:

- Identified areas of cooperation and unique contributions across the centers
- Adopted practices for significant improvements in efficiency, value, and capability of climate models
- Identified important areas of need for computing infrastructure improvements and for modeling advances, including gaps in physical climate models and seamless predictions at weather-to-climate time scales
- Planning for a meeting focused on models for decision makers, including development of a new class of finer resolution assessment capabilities that bring together Integrated Assessment and Impact, Adaptation, and Vulnerability Models
- Recommended increased and coordinated interaction with climate model stakeholder communities

Temporal Resolution. Increased computational resources, observational assets, and deeper understanding of climate dynamics have led to the prospect of improved capability to forecast longer-term weather and climate anomalies a few weeks to a few seasons ahead of time. USGCRP is working to leverage improved understanding of key phenomena to develop and test multi-model systems that explore forecasts for conditions such as drought, atmospheric rivers, and the El Niño/Southern Oscillation. Success in this area would enhance planning capabilities in sectors such as agriculture and water-resources management.

Model Intercomparisons. The field of model intercomparison has recently expanded—from its role as an experimental protocol for global general circulation models (Coupled Model Intercomparison Project)—to a greatly expanded suite of topically-focused Model Intercomparison Projects (MIPs). Among the ongoing MIPs is AgMIP, which studies agricultural response to climate change, and Obs4MIPs, which facilitates model data comparison with observational datasets. The MIPs all drive new understanding in Earth system science, assess how different approaches add realism to model representations, and develop appropriate metrics. USGCRP will continue to foster these efforts to build on progress in linking the climate community with experts on components of the natural or human systems. This includes agriculture, where deep knowledge exists about responses of crop plants to current conditions, to gain foresight into responses under future climate conditions.

Integrated Modeling and Observations. Recently observed changes in the Earth system are driving new research efforts by USGCRP-funded scientists to improve understanding of the

underlying mechanisms. The dramatic decline in Arctic sea ice, the mass loss and surface melting of ice sheets in Greenland, and instability of West Antarctic ice sheets, are unsettling examples of changes observed by satellite systems. Declines in the annual minimum Arctic sea-ice extent and the apparent decadal climate variability (see Objective 1.1) are two additional examples where improved understanding is needed to capture knowledge for improving models. USGCRP's ability to detect these phenomena reflects strong observing capabilities, but also its capacity to coordinate and combine research to improve understanding of the underlying physical processes that leads to the skillful modeling of critical parameters. The improved mechanistic understanding of interconnected phenomena with different characteristic spatial and temporal scales helps bridge scales, leading to improvements in global models. USGCRP is capitalizing on improved observational assets and the detection and attribution techniques being developed in the science community, to build deeper understanding into the integrated modeling framework. It will also emphasize the use of new observational data and reanalyses (see Objective 1.3) to improve model representations.

Earth and Human Systems. USGCRP efforts are enriching models that better capture both human and Earth system components (see discussion of integrating Integrated Assessment Models and Impacts, Adaptation and Vulnerability models in Objective 1.2). Recent progress is also motivated by domestic and international mitigation actions. New observations (such as for global carbon) and modeling efforts, to understand progress by nations reporting under the United Nations Framework Convention on Climate Change requirements, are already improving modeling of carbon storage sinks and sources, which can be used to inform decision making. The USGCRP agencies have continued to explore and make progress in addressing the economic implications of mitigation in models (e.g., benefits of mitigating emissions, avoided costs of climate change) and build cohesive frameworks to explore economic costs within the context of the CMIP5 ensemble[3], as the scientific community continues to build Shared Socioeconomic Pathways that complement the existing Representative Concentration Pathways (RCPs). USGCRP supports efforts underway to advance energy and land-use models relevant to global change scenarios, analyze climate impacts on human systems (such as weather extremes) under different RCP scenarios, and build on work in behavioral modeling. Recent USGCRP workshops on demographic and land-use scenarios are leading to efforts across agencies to align land-use/land-cover modeling efforts and deliver findings to decision makers. Another example of recent progress across USGCRP is the collaboration between human health and climate science modeling evidenced in the recent report *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* that was developed as part of the sustained-assessment process (see Goal 3).

Navigating Challenges

Clear progress has been made across the Federal modeling enterprise as USGCRP adjusts to the changing landscape—from increasing computational capacity, to improved scientific understanding, to responding to startling new discoveries. Still, challenges remain to be navigated in the near-term. Fuller integration among models of human systems is needed to assess tradeoffs in many cross-sectoral areas, such as between energy, water, and land use. Other aspects of global change, such as pollution and human population, increase along with a changing climate. Coupling models of human systems (e.g., agriculture, land-use change)

[3] The World Climate Research Program's Coupled Model Intercomparison Project.

and natural systems remains difficult, and modeling advancements are needed to improve the understanding of multi-dimensional interactions within and between human and natural systems. For instance, USGCRP efforts to deepen the interplay between Earth System and Integrated Assessment Model communities are underway to better constrain the decision space for mitigation and adaptation. The community is also challenged to support the numerous MIP activities, including coordinating with international efforts for the forthcoming Intergovernmental Panel on Climate Change Sixth Assessment Report. Improved characterization of uncertainty for decision making calls for increasing the transparency of model assumptions, enhancing model reproducibility, and developing a capacity to characterize model integrity. Decision makers are demanding clear guidance on best practices for use of climate model outputs, such as downscaled climate data, requiring USGCRP leadership in clarifying how to scientifically assess climate models and the quality of downscaling techniques.

Objective 1.5: Information Management and Sharing

Maintaining Directions

Since 2012, there have been continual increases in availability, volume, variety, and storage capacity of global change data. Simultaneously, curation methods and practices have improved and the USGCRP agencies have continued to build capacity to store and serve global-change data. These increases will continue and likely accelerate with the addition of new satellite and *in situ* observing capabilities. Most of these data are now available online, and web-based services allow researchers, decision makers, and other users to obtain data tailored to their needs. The USGCRP agencies will continue to support improvements to curation methods and practices to enhance scientific investigations and transparent information sharing consistent with the Information Quality Act, emphasizing a "high degree of transparency about data and methods to facilitate reproducibility of disseminated scientific information."

Figure 19: Climate Data and Tools

Launched in 2014 in support of the President's Climate Action Plan, the Climate Data Initiative (CDI) and the Climate Resilience Toolkit (CRT) are overseen by the Climate Data and Tools (CDAT) Interagency Working Group of the President's Council on Climate Preparedness and Resilience. USGCRP agencies participate on the CDAT Working Group, help lead the development efforts and contribute data and tools to both CDI and the CRT.

The USGCRP agencies have continued to integrate across networks to provide improved access and interoperability, a process greatly enhanced by the Climate Data and Tools effort (see Figure 19).

Topic-specific portals bring together information from multiple agencies, as well as from non-Federal sources, to address important community-specific needs such as drought or sea-level rise. Efforts such as the Hurricane Sandy Task Force, which brought together Federal, state and local agencies, demonstrated how improved data access and interoperability enable communities to adapt to climate-change challenges. The USGCRP agencies have continued to integrate across networks to provide improved access and interoperability, a process greatly enhanced by the Climate Data and Tools effort (Figure 19). Such Federal efforts complement and

enable regional and local efforts to understand and address current and future global-change impacts (see Goal 2 for discussion of the web-based Resilience Dialogues, conducted through a private-public collaboration).

USGCRP agency and interagency portals will continue to provide information in multiple data formats for both scientific and non-scientific stakeholders. Users will continue to have the ability to customize information to their needs by putting more emphasis on application and interactivity rather than data pre-processing. The emergence of multi-agency data portals and cross-publishing of datasets from multiple portals will foster the development of tools that tap into common data sources for stakeholder convenience. Additionally, interactive, web-based maps will continue to provide "on the fly" visualization capabilities that do not require end-user processing. To enhance the discoverability and user experience of existing Global Change Information (GCI) products and tools, USGCRP established a GCI Interagency Task Force in 2016. The Task Force will conduct surveys on the GCI user experience, using the results to leverage Federal interagency coordination of GCI activities, and with the goal of understanding how to make data, products and tools provided to inform adaptation and mitigation decisions more responsive to user feedback.

Building on Progress

Data Volume. Technological advances continue to increase the ability to capture, aggregate, and process an ever-greater volume and variety of data. The USGCRP agencies will continue to take the lead in addressing this growing data volume challenge by maintaining, expanding, and evaluating existing collaborative, virtual, data-sharing environments and portals. New and innovative ways to do so, such as data alliances, partnerships, remote data access, and research agreements, have made large collections of global change and Earth science data from the USGCRP agencies available through cloud computing environments. Computational environments that can efficiently process big data volumes with high input and output demands are critical for reprocessing large datasets from multi-sensor observing systems. Such reprocessing is a key to the seamless integration of observing system datasets with minimum time-dependent biases for comprehensive monitoring of the Earth's changing environment.

Enhanced Data Discoverability, Integration, and Interoperability. USGCRP is building on advances in information management and sharing, including the Global Change Information System (GCIS) to increase scientific data discoverability, integration, and interoperability. GCIS is an open source, web-based resource developed by USGCRP that provides structured links between global-change information resources. Following the initial release of GCIS in support of the NCA3 and the USGCRP website GlobalChange.gov in May 2014, the structured provenance data in GCIS has been used by the global change community as a resource to understand how data and resources are connected. GCIS supported the development and April 2016 release of *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* and is key foundational infrastructure for the sustained-assessment process, including a climate-change indicators pilot (see Goal 3). These enhancements are being made for both traditional physical science datasets and social and economic data needed to assess the vulnerability of individuals and communities to climate-related global changes. Extending GCIS beyond assessments into other areas of the Program will help tie various agency efforts together. In particular, the USGCRP member agencies are developing databases of stakeholder

needs and details of their adaptation and mitigation projects, efforts, experiences, and best practices to support decision making. GCIS will be further developed to allow users to access this information from a central site, linking multiple agencies and tracing the connections from observations, models, and research to decisions.

The USGCRP member agency efforts are improving discoverability of global-change data and the integration and interoperability of data management systems through the use of advanced technological and computational capabilities (e.g., EarthCube geoscience data management and access cyber-infrastructure). USGCRP efforts to improve discoverability and usability of earth observations data held by its member agencies require coordinating assessments, data management, and planning across the agencies, and fostering international collaboration. The Program will continue to promote this coordination and build upon existing efforts. These include the draft Common Framework for Earth Observations Data by the U.S. Group on Earth Observations, and work being done under the Big Earth Data Initiative to enhance discoverability and interoperability of Federal Earth observations, data, and information products.

Navigating Challenges

There has been significant progress in documenting the methodologies for data collection and agency metadata practices that enhance reproducibility and enable discoverability. However, further improvements in widespread consistency on best practices are needed, such as standard, adequate citation of datasets in peer-reviewed publications to ensure their information is readily available. Data management plans, although required by many agencies, may be incomplete and lack incentives for full implementation. The need for consistent, well documented and readily available, climate-relevant datasets, including social-science datasets, extends beyond USGCRP agencies. The USGCRP agencies will continue to work with their internal and externally-funded scientists to share best practices and motivate compliance with agency data policy.

Progress has been made toward standards (e.g., the Obama Administration mandate on machine-readable data formats), but further work is needed to create a culture of data identification featuring persistent, resolvable identifiers and documentation, with machine-readable metadata. USGCRP will continue to demonstrate the value of metadata development and documentation, encourage scientists to comply with existing policies, and work with universities, journal publishers, and data archives to facilitate these efforts. To encourage traceability, many USGCRP agencies will continue to develop better practices of documentation and identifier creation for datasets.

Both researchers and decision makers need to combine model datasets with observational datasets to better understand global change and its impacts. Agency data centers (or portals) can help by continuing to provide guidance to users on how one type of data can be used with another (e.g., integrating model data with observations). Providing this kind of guidance will require working with researchers and decision makers to capture recommended approaches for combining and harmonizing these data for specific applications, including conveying the uncertainty in the combined products. In addition, more tools, application-specific portals that include both model and observational data, and blended (i.e., assimilated) datasets may be needed.

Looking forward, USGCRP must leverage high capacity and cloud computing to continue to serve global change observation and modeling outputs. Cloud computing can help address the computational needs of model downscaling and the ability to consider vast amounts of observational data (physical, biological, economic, and social) alongside model data (see Objective 1.4). Trends in high capacity and cloud computing are increasingly leveraged by individual USGCRP agencies, but additional coordination is needed for more efficient integration of individual cloud initiatives and better identification of data user demand.

The aforementioned challenges are heightened by a reach beyond the traditional bounds of information sharing and management created by the integrative, complex global-change research that USGCRP pursues. Increasingly, global-scale challenges call for expanding the integration of social and economic data into the Program's analysis and models. This integration requires careful consideration of privacy and data access issues inherent in social science and economic data, as well as the technical and science challenges surrounding the variety of data and metadata formats and requirements. Integration solutions must combine scientific and technical innovations, careful and nuanced understanding of the linkages between the data, and comprehensive and sound policies around data access, privacy, security, and management.

Goals 2, 3, and 4: Making Science Actionable and Accessible

Goals 2, 3, and 4 of the 2012–2021 Strategic Plan describe a set of philosophies and activities focused on ensuring that USGCRP's science is accessible to a wide range of decision makers as they develop responses to climate-related global change (see Figure 20). As such, they are central to USGCRP's core capability of actionable and accessible science (see Chapter II, p. 15–22). As with Goal 1, the Strategic Plan remains the guiding blueprint for USGCRP; this update highlights selected areas where significant progress has been made, and discusses how the Program will build on progress and navigate challenges.

Progress in these three goals relies on the strength of USGCRP's basic science, which provides the basis for delivering actionable science to decision makers and the public. The Program's work in these three goal areas is dependent upon and benefits from continuous connection with Goal 1, as USGCRP seeks both to improve the utility of knowledge gained from fundamental research and to use feedback from these latter three goals to inform research priorities. These goals act together to: help the USCGRP to continuously identify needs for science, capacity-building (e.g., science translation, training, and education) and communications; provide timely and relevant information in collaboration with decision

Figure 20: USGCRP Goals for Making Science Actionable and Accessible

Goal 2. Inform Decisions: Provide the scientific basis to inform and enable timely decisions on adaptation and mitigation.

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.

Goal 4. Communicate and Educate: Advance communications and education to broaden public understanding of global change and develop the scientific workforce of the future.

makers; improve the Nation's ability to anticipate and respond to global changes; and evaluate success in meeting users' information needs. Achievements in these three goals often use similar processes and tools and produce similar outcomes. For example, products of the sustained-assessment process, particularly NCA3, have been used for communication about climate impacts, education about risk management, and have been adapted to inform a wide range of decision-making processes. For that reason, this update treats these three goals as a set, similar to the way objectives under Goal 1 are discussed.

Several significant changes have affected USGCRP's sphere of work since the release of the Strategic Plan. The development and May 2014 release of the NCA3 provided an unprecedented opportunity to communicate about climate science and impacts, as did the release of the IPCC Fifth Assessment reports in 2014, in which USGCRP participated. These reports also created demand for ongoing assessment activities, capacity, and tools. The communication and engagement conducted around the reports engendered a Federal infrastructure for outreach that can be adapted and expanded for new products and emerging issues. Similarly, the announcement of the President's Climate Action Plan in June 2013 and related policies encouraging domestic and international response to climate change have prompted an increased emphasis on research and communication around climate response strategies. Additionally, such policies created strong agency needs for climate information, training, and development of risk assessment capabilities.[4] Actions in response to these announcements also highlighted the importance of regional collaboration and increased the demand for assessment and decision-support products at sub-national scales.

Expanding the engagement of USGCRP within and beyond the Federal government is a key part of Goals 2, 3, and 4, and it remains a work in progress. In general, there has been a marked increase in demand for climate science, including science translation, downscaled information, climate information in risk-based frameworks, training and guidance, and monitoring and evaluation of response effectiveness. The increase in demand comes from all levels of government and across the private sector. The increasing demand for climate information presents opportunities to reach new audiences while also presenting the challenge of defining USGCRP's role in responding to a large and diverse set of new information needs. In this respect, USGCRP sees its primary role in the provision of scientific information that can be used by its members or other agencies and entities for research and/or operational purposes. USGCRP stakeholder engagement occurs largely through the sustained-assessment process and its outreach activities (see Goal 3), and via the agencies and their stakeholders, including the agency regional science organizations. USGCRP will strengthen these pathways toward a better understanding of user needs and their consideration in science planning and coordination. It will also use selected pilot projects (see Goal 2) and Program areas (such as the interagency priorities discussed in Chapter II) as targeted opportunities to improve its broader engagement efforts, including with the private sector.

In addition, there are opportunities to deliver information across a variety of time and distance scales, in more coordinated ways, which also present challenges in articulating the suitability of various climate information products for different decision needs. Recent extreme events have been one driver of the increased demand for translated science information, drawing on the latest scientific advances in understanding the relationship between climate change and

[4] See, for example, Executive Orders 13653 and 13677; Recommendations of the State, Local, Tribal Task Force; new greenhouse gas reduction targets and methane reduction strategies.

extreme events to communicate with the public. Extreme events also provide effective focal points for decision-support activities such as the development of a sea-level rise projection tool in the wake of Superstorm Sandy.

Goal 2: Inform Decisions

In the face of a changing climate, USGCRP is linking decision makers with resources and experts (see Figure 21) in areas such as ecosystem adaptation, water-resources management, public health, and other climate-sensitive sectors, central to making USGCRP's science actionable and accessible. The USGCRP agencies are implementing the President's Climate Action Plan and their 2014 Federal Agency Climate Change Adaptation Plans and assessing vulnerabilities to climate change both domestically and internationally. Agencies and their stakeholders draw on resources such as the NCA3 (with data provided through the GCIS), the Climate Data Initiative, Climate Resilience Toolkit, the IPCC Fifth Assessment Report, and the USGCRP Federal Adaptation Resource Library. The USGCRP agencies are delivering decision-support resources tailored to adaptation and preparedness decision making from the local to the global level, accomplished through sustained Federal coordination of international partnerships, Federal communities of practice, and regional science organizations that serve a range of sectors at the community level. Through its adaptation science and assessment working groups, USGCRP provides sustained dialog among the agencies, identifies joint projects and resources of interest, and acts as a liaison to other groups, such as the Interagency Forum on Climate Impacts and Adaptation, Climate Action Champions, and Resilience AmeriCorps.

Figure 21: Goal 2. Inform Decisions

Provide the scientific basis to inform and enable timely decisions on adaptation and mitigation.

- **Objective 2.1. Inform Adaptation Decisions:** Improve the deployment and accessibility of science to inform adaptation decisions
- **Objective 2.2. Inform Mitigation Decisions:** Improve the deployment and accessibility of science to inform decisions on mitigation and the mitigation-adaptation interface
- **Objective 2.3. Enhance Global Change Information:** Develop the tools and scientific basis to enable an integrated system of global change information, informed by sustained, relevant, and timely data to support decision making

Recent efforts include programs and activities that equip regions, states, and tribes with climate data, tools, and resources specific to their needs. These resources present foundational climate science and provide access to information on diverse topics including observed climate trends and projections, scenario planning, and community engagement strategies, intended to help inform decisions on climate preparedness and resilience. In addition, local and community-scale information and tools are increasingly being provided by other governmental and private sector organizations that utilize USGCRP information such as the NCA3. Identifying ways in which climate impacts may compound existing stressors on natural, managed, and socioeconomic systems, as well as provide potential opportunities, helps communities integrate climate change into their assessments of vulnerability and risk management practices. Since the release of the Strategic Plan, there has been increasing demand for science translation, downscaled information for decision making, decision-support tools, training and guidance, and monitoring and evaluation of the effectiveness of adaptation strategies and

research. USGCRP member agencies are working with their constituent networks to improve delivery of science to inform adaptation and mitigation decisions. Examples of progress and challenges in these areas are provided below.

Maintaining Directions

USGCRP continues to engage with its stakeholders to understand their research and information needs (see also Goals 3 and 4), and identify and deliver actionable science needed to inform decisions on the ground. This includes the continued collection, delivery, and translation of data and information resources at various spatial and temporal scales. Initiatives such as the National Fish, Wildlife, and Plants Climate Adaptation Strategy highlight USGCRP interagency efforts to provide information resources to support adaptation planning. USGCRP engagement also includes working with other governmental, boundary, and private sector entities to help support various types of decision makers in both the public and private sectors (e.g., resource managers, engineers, healthcare professionals, industry representatives, state, tribal, and local officials, etc.). Examples of USGCRP member agencies engaging with stakeholders and decision makers at the regional and local levels to guide the selection, application, and translation of relevant science and information include the work of the USDA Climate Hubs, NOAA Regional Integrated Sciences & Assessments, DOI Climate Science Centers, and HHS/CDC Climate-Ready States and Cities Initiative. Members from the agency regional science organizations play leadership roles in USGCRP adaptation and assessment groups, providing a vehicle for incorporating their perspectives and insights from activities at regional to local scales in USGCRP planning and coordination.

The USGCRP agencies will continue to provide guidance on how to assess the certainty and reliability of available data, how to interpret and use climate science and information, as well as strategies to integrate the perspectives of social, behavioral, and economic sciences for adaptation and mitigation responses. The National Integrated Drought Information System (NIDIS) Drought Early Warning System continues to showcase the collaborative work of USGCRP agencies to provide an easy to use, accessible resource for managing drought risks and impacts. USGCRP agency collaborations can also advance innovative data sharing and information exchange approaches (e.g., citizen science, participatory scenario planning, etc.) to facilitate the continued development of user-driven science.

Building on Progress

USGCRP will continue to advance the 2012–2021 Strategic Plan, including in the areas highlighted below. These topics represent important opportunities for USGCRP to build capacity in order to make its science actionable and accessible (see Chapter II, p. 15–22). Research areas that provide a foundation for this section are discussed under Objective 1.2.

Decision-Scale Knowledge. USGCRP directly, or through collaborations, will support research, collaboration, data sharing, and knowledge exchange on temporal and spatial scales of decision making ranging from years to decades, from a national to a local level. Examples of recent USGCRP efforts include collaboration among NOAA, USACE, and the Federal Emergency Management Agency (FEMA) on Climate Change Preparedness and Resilience Exercises for Texas (Houston-Galveston), Alaska, Colorado (Fort Collins) and Virginia (Hampton Roads), using

information from NCA3. Another example is the FEMA-led effort involving USGCRP agencies and staff to develop the Sea-Level Rise Tool for Sandy Recovery. Through its working groups, the Program will share and use effective practices, lessons learned, and approaches captured from an evaluation of adaptation and mitigation actions, to inform more resilient actions at multiple scales. Doing so will enable flexible and responsive management approaches, and will facilitate identification of potential areas of improved collaboration between the public and private sector, including the Federal government, NGOs, private companies and academia. USGCRP's engagement in the OSTP-led effort to encourage public-private collaborations through activities such as the Resilience Dialogues and Partnership for Resilience and Preparedness (PReP) exemplifies the opportunity to collaborate at the Federal and non-Federal levels (see Figure 22).

It will be important for USGCRP to have a clear understanding of what the private sector and the Federal Government can and should, respectively, provide. No single entity can address this issue independently; collaboration can encourage a "whole community" approach to tackling the challenges and opportunities that continue to emerge in the face of a changing climate. As part of this effort, USGCRP will use its adaptation information and knowledge resources and capabilities to support engagement, education, and training (see Goal 4).

Resilience and Vulnerability Research. Accurately assessing risks and vulnerabilities is essential to understanding and managing the societal, sectoral, and systemic impacts of a changing climate. A baseline assessment of climate-related risks to populations, natural resources, infrastructure, supply chains, etc., facilitates the incorporation of adaptation and resilience strategies into decision-making processes. Consistent with several Executive Orders[5] on Federal sustainability and adaptation in the face of climate change and on climate-resilient international development, USGCRP and its member agencies are engaging in scientific research to inform adaptation decisions in these areas. Regional and sectoral assessment tools and location-specific research, developed by

Figure 22: Public-Private Collaboration to Support Climate Preparedness and Resilience

USGCRP is working closely with the Office of Science and Technology Policy to develop public-private collaborations that can help communities across the United States better access relevant information, tools, and resources to adapt to a changing climate. The following efforts are currently underway to expand community access to technical assistance to facilitate climate-change preparedness and resilience activities around the country.

The Resilience Dialogues is an online service that enables facilitated dialogues among scientists, resilience practitioners, and community leaders. The Resilience Dialogues provides the opportunity for communities to get assistance in initiating climate preparedness and resilience planning. While the service does not support communities through a complete climate assessment or resilience planning effort, the Resilience Dialogues help communities understand climate risks and identify the relevant resources and tools available for climate risk management.

The Partnership for Resilience and Preparedness (PREP) is a public-private collaboration working toward increasing access to and usability of climate-related Federal datasets. Federal agencies are working with the private sector and civil society to leverage innovations in information and communication technology. PREP aims to create an open architecture and the building blocks for countries, states, and communities to develop their own climate risk dashboards, including customized online sites containing data, information, tools, and other dynamic resources needed to mainstream climate risk information into planning and investment decisions.

[5] Executive Orders: 13693 (2015), 13690 (2015), 13677 (2014), 13653 (2013), 13547 (2010), and 13514 (2009)

the USGCRP agencies conducting such investigations, help to inform decision makers and climate preparedness efforts. The USGCRP agencies will continue to build on this research, developing tools and resources to assess climate-related vulnerabilities at a national, regional, and state scale. Such tools should reflect social-science dimensions, for example incorporating social-science research findings on how individuals perceive and make decisions about climate impacts. The application of new scientific research for vulnerability assessments will provide more refined perspectives on climate-change impacts at various spatial and temporal scales, enabling the development of more effective resilience solutions over the long-term.

Integration of Social and Behavioral Sciences. USGCRP and its member agencies participate in a number of efforts to develop resources and tools for adaptation to climate change and its impacts. Increasingly, these efforts are incorporating social-science perspectives (e.g., the Social Vulnerability Index) and combining climate science and demographics in ways that allow the user to customize datasets and visualizations to their topic and location of interest (see, for example, the Climate Explorer or Climate Resilience Toolkit). EPA's Climate Change Impacts and Risks Analysis is another example of a framework that addresses the socioeconomic opportunities and potential risks associated with different mitigation and climate scenarios. USGCRP will continue to support and prioritize such efforts, and explore emerging opportunities to better integrate social sciences into its decision-support portfolios. In doing so, it will build on current agency activities that include joint efforts aimed at moving basic science to the decision support sphere, consideration of innovative approaches to decision making, and more systematic engagement with the regional science centers. As Federal entities that interface directly with decision makers, regional science centers utilize and advance social science to improve understanding and inform decisions. USGCRP's social science and adaptation science working groups (see Figure 16) will work together to foster the translation of research discussed in Objective 1.2 for use in decision making.

Informing Agency Adaptation Planning. USGCRP will provide expanded support for agencies to meet climate policies through the utilization of actionable science, including continued analysis of collective agency science needs for their adaptation planning. This will include supporting agencies as they work to fulfill requirements related to adaptation and resilience outlined in recent Executive Orders 13953 (*Preparing the United States for the Impacts of Climate Change*) and 13693 (*Planning for Federal Sustainability in the Next Decade*). Based upon the common research and information needs specified in the Federal Agency Climate Change Adaptation Plans (CCAP), the Program and its member agencies will continue efforts to fill those gaps. Resources such as the Federal Adaptation Resources Library are structured around the sector-specific needs identified in the CCAPs, aggregating Federally-developed tools, reports, and resources on globalchange.gov. Other notable resources include the Climate Explorer, (developed as part of the U.S. Climate Resilience Toolkit), which provides historical and projected climate data in an interactive format that can be used to inform resilience-building efforts.

Research Translation to Inform Adaptation and Mitigation Decisions. The USGCRP agencies have long supported translating basic research into more actionable science that can be applied to the needs of decision makers. USGCRP is building on this core of applied research by leveraging existing agency mechanisms and supporting new approaches at the regional level. The NCA and USGCRP's sustained- assessment effort (Goal 3) are major sources for research translation, as are the regional science centers supported by member agencies. The Program

is accelerating its work in translational products such as scenarios, which are descriptions of potential future conditions that serve as input to more detailed analyses or modeling, intended to support the information needs of regional decision makers. Prior research based on stationary climate conditions needs to be reconsidered in light of new understanding of local climate change, using new tools and consistent future scenarios of climate, population, and land use across the Federal agencies.

In order to build on progress already made in facilitating engagement between scientists and decision makers, USGCRP will identify components, characteristics, and metrics of successful science translation, and implement best practices for enhancing and mainstreaming translational capacity. To extend translational capabilities, USGCRP will provide guidance on scales and levels of uncertainty in interpreting climate projections useful for decision making for specific audiences (such as the Regional Climate Scenario Summaries). USGCRP's sustained-assessment activities (see Goal 3) will provide extended translational capacity and guidance. In addition, initiatives such as the Resilience Dialogues (see Figure 22) will provide a platform to facilitate science translation to inform adaptation decisions on the ground.

Navigating Challenges

There are challenges in the Inform Decisions portfolio that USGCRP will need to navigate over the next few years. Central among these is the importance of analyzing climate-change risks and opportunities at the interface of climate and non-climate stressors (e.g., economic changes, land-use concerns, national security, sector-specific decisions, etc.). To do so, the Program will need to view Earth and human systems as a whole, rather than by individual sectors or entities (see discussion of models for decision support in Objective 1.2). This holistic approach helps to illustrate how climate change can amplify existing threats, stressors, or hazards (e.g., instability from large-scale human migration, public-health impacts, hazardous chemical spills, or ocean acidification), enabling the identification of both conflicts and co-benefits resulting from various strategies to enhance sustainability and resilience over time.

Building from its interdisciplinary research efforts, USGCRP will continue to improve engagement between science producers and decision makers. Users are making decisions at various scales of management and planning, so it is important for the development of research to be framed, in part, by user needs. The Adaptation Science IWG (ASIWG) is an example of a venue where science producers and users regularly convene to collaborate and exchange information. Such interagency efforts underscore the needs of science users, enabling science producers to develop appropriate resources, and guide users to such resources. Through joint identification of research needs in targeted areas, and joint development of knowledge (often called co-production), the Program will engage with users early in the production process. Engagement at this stage will help define the scope of USGCRP products, as well as encourage the development of actionable science that is most relevant to decision makers and can be applied to address climate-related management challenges.

The USGCRP member agencies support coordination amongst stakeholders at the Federal, regional, and, on occasion, local levels. Research and engagement efforts at the various scales to understand decision contexts, analyze risk, and provide support for decision makers have

grown in scope in recent years to meet rapidly rising demand. Much of this work occurs at the regional level via regional science organizations and programs operated by the USGCRP agencies. The interaction between USGCRP and the regional science organizations must be part of a feedback loop, with USGCRP providing research and information that meets collective needs, and the organizations providing feedback on their directions and needs. In addition, USGCRP will work to find a balance between ensuring that regional organizations are well informed of priorities and activities and engaging them as appropriate, while recognizing that regions, states, and tribes must also self-organize and develop networks and information exchanges that work for their particular needs and constituencies. Public-private collaborations such as the Partnership for Resilience and Preparedness (PReP) exemplify such a balanced approach, with USGCRP agencies providing access to datasets and metadata while the public and private sector provide boundary expertise and feedback. Such collaborations will provide access to critical global change information and knowledge, enabling stakeholders to make informed adaptation and mitigation decisions on the ground, while providing direction to USGCRP to inform future research investments.

An ongoing challenge for USGCRP relates to the use of its science to inform mitigation decisions. USGCRP works in close collaboration with other parts of the Executive Office of the President that focus attention in this area to understand mitigation science needs that fall within the Program's purview.

Goal 3: Conduct Sustained Assessments

USGCRP's sustained-assessment effort (see Figure 23) is a powerful approach for science synthesis, strategic planning, and Program engagement, and is a linchpin in USGCRP's core capability of making its science actionable and accessible (see Chapter II, p. 15–22). A number of U.S. and international special assessment reports (see Figure 23) provide timely science updates in key topics and document scientific progress from USGCRP and other organizations. They help identify research and capability needs that feed back into USGCRP scientific planning and prioritization. They also provide a focus for sustained engagement and report co-design (and sometimes co-production) with stakeholder groups. Such engagement includes processes that promote continuous and transparent participation of scientists, stakeholders, and decision makers across regions and sectors, enabling new information and insights to be synthesized as they emerge and providing learning opportunities for the Program as a whole in strengthening interactions with information users and producers. As required by the GCRA, the process also supports the quadrennial National Climate Assessment (NCA), as well as international collaborations. Agencies are investing in research, tools, and products to support a sustained-assessment capacity, including scenarios, climate-change indicators, data access and transparency, and engagement efforts.

Maintaining Directions

The Program has made significant recent progress in assessment capabilities and continues to strengthen implementation of the sustained-assessment process, based on principles established in the Strategic Plan. USGCRP has identified and maintained the strongest elements of the successful approach built around methods developed for the NCA3 and IPCC.

This process has already supported several ongoing assessment activities, such as the recent report The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, and will benefit from a range of newly identified assessments such as the Climate Science Special Report. NCAnet continues to be a central mechanism for the program to connect with interested parties across the Nation—both to communicate USGCRP activities and to develop innovative capacity building actions. USGCRP will continue to participate in international assessments on topics such as the Arctic, biodiversity and ecosystems (see Chapter IV) and ozone, as well as the IPCC Sixth Assessment Report.

Building on Progress

USGCRP will continue to advance the 2012–2021 Strategic Plan, including in areas highlighted below. Both products and processes associated with this goal are important outcomes that support USGCRP's core capability in making science actionable and accessible (see Chapter II).

Sustained-Assessment Overview. The success of the NCA3 and its procedures provides a strong platform on which to build a sustained-assessment process that shifts focus from the single end-product, such as a comprehensive assessment report, to delivering multiple types of products and engagement activities to meet the decision-making needs of diverse groups. These include special assessment reports and the quadrennial NCAs, along with engagement and tools such as scenarios and indicators, which can draw on one another as appropriate. Generating these products, in consultation with users, is sustaining the momentum generated by the NCA3 and responding to the demand for more knowledge about climate impacts and adaptation options. USGCRP is developing a dynamic and adaptive framework for sustained assessment that will provide projections and scenarios that can be used for assessing climate risk and impacts in the context of multiple stressors, moving beyond those currently available. In doing so, the Program draws from a report prepared by the National Climate Assessment Development and Advisory Committee on Building a Sustained National Climate Assessment Process, and will be guided by the Advisory Committee for the Sustained National Climate Assessment, which will advise USGCRP on sustained-assessment activities and engagement.

NCA 4 Overview. Planning for the Fourth National Climate Assessment (NCA4) is well underway with leadership from USGCRP member agencies through a Federal steering committee. A public comment period with a request for information (RFI) on the draft annotated outline for NCA4 was open in July 2016, with comments received from individuals from government agencies and regional government programs, tribal communities, professional societies, public and private universities and research institutes, the private sector, and non-profits. Discussions are also underway with regional science organizations (e.g., Department of Interior's Climate Science Centers and Landscape Conservation Cooperatives, NOAA's Regional Integrated Sciences and Assessments programs, and USDA's Climate Hubs) on how to collaborate to best serve regional stakeholder needs. A Federal Register Notice—with a call for authors and technical inputs and a revised outline and chapter list informed by the previous RFI—is expected to be open in the early autumn of 2016. The sectors and regional analyses covered by NCA4 will generally be similar to those in NCA3; efforts are being made for more detailed regional analyses, and to better identify the needs and opportunities for adaptation measures, as well as the benefits (avoided risks) of mitigation pathways.

Building Scientific Foundations

Sustained-Assessment Reports. Where urgent needs exist to assess the country's state of knowledge (e.g., changing patterns of weather extremes, including drought) or where there is an emerging topic of interest with a sufficient body of science, USGCRP will promote synthesis of new information and insights as they emerge, without waiting for the next quadrennial report (see Figure 24). The consistency of the transparent development and engagement processes developed as part of the NCA3 will be retained and expanded for interim assessments and subsequent NCAs. A strong example of this is the use of traceable accounts, or links that connect scientific findings to the underlying publications and datasets through the Global Change Information System (GCIS). These efforts increase transparency, communicate confidence levels and provide enhanced discoverability within USGCRP assessments. The recent assessments on *Climate Change, Global Food Security, and the U.S. Food System*, *The Impacts of Climate Change on Human Health in the United States*, and the *Effects of Drought on Forests and Rangelands in the United States*, are the first examples of sustained-assessment reports that embody the strategy of leveraging capacity from the NCA3 process and point towards improvements in the process that will inform future reports.

Figure 23: 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:** Integrate emerging scientific understanding of the integrated Earth system into assessments and identify critical gaps and limitations in scientific understanding
- **Objective 3.2 Ongoing Capacity:** Strengthen and evolve the ongoing capacity to conduct assessments with accessible, transparent, and consistent processes and broad participation of stakeholders across regions and sectors
- **Objective 3.3: Inform Responses:** Inform responses to global change with accurate, authoritative, and timely information that is accessible to multiple audiences in multiple formats
- **Objective 3.4: Evaluate Progress:** Ensure ongoing evaluation of assessment processes and products, and incorporate the findings into an adaptive response for systemic improvement

Scenario Development and Use. USGCRP has identified the need for a systematic approach to scenarios, encompassing climate, land-use and land-cover change, demography, and other key global change drivers, to support the sustained-assessment enterprise and its emphasis on decision support. Consistent, informative sets of scenarios that address key areas of need (e.g., regions, changing characteristics of extreme events) can support risk assessment and decision making, and also identify scientific gaps in need of future research. USGCRP will pursue such scenarios efforts, leveraging the full capabilities of the USGCRP modeling enterprise (see Models for Decision Making, p. 28). Key tasks include identifying needed products (e.g., downscaled projections, contextual framing) and their features (e.g., spatial and temporal scales, variables of interest, uncertainty). Also key is providing strategic and implementation guidance for use of such USGCRP products within research, assessment, and decision communities, including mechanisms for access and opportunities for users to engage in product development and use. USGCRP is working with member and non-member agencies to provide guidance on climate scenarios for sustained-assessment activities and is fostering strong alignment with other Federal projects for coordinated demographic and land-cover projections to inform adaptation planning.

Climate Indicators. USGCRP recently launched a pilot indicators effort, as called for in the 2012–2021 Strategic Plan, and created an Indicators Interagency Working Group to provide recommendations and facilitate the development of a robust resource and a usable set of indicators. Indicators are typically constructed from long time-series observations that can be used to measure the status or trend of a system, point out key impacts and vulnerabilities, and inform decision making at local, state, and national levels. The USGCRP indicators are intended for use by multiple audiences and will be expanded over time. The efforts will also focus on key datasets that will be used to support NCA4 and other USGCRP products. The effort will serve as a "platform" and leverage existing indicator efforts from Federal agencies and include non-governmental organizations, academia, and the private sector. In addition to communicating key aspects of climate change, the indicators and any future developments are intended to support planning and decision making, with a broader range of indicators that include climate vulnerabilities and preparedness.

Figure 24: Special Assessment Reports

USGCRP sustained assessment and technical reports completed or in progress:

- Climate Change, Global Food Security, and the U.S. Food System
- The Impacts of Climate Change and Human Health in the United States: A Scientific Assessment
- Effects of Drought on Forests and Rangelands in the United States
- Climate Science Special Report (in progress)
- Second State of the Carbon Cycle Report (in progress)

IPCC planned special assessment reports during the Sixth Assessment Report cycle:

- Impacts of Global Warming of 1.5oC above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways
- Climate Change and Oceans and Cryosphere
- Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes from Terrestrial Ecosystems

Risk Framing. At USGCRP's request, the National Academies of Sciences Board on Environmental Change and Society organized a workshop to address risk framing for National Climate Assessments. Discussions focused on approaches needed to provide information about climate-related hazards, risks, and opportunities in formats that are understandable, credible, and useful to decision makers. It considered decision making relative to reducing greenhouse gas emissions, and to reducing vulnerability and increasing resilience to climate change in regions and various sectors. Speakers included White House representatives, USGCRP leadership, numerous leaders in climate risk analysis and risk communication, participants in the most recent NCA, and various users of climate assessments.

Sustained-Assessment Engagement

Tools for Sharing Assessment Findings. Reaching stakeholders with assessment information in forms that are easy to use and share is an essential foundation for broader engagement, and was a focus in the design of the NCA3 website. Since the release of the 2012–2021 Strategic Plan, USGCRP has built a cadre of powerful tools that greatly increase assessment capacity, provide efficient and effective support for assessment processes and products, and make assessment products more accessible and useful to decision makers and citizens. The ongoing development of such tools is a key aspect of this Goal, and the NCA3's innovative website's visibility, traceability, and content are models for communicating effectively across the

Federal Government and beyond. USGCRP's GCIS improves information content, transparency, and traceability across recent reports, including the recent *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*, and USGCRP's pilot indicators effort. USGCRP's Review and Comment System, used now for multiple national and international assessments, streamlines widespread distribution, review, and comment collection for global-change reports and assessments. Website analytics provide insight into stakeholder interest and constitute one avenue for evaluation of the NCA3. Looking forward, USGCRP will leverage the Federal capacities, such as the Climate Resilience Toolkit and the Climate Data Initiative (see Figure 19), by embedding their capabilities within the report websites to link information to specific case studies, tools and actions at all scales of governance.

USGCRP will continue to foster cooperation that supports the agencies building these tools and make them available across the Federal Government to improve the Nation's ability to inform responses to climate change and build capacity for scientific assessments and information sharing.

Stakeholder Engagement. USGCRP recognizes that engagement is critical to the success of the Program overall and of initiatives such as the NCA, and uses multiple approaches to foster stakeholder engagement (see Figure 25). While the specific targets for engagement—members of the scientific community; representatives from local, state, Tribal, and Federal governments; the private sector; community groups; or other individuals and organizations—will depend on the scope of a particular project, USGCRP strives to include individuals and organizations whose activities, decisions, and policies are sensitive to or affected by climate. Ultimately, successful engagement will increase awareness of USGCRP's work, leverage the diverse array of science and user perspectives across the United States, and develop a consistent and routine capacity to generate and apply climate science findings within and outside of the Federal Government. USGCRP has endeavored to engage stakeholders at every stage of its work, from program planning and implementation to delivery of results and program evaluation. For example, a recent Request for Information invites stakeholders to provide input to the design of NCA4. Engagement with National Academies panels provides key engagement with broad and varied groups of thought-leaders. NCO staff regularly participate in numerous public events and forums to understand stakeholder issues and communicate USGCRP findings. More robust and regular engagement between scientists and stakeholders through sustained-assessment activities strengthens the ability of the United States to respond to the challenges of climate and global change.

USGCRP has fostered an innovative platform—NCAnet—for collaboration that identifies new resources and capacity to enable complementary climate assessment efforts outside the Federal Government. This self-organized network of more than 180 organizations is immensely valuable for the broad dissemination of USGCRP products, harnessing the power of existing networks in which NCAnet participants operate to extend the reach of USGCRP information to audiences including non-governmental organizations, youth, and faith-based groups. USGCRP will continue to support this approach to sharing information through sustained interaction via various affinity groups that form amongst the participants.

Integrating Social Science. USGCRP's Social Sciences Coordinating Committee (SSCC) is providing specific recommendations to the Program on ways to better incorporate social sciences in the next NCA. The group analyzed NCA3 to find good examples of inclusion of social sciences, as well as areas where social sciences could have improved the report from the perspective of science, research, communication, or usefulness to readers. The group's ideas for the next report range from new topics and ways to structure chapters, to best practices for representing social-science inputs, such as economic valuation of climate-change impacts. The SSCC is working to convene a workshop involving several social-science professional associations, together with USGCRP staff and affiliated Federal researchers and program managers. Drawing on current research perspectives from several social-science disciplines, the objective is to identify specific, implementable actions that USGCRP or its member agencies could take to enhance the effectiveness of Federal climate-change activities.

Figure 25: USGCRP Engagement Tools

- Open forums, including town hall meetings at scientific society meetings, regional meetings focusing on draft products, and other listening sessions that provide an opportunity for dialogue with various USGCRP stakeholders
- Workshops that bring together technical experts and information users to discuss methods for assessment
- Requests for Information that allow individuals and groups to submit their areas of interest and concern for upcoming assessments
- Requests for nominations of Federal Advisory Committee members, report authors, and other technical contributors to USGCRP products
- Networks that bring together interested individuals and organizations to collaborate on activities that further communicate to and engage with users of USGCRP products
- Public comment periods to gather comments and technical input on topics for the National Climate Assessment, request review of draft products such as the Strategic Plan and various assessment reports, and obtain feedback on current and future activities related to the sustained-assessment process

Navigating Challenges

Despite strong progress towards implementing the objectives of this goal, challenges remain. Overall, the high expectations created by the success of the NCA3 require USGCRP to balance resources and effectively leverage Federal capacity, while building on grassroots enthusiasm. Recent Executive Orders directed agencies to integrate climate into their operations and decisions based on the results of the quadrennial NCA reports. However, including climate risk assessment and adaptation responses into Federal agency planning has greatly increased the need for USGCRP to foster coordination and cooperation around climate issues. Around the Nation, communities are also increasingly relying on USGCRP and Federal products for data, information and knowledge around climate issues. To deliver appropriate support, USGCRP will need to better define key aspects of the sustained-assessment process and products that can meet these needs while managing expectations. Utilizing the new Federal Advisory Committee for Sustained Assessment, leveraging engagement activities such as NCAnet, and active outreach to key stakeholders, are required to address this challenge.

USGCRP needs to continue to share its assessment capabilities and technical expertise with domestic and international partners to foster global capacity under the Strategic Plan (Goal 4). Regional assessments, such as those in collaboration with the Arctic Council, support for other national assessments such as in India, thematic assessments such as for ozone, and the next IPCC assessment, are important endeavors, and will require careful consideration and marshaling of USGCRP resources.

Ensuring ongoing evaluation of assessment processes and products, and incorporating the findings into an adaptive response for systemic improvement, requires defining and measuring metrics of success. USGCRP is working with the National Academies of Sciences, Engineering and Medicine's Committee to Advise USGCRP to review USGCRP's three NCAs and their role in reflecting and shaping USGCRP science. USGCRP is also conducting an ongoing, comprehensive outside evaluation of the NCA3 report, currently underway, and will adaptively incorporate recommendations as the NCA4 process moves forward. Incorporating risk-based framing into assessments more comprehensively over time will require providing guidance on the consistent use of recent research and approaches, a topic of the recent National Academies Workshop on Risk Framing. USGCRP will build on agency efforts to apply risk framing and climate information in a consistent framework, and will embed those efforts into sustained-assessment activities and reports.

Goal 4: Communicate and Educate

Goal 4 seeks to foster greater public understanding of global-change science and response capabilities through communications and education, and to gain greater awareness of the public's science and information needs through engagement and dialogue (see Figure 26). Communication, education, and engagement are essential tools for achieving the objectives outlined in the three other goals of the Strategic Plan. Capacity building in these areas, as discussed below, is also central to strengthening USGCRP's core capability in making science actionable and accessible (see Chapter II, p. 15–22). Together, the four objectives of Goal 4 (see Figure 26) support the engagement of diverse audiences in communications, education, and capacity building efforts that enable an informed national response to global change.

Figure 26: 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:** Strengthen the effectiveness of global change communication and education research to enhance practices
- **Objective 4.2. Reach Diverse Audiences:** Enhance existing and employ emerging tools and resources to inform and educate effectively, providing for information flow in multiple directions
- **Objective 4.3. Increase Engagement:** Establish effective and sustained engagement to enable a responsive and wholly integrated Program
- **Objective 4.4. Cultivate Scientific Workforce:** Cultivate a capable, diverse scientific workforce that is knowledgeable about global change

Like many of the activities conducted in support of the Strategic Plan, agencies' communication, education, and engagement efforts are often coordinated through interagency working groups and other USGCRP collaborations, but with much of the implementation carried out by the agencies. In some cases, especially when communication, education, and engagement efforts are focused on primarily interagency products such as the National Climate Assessment or other sustained-assessment products (see Goal 3, Figure 23), USGCRP takes a lead role in developing and implementing products and activities that are disseminated through the Program and individual agencies.

Maintaining Directions

USGCRP has made significant progress in communicating and educating about interagency global-change research priorities, scientific assessments, and activities. Areas where the Program will maintain its current direction include coordinating education research investments and making research results more accessible via the Education Interagency Working Group; supporting forums for dialogue, including USGCRP-focused communities of practice such as NCAnet; and participating in Federal and non-Federal communities of practice that focus on communication, education, and engagement. Another important direction is engaging stakeholders in the scientific assessment process through calls for public comment on draft materials (e.g., interim steps of the NCA, special assessment reports), in-person and virtual public forums, and requests for information relevant to emerging activities, such as the sustained-assessment process (see Figure 25).

Yet another important activity of the USGCRP member agencies is providing Federal grants and other resources that build science understanding and strengthen climate literacy by supporting networks of scientists, educators, and other professionals to work within their disciplines and with the broader public. Specific efforts include assisting in the White House OSTP's Climate Education and Literacy Initiative, supporting the implementation of the climate-related National Academies Framework for Science Education and the resulting state education standards, and creating and participating in forums that deliver USGCRP research findings to educators. USGCRP member agencies continue to fund training for young scientists to improve abilities to evaluate, understand, interpret, and apply climate science.

Building on Progress

Through USGCRP, Federal agencies collaborate on and coordinate a comprehensive strategy for climate and global change education, engagement, and communication that enhances the work of individual agencies. The Program will continue to leverage work done across its working groups, communities of practice, Federal-university networks, etc., to enhance dialogue and more effectively reach decision makers and key stakeholders. USGCRP will build on this progress in a number of ways, including those highlighted below.

Understanding Audiences and Communicating Effectively. Data from digital media (e.g., web traffic, social media tracking) and print orders will be used to explore which products and sections of products are seen, and potentially used most often, to identify areas in which to focus additional attention. By expanding USGCRP research to more fully incorporate social and behavioral sciences, including through the Social Sciences Coordinating Committee (see Figure 16), the Program can better understand behavioral responses to information provided to stakeholders about climate change and associated risks and opportunities. These results can be used to establish a knowledge base that relates to readers' past experiences, knowledge, and social context. This knowledge base can inform human responses to climate and global change through offering coordinated education, communication, and decision-support programs, as well as other partnerships and collaborations. Such communications may include providing the science that specific sectors find most compelling, such as informing the health community about the health implications of climate change.

Building and Maintaining Communities of Practice, Partnerships, and Collaborations. NCAnet, with more than 180 participating entities, many of which are associations with many individual or professional members, has proven to be an effective means to engage with a variety of organizations, especially through the use of affinity groups that address particular topics of interest. Supporting additional affinity groups and encouraging existing and new NCAnet participants to engage with these groups can drive the development of activities and materials that use NCA3 and other USGCRP products. USGCRP is also participating in communities of practice that focus on other areas of activity, such as climate adaptation, climate education and climate change and human health. Developing collaborations and partnerships with organizations that include, for example, educators, labor and industry groups, and researchers can increase the awareness and use of USGCRP products, as well as other Federal efforts such as the Climate Resilience Toolkit and Climate Data Initiative (both initiated as part of the President's Climate Action Plan). Finally, leveraging the results of climate-change education investments through stronger connections to, and closer collaboration with, other Federal funders and the private philanthropic community can help operationalize projects that proved successful in the pilot phase, avenues that USGCRP member agencies are developing.

Scientific Information and Tools. Through efforts such as NCAnet and the interagency community working on the Climate Data Initiative and the Climate Resilience Toolkit (see Figure 19), USGCRP will continue to facilitate discussions about how to engage with stakeholders and how to assess their needs for climate information and tools. The Program will continue to build scientific capacity by increasing awareness of these tools and integrating them into education and communication efforts targeting multiple audiences, and by fostering increased ability for people to understand and interpret climate science findings for their particular needs. For example, USGCRP may facilitate discussions on efforts to enhance and complement Federal trainings for place-based educators with these tools. The Program has already demonstrated the ways in which new communication technologies can be deployed in developing, disseminating, refining, and using climate tools. Further learning from these will enrich future efforts.

Coordinating and Extending Citizen Science Opportunities. An emerging opportunity is integrating data and information from new sources, including from citizen science and crowdsourcing, with Federal sources. USGCRP is exploring these opportunities through participation in communities of practice such as the Federal Community of Practice on Crowdsourcing and Citizen Science and associated workshops on climate-change indicators, health, and Earth observations. USGCRP's focus includes the use of citizen science as both a form of education and outreach, and as an approach that can support research and observing activities.

Training the Workforce. In response to Executive Orders and requests from a number of Federal agencies, USGCRP is collaborating with agencies across the Federal Government and with organizations outside of the government to develop and provide training resources on climate change for a variety of fields. While such development has often been in response to specific requests (for example, the recent launch of Resilience AmeriCorps), USGCRP is also working with groups such as the Interagency Adaptation Community of Practice to create a more comprehensive inventory of existing resources and remaining needs. Through their extramural funding and early career employment opportunities, USGCRP member agencies continue to train the next generation of scientists and technologists working in areas related to climate change.

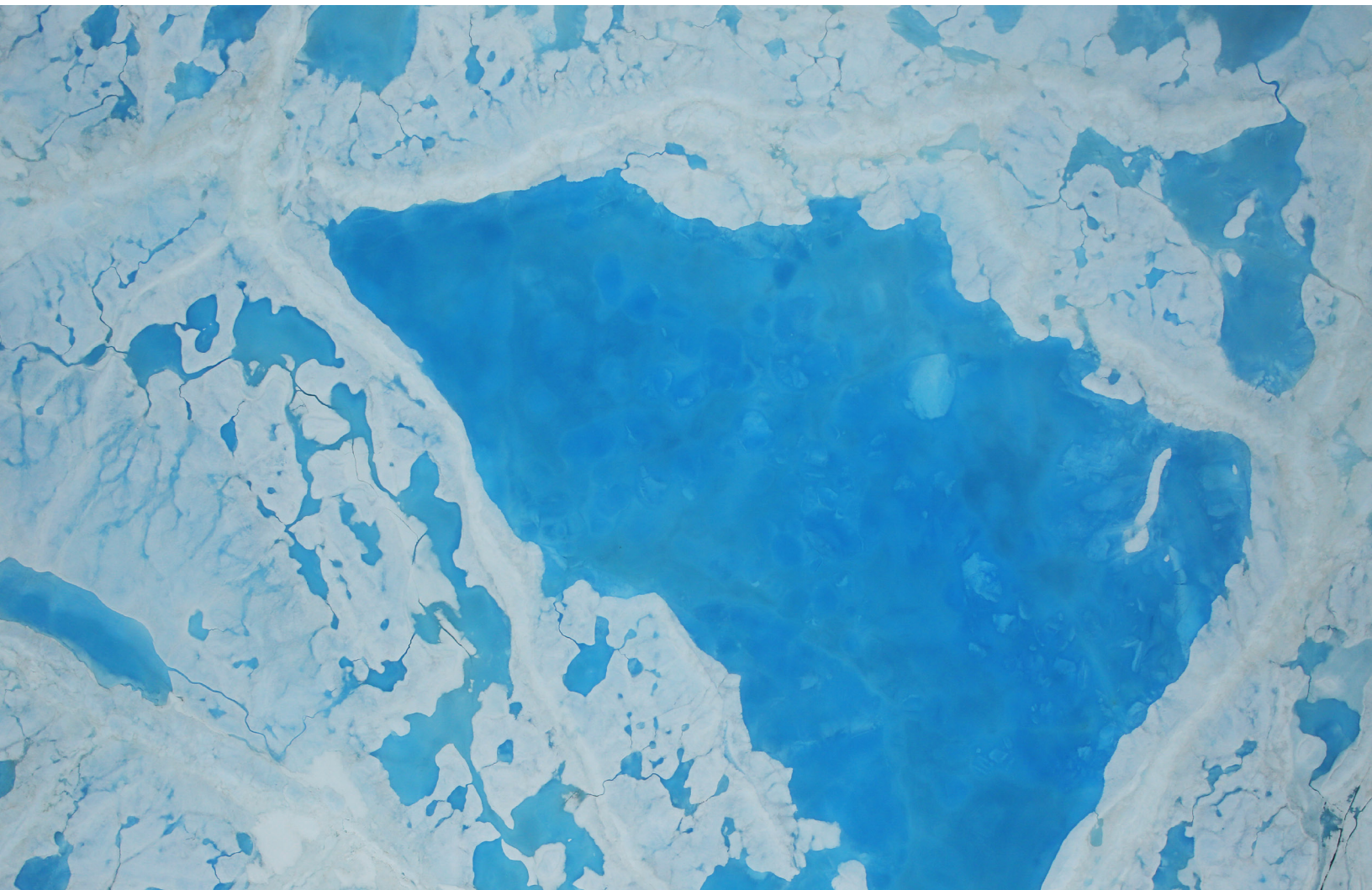
Navigating Challenges

There are a number of areas related to communicating and educating where USGCRP is facing challenges, some recognized in the Strategic Plan. Particular areas where the Program may consider focusing efforts include areas where progress has already been made, but challenges remain, as identified below.

Coordinating, translating, synthesizing, and disseminating relevant communication research across USGCRP can still be a challenge. The Program is considering establishing an interagency group focused on communications research, or communications more broadly, where the consideration will need to take into account competing priorities within USGCRP and workload realities for agency participants. If formed, such a group could conduct a research-needs assessment, identify and catalog relevant Federal and non-Federal communications research, using the Tri-Agency Climate Education catalog as a model, and translate and disseminate relevant research findings. The USGCRP agencies have partial understanding of the motivations, needs, and learning styles of diverse stakeholders relevant to climate-change risks. A better understanding of these audiences, building on social-science insights, is essential to providing information in ways that can be used by different audiences; this is key to building an informed citizenry and developing tools and resources related to communication, education, and engagement activities. Developing such an audience map is another area where coordination among agencies would benefit from an interagency working group on communications research.

Foundational climate-change knowledge and understanding of related effects on sectors such as health, economy, agriculture, and disaster risk is required for the workforce in an increasing number of economic sectors. As a result, efforts to build a diverse, scientifically-literate future workforce will require building the necessary knowledge and skills prior to college, including among underrepresented groups. Efforts to deepen science and climate literacy across higher education, including in community colleges and technical training programs, and in a wide array of disciplines, will require new translation for USGCRP research results to ensure appropriate use, as well as training in evaluating, understanding, interpreting and applying relevant science. Many professional fields, such as architecture and planning, engineering, and law, include professional development and training requirements that could provide opportunities to build climate literacy through incorporating USGCRP research.

For the past decade, the USGCRP agencies and non-Federal organizations have supported extensive efforts to implement climate-change education, build public awareness of the impacts of climate change, and engage communities on this issue. These efforts are increasing the public's ability to engage on critical climate-change issues, although political and social barriers remain. Many such programs have achieved positive on-the-ground results around the country. However, immense challenges still exist in coordinating initiatives across various audiences, leveraging resources, and scaling from demonstration projects to large-scale practice.



Chapter IV: International Cooperation

Global change is, at its core, an issue that requires a coordinated international response. The U.S. Congress recognized the importance of international cooperation and collaboration and codified it in the Global Change Research Act of 1990 (GCRA) (see Figure 27). Through international cooperation, USGCRP and its member agencies are leveraging existing and emerging scientific knowledge to accomplish programmatic goals and strategic priorities.

The Changing Landscape

The landscape of international cooperation on global-change research is undergoing transformational change, to which USGCRP is in an excellent position to contribute and respond. The Paris Agreement, adopted in December 2015 by the 21st Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC), created new and urgent demands for science to inform mitigation and adaptation decision making. There has been considerable progress in improving disciplinary Earth system knowledge as well as cultivating cross-disciplinary research collaborations in pursuit of a sustainable and resilient world. More than two decades of successful international scientific collaborations governed by the International Council of Scientific Unions (ICSU), the International Social Science Council (ISSC), the World Meteorological Organization (WMO), and the Scientific Committee on Oceanic Research provided the foundational science of biological, human, and biogeochemical Earth systems, the climate system and ocean research (see Figure 28 for individual programs).

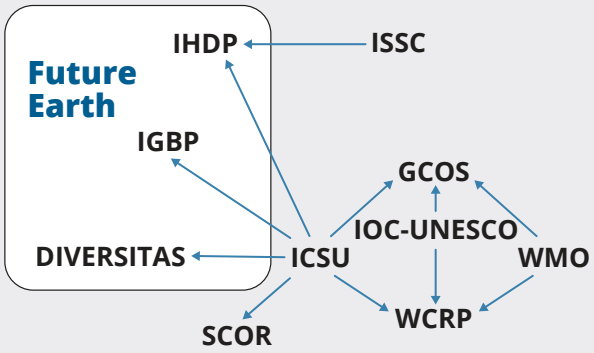
Figure 27: USGCRP International Activities

The Global Change Research Act mandates USGCRP to do the following:

- Promote international, intergovernmental cooperation on global-change research
- Involve scientists and policymakers from developing nations in such cooperative global-change research programs
- Promote international efforts to provide technical and other assistance to developing nations which will facilitate improvements in their domestic standard of living while minimizing damage to the global or regional environment

USGCRP has supported and engaged with these scientific organizations directly, via professional societies, and through scientist-to-scientist interactions, with the intent of building a greater understanding of the Earth's integrated human and natural systems. Recently, many of the programs under ICSU and ISSC have combined into Future Earth, an international platform to coordinate interdisciplinary research on global environmental change and sustainable development. The United States hosts an office serving as one of the five Future Earth global hubs, supported in part by USGCRP (along with the World Climate Research Program (WCRP) and START (global change SysTem for Analysis, Research, and Training). This engagement provides USGCRP and the broader research community with unique opportunities to help shape and benefit from research advancements emerging from this integrated initiative. The Belmont Forum, a group of many of the world's major and emerging funders of global environmental change research, provides another venue for countries to jointly identify research topics of common interest and develop Collaborative Research Actions that address major societally-relevant global environmental change challenges.

Figure 28: International Global-Change Research Organizations



GCOS: Global Climate Observing System

ICSU: International Council of Scientific Unions

IGBP: International Geosphere-Biosphere Programme

IHDP: International Human Dimensions Programme

IOC-UNESCO: Intergovernmental Oceanic Commission of the United Nations Educational, Scientific, and Cultural Organization

ISSC: International Social Science Council

SCOR: Scientific Committee on Oceanic Research

WCRP: World Climate Research Programme

WMO: World Meteorological Organization

Description of the historical relationships between international global change-related scientific collaborations associated with the International Council of Scientific Unions, where the arrows represent organizational governance relationships. DIVERSITAS, the International Geosphere-Biosphere Programme, and the International Human Dimensions Programme recently combined into the interdisciplinary research cooperative Future Earth, which maintains a strong partnership with the World Climate Research Program. USGCRP provides support to Future Earth and WCRP, and also to START (global change SysTem for Analysis, Research and Training).

Science assessments play an important role in bringing together the international science community. Several significant national and international scientific assessments have been completed since the USGCRP 2012–2021 Strategic Plan was released, including the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment (AR5) report, the United Nations World Ocean Assessment, Arctic Council assessments on Short-Lived Climate Pollutants (including black carbon and methane), the 2014 World Meteorological Organization/United Nations Environment Programme Scientific Assessment of Ozone Depletion (Ozone Assessment), and the World Health Organization's Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s, which provides a global complement to *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* released in April 2016. These assessments review and synthesize the most current state of scientific knowledge on global-change issues. USGCRP's experience in engaging with international scientific assessments has demonstrated that cutting edge science is built by a global research community. For international assessments to have credibility, and to ensure the best available expertise is utilized, the involvement of, and leadership from, all countries is critical.

Maintaining Directions

International cooperation is an integral component of the four goals of the Strategic Plan. Global-change science is by definition, an international endeavor: the product of observations, collaborations, and deliberations on a global scale. As the nations of the world respond to a changing climate and other manifestations of global change, the international research enterprise has evolved toward Goals 2 (Inform Decisions) and 3 (Conduct Sustained Assessments), in part as a reflection of continued U.S. leadership in all four goal areas.

Advancing Science. Since its inception, USGCRP has invested and been involved in international global-change research through the international global-change research organizations (see Figure 28). Member agencies continue to be actively involved in international scientific research efforts by establishing U.S. offices for projects and programs, providing representation to the appropriate steering committees and secretariats, or facilitating involvement in strategic planning. USGCRP actively engages with international partners to ensure that cooperation on modeling continues to advance understanding of the climate system and to provide information at scales relevant to decision making. This is achieved through engagement with research initiatives such as WCRP, the 5th Coupled Model Intercomparison Project (CMIP5) and its successor CMIP6, and the Coordinated Regional Climate Downscaling Experiment (as well as data accessibility services such as the Program for Climate Model Diagnosis and Intercomparison and the Earth System Grid Federation. The United States continues to engage with various international observation networks, including but not limited to Committee on Earth Observation Satellites Group on Earth Observations (GEO), the Global Climate Observing System, Intergovernmental Oceanographic Commission, the Coordination Group on Meteorological Satellites), and WMO's Expert Team on Satellite Systems (where WMO is the primary sponsor of WCRP, alongside the United Nations Educational, Scientific, and Cultural Organization (UNESCO), IOC, and ICSU). Such efforts provide the United States with the ability to coordinate resources and leverage investments from other countries while fostering strategic planning for the establishment of Earth observations—both remote and non-satellite.

Inform Decisions. USGCRP will continue to work with partners to develop and enhance the capacity of researchers and decision makers in less-developed countries, as called for in the GCRA. These partnerships promote global-change research cooperation and focus on efforts to improve early-warning systems (including those for heat, famine, drought, and infectious disease surveillance) to help prepare for and prevent climate-related outbreaks and health emergencies. The USGCRP-supported START works in Africa and Asia to foster informed decision making on global change. The WMO-governed Global Framework for Climate Services (GFCS) is a valuable partner of USGCRP, as it provides an international mechanism to enhance the use of climate research across all time scales in decision making at global, regional, and national levels. USGCRP will continue promoting and fostering regional cooperation in global-change research through partnerships with key regional institutions, such as the Inter-American Institute for Global Change Research and the Asia-Pacific Network for Global Change Research.

Conduct Sustained Assessments. USGCRP will continue to build on its extensive experience in contributing to global, regional, and thematic scientific assessments. USGCRP has hosted a technical support unit (TSU) for the last several IPCC assessment cycles, mobilizing the U.S. scientific community to author and provide commentary for the IPCC and other assessments

(e.g., UN World Ocean Assessment, Climate Action Reports). USGCRP will not host a TSU in the 6th Assessment Report Cycle, but will continue to be closely involved in the assessment process. Research and researchers supported by USGCRP have also contributed to the annual Global Carbon Budget (GCB) released by the Global Carbon Project (GCP) over the last 10 years, of which USGCRP's U.S. Carbon Cycle Science Program (CCSP) is a major part. USGCRP has been involved in thematic assessments including the Ozone Assessment and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) assessment currently underway. These efforts provide important information about the state of global environmental, social, and economic aspects of global change. USGCRP will continue to work with partners to identify and scope themes, develop assessment processes, and mobilize the U.S. scientific community to draft and review these assessments. USGCRP provides travel support to enable non-Federal U.S. scientists to attend author meetings for key international assessments (e.g., IPCC). USGCRP contributions to such regional and global scientific undertakings help inform the direction of the U.S. research community.

Communicate and Educate. An increasing number of fields, including healthcare, agriculture, emergency preparedness and response, and city and regional planning, require knowledge about climate-related global-change science and impacts for decision making. At the international scale, USGCRP serves a critical role by coordinating the Education, Training, and Outreach reporting requirements of the U.S. National Communication to the UNFCCC. USGCRP member agencies also support the Global Learning and Observations to Benefit the Environment (GLOBE) Program to foster student and public participation in data collection and the scientific process.

Building on Progress

Increasing Global Access and Exchange of Data. The United States and USGCRP have always enacted and promoted open data sharing policies, and the global community is increasingly pursuing open data sharing policies to advance international scientific cooperation and innovation. This is evident through national-level initiatives as well as international efforts such as the G7 Open Data Charter, the Organisation of Economic Co-operation and Development Open Government Data Project, the Global Earth Observing System of Systems (GEOSS) Data Sharing Principles, the World Bank's Open Data Initiative, and the Belmont Forum's E-infrastructure and Data Management program. This gradual shift in policy in other countries will benefit each U.S. research effort through expanded access to observation and monitoring data that improve model skill. As progress is being made on the exchange of physical and biological data, there is increasing attention being focused on the incorporation of socio-economic data in research efforts for global sustainability. This is an emerging area that USGCRP will need to continue exploring through multilateral and bilateral partnerships.

International Field Campaigns. The USGCRP agencies and the scientists they fund participate in a number of international field campaigns to study climate-related global change issues (see Chapter III, Figure 15). Multinational cooperation allows for various combinations of satellite, land based, and airborne and marine platform observations to be combined for greater insight and to validate remote sensing observations (e.g., Oceans Melting Greenland (OMG), validation of the Global Precipitation Measurement satellite (GPM), the Next Generation Ecosystem

Experiments in the Tropics (NGEE-Tropics) and Arctic (NGEE-Arctic), and the Arctic-Boreal Vulnerability Experiment (ABoVE)). There is also increasing cooperation in providing international access to the field stations of multiple countries, particularly in remote areas with difficult access, and in building international scientific partnerships through collaborative work on focused field campaigns. International cooperation to support and operate surface-based networks is also critical to measuring global atmospheric characteristics, and they leverage resources effectively. Networks such as those used in the Advanced Global Atmospheric Gases Experiment bring together science agencies and academic communities worldwide, measuring the composition of the global environment since 1978. Another example is the Aerosol Robotic Network that uses a global array of ground-based networks to measure optical, microphysical and radiative properties of aerosols. The USGCRP agencies will continue to help develop and utilize these opportunities for strengthening scientific results and leveraging international investments.

Advancing Activities in Specific Research Areas. There are numerous research areas in which U.S. scientists and the USGCRP agencies cooperate internationally to leverage resources and achieve common science objectives. Informal cooperation among scientists of different countries occurs in virtually every area of USGCRP science. More formal relationships exist in WCRP's core projects, Climate Variability and Change (CLIVAR) and Global Energy and Water Cycles (GEWEX) studies (e.g., via the North American Carbon Program (NACP) and the Global Carbon Project (GCP), now housed within Future Earth), and included a USGCRP role in the internationally coordinated effort to quantify regional carbon fluxes (Regional Carbon Cycle Assessment and Processes (RECCAP)). USGCRP will continue to build on longstanding facilitation and coordination efforts, conducted by USGCRP member agencies with global partnerships, in key research programs, such as SERVIR, SilvaCarbon, and Dynamics of the Madden-Julian Oscillation (DYNAMO).

The Role of USGCRP in Future International Scientific Assessments. USGCRP will continue to help organize and support U. S. research community participation in international assessments, including the IPCC, the Arctic Monitoring and Assessment Program's (AMAP) Adaptation Actions for a Changing Arctic (AACA), and IPBES assessment now underway. Having played a significant role during the IPCC's Fifth Assessment Report cycle—hosting the U.S.-based Technical Support Unit responsible for all Working Group II (WGII) deliverables, and managing the Government review and expert nominations processes on behalf of the Department of State (DOS)—USGCRP will continue to be actively involved in the IPCC during its Sixth Assessment Report Cycle (AR6). In close collaboration with DOS, technical agencies, and the climate science community, USGCRP will manage nominations of U.S. experts to participate in scoping meetings and workshops, and to serve as writing team members and reviewers on a number of upcoming IPCC assessment products, both topical reports and the AR6 Synthesis Report.

USGCRP will also seek opportunities to cooperate with other international scientific assessments that build on priorities identified in this 2012–2021 Strategic Plan, as well as with those noted above. All assessments will involve USGCRP organization of U.S. Government reviews, including open calls to ensure broad participation of the scientific community, public comments collection vehicles, and expert panels to establish the U.S. position. USGCRP also will continue to administer a Climate Assessment Travel Fund that facilitates the participation of U.S. non-Federal scientists in international assessment activities.

Leveraging and Building on Successful Domestic Efforts. USGCRP is beginning to share its best practices and approaches in information technology with other countries, such as India, to support other national assessments. USGCRP has had a variety of successes that other governments and organizations are interested in leveraging for their national or organizational contexts. The NCA3 captured national and global attention for its scientific rigor, topical comprehensiveness, and accessibility. Sharing the results and lessons learned, and providing technical assistance, where feasible, are opportunities USGCRP will welcome. There is also emerging interest in expanding sustained-assessment efforts to include focused assessments in key regional transboundary areas such as the Arctic, which are supporting the U.S. Chairmanship of the Arctic Council (2015–2017) and other Arctic-related priorities for the United States and USGCRP.

Navigating Challenges

International opportunities for USGCRP to significantly leverage domestic investments in global-change research and scientific collaboration include participation in joint research calls for proposals, such as the Belmont Forum's Collaborative Research Actions. Beyond technical advancements in understanding the biophysical world, there is growing interest in cross-disciplinary collaboration among various stakeholders and disciplines in global-change research that have not traditionally been engaged. For example, integrating and advancing social-science research within the environmental context—a key goal of Future Earth and WCRP—is a challenging but essential component of basic global-change research and its societally-relevant aspects. While these new collaborators bring unique and valuable perspectives, as well as potential resources, an enhanced approach to research and funding mechanisms may be needed. The Belmont Forum has been able to quickly adapt to accommodate growing interest and participation by partners. USGCRP has been at the forefront in supporting recent success around the areas of identifying mechanisms for cooperation in multilateral research funding. This initial progress brings with it higher expectations and unique challenges in meeting those expectations.

The approval of the Paris Agreement adopted under the UNFCCC signifies a new era of global climate action. This presents a number of opportunities for USGCRP in the realm of capacity building, adaptation planning, development of Nationally Determined Contributions, and greenhouse gas emissions monitoring and reporting. Technical agencies will continue their collaboration with DOS (as U.S. Government lead in the UNFCCC) to best articulate how the expertise of the USGCRP enterprise can be most effectively leveraged to advance implementation of the Paris Agreement—both domestically and abroad.

The GCRA mandates the provision of technical assistance to developing nations and engagement with developing nations in cooperative global research programs—within the context of "facilitating improvements in the domestic standard of living while minimizing damage to the global or regional environment." USGCRP will continue supporting broad international initiatives, such as those discussed above, that help fill this gap at regional and national levels, considering those avenues where it can most effectively provide technical assistance to developing nations, given resource constraints. USGCRP recognizes the benefits of research in the development context and the importance of sustained collaborations.

The changing landscape of international cooperation is providing USGCRP with opportunities to both benefit from and contribute to global-change research advancements across the world. Building upon the progress made since 1989, both domestically and internationally, USGCRP is in an excellent position to take advantage of these opportunities, advance its position as a leader in global-change research coordination, and continue to execute the vision of international cooperation laid out in the GCRA.

Chapter V: Implementation Strategy

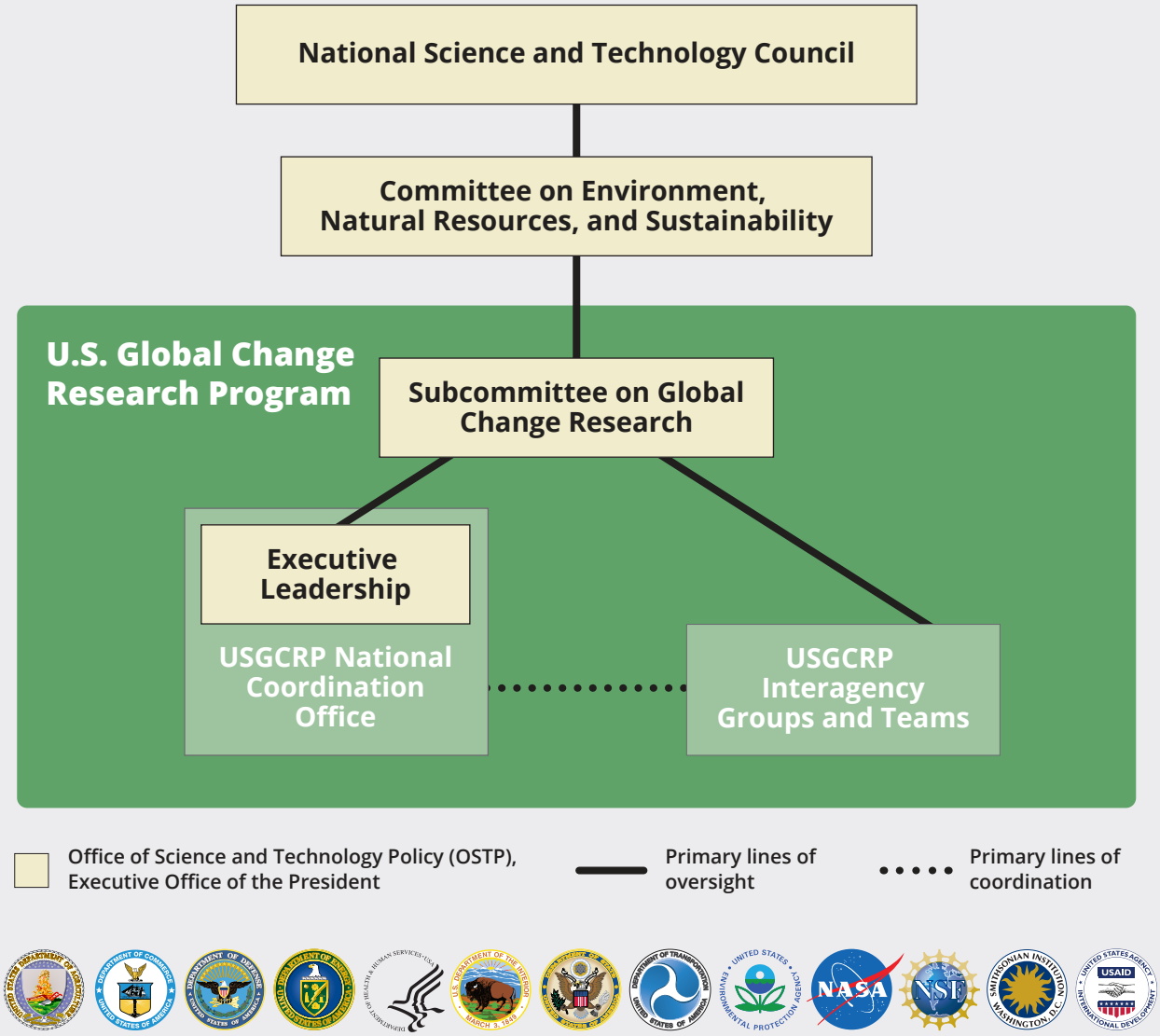
Since the release of the 2012–2021 Strategic Plan, USGCRP has adopted new, and refined prior, approaches to program implementation, with a focus on both advancing fundamental science and supporting its use in decision making. This chapter speaks to USGCRP governance and Program coordination, planning, and implementation, and the role of collaborative relationships in accomplishing USGCRP's goals. It also discusses USGCRP's sustained-assessment process, initiated under the 2012–2021 Strategic Plan, and its role as an important avenue for the Program in translating its science for decision makers, and incorporating decision maker needs into USGCRP's science planning and prioritization.

USGCRP Governance and Program Coordination

USGCRP consists of 13 Federal agencies that conduct or use research on global change and its impacts on society (see Figure 1). Research and related activities carried out by the agencies in support of USGCRP are guided and overseen (see Figure 29) by the Subcommittee on Global Change Research (SGCR), which is chartered under the Committee on Environment, Natural Resources, and Sustainability (CENRS), part of the National Science and Technology Council (NSTC). The SGCR consists of a Principal from each member agency, with liaisons to the Executive Office of the President's Offices of Science and Technology Policy (OSTP) and Management and Budget (OMB), and the Council on Environmental Quality. The SGCR Chair and co-Chair are nominated from one of the USGCRP member agencies. USGCRP Executive and Deputy Executive Directors, Federal employees on detail to the NSTC and OSTP, are responsible for overseeing coordination, integration, and planning activities of USGCRP, and the implementation of interagency efforts. In addition, they direct the activities of the National Coordination Office, an executive secretariat staffed by contractors and Federal detailees, which provides day-to-day coordination and support for the interagency activities of USGCRP. OSTP and OMB work closely with the SGCR to establish research priorities and funding plans to ensure that USGCRP's work aligns with national priorities, reflects agency planning, and meets the requirements of GCRA.

USGCRP's interagency groups and task teams are major vehicles for implementing the Program's strategic goals. They coordinate and implement research and related activities across the agencies and interact with agency stakeholders to use USGCRP's advancing science to shape actionable and accessible science, and feed stakeholder needs into the Program's strategic planning and prioritization (see Figure 30). The groups contribute to USGCRP strategic program planning, share information and maintain cooperation across the agencies, and report on their activities to the SGCR and the agencies. They contribute members to the task teams for the Arctic Research and Resilience, Water-Cycle Extremes, and Methane Cycling within the Carbon Cycle Context Priorities (see Chapter II, p. 15–22). As appropriate to their particular area of expertise and the stage of their projects, the IWGs develop reports, products,

Figure 29: USGCRP Governance

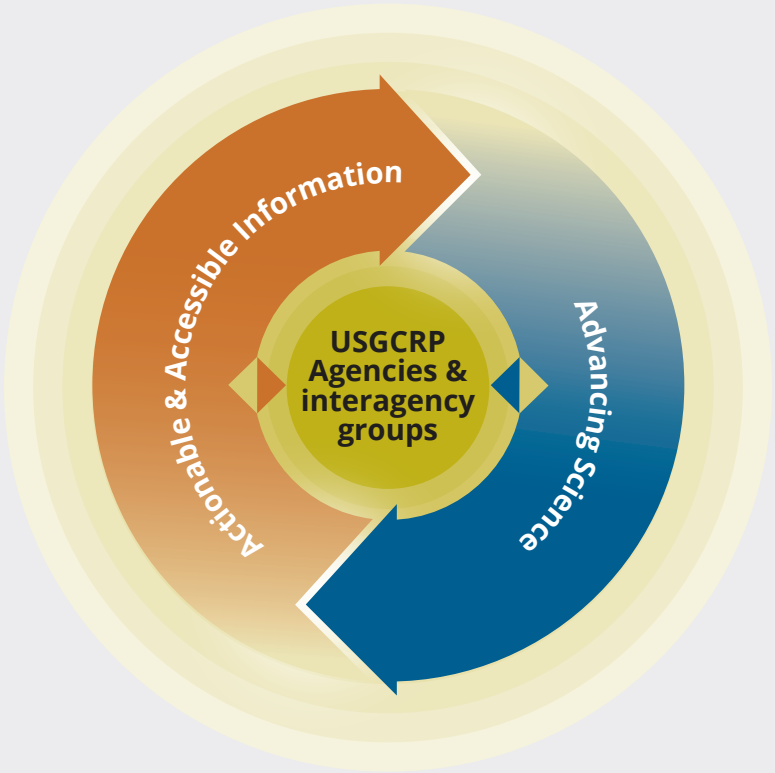


See paragraph on previous page for full explanation.

and tools for national use; develop or capitalize on interagency research solicitations; host webinars and workshops; and publish scientific papers. Upon request, some interact with the Executive Office of the President on particular activities, such as national prioritization efforts, climate preparedness exercises, and data portal development. A subset of agency and IWG activities may be seen in the annual *Our Changing Planet* report to Congress.

The interagency groups and teams coordinate both longstanding and emerging Program activities. Several are new since 2012, bringing together cross-agency expertise in areas of need identified in the 2012–2021 Strategic Plan. Cross-cutting groups, such as those for Carbon

Figure 30: USGCRP Implementation Strategy



USGCRP's Interagency Working Groups (IWGs) are key mechanisms in connecting basic science to actionable information needs. Current USGCRP IWGs include: process research, observations, integrative modeling, carbon cycle, climate change and human health, education, international activities, sustained assessment, indicators, scenarios, global change information, social-sciences coordination, and adaptation science. These groups contribute membership for the task teams charged with implementing the USGCRP interagency priorities of Arctic Research and Resilience, Water-Cycle Extremes and their Impacts, and Methane Cycling in the Context of the Carbon Cycle.

Cycle, International, Climate Change and Human Health, and Social Sciences Coordination, link across many areas of USGCRP activities and working groups. Priority Task Teams have been established to guide evolution and track progress in the USGCRP Interagency Priorities. The Task Teams foster cooperation across the working groups and all four pillars of the 2012–2021 Strategic Plan. Twenty non-member agencies participate in USGCRP working groups, bringing a response-oriented perspective to Program planning. Communication and cooperation among IWGs and the SGCR occur through a variety of mechanisms: IWG joint projects and planning; participation in developing the USGCRP annual interagency priorities and their implementation; IWG co-chair workshops and an annual all-IWG meeting; and regular programmatic reporting. The SGCR establishes interagency task teams as needed to scope potential new areas of USGCRP activity, conduct near-term planning, or other tasks.

Program Planning and Implementation

Strategic Framework

Structured around the GCRA, the 2012–2021 Strategic Plan is the cornerstone of USGCRP's strategic planning efforts, and its goals and objectives remain the guiding document for USGCRP priorities and activities. Triennial updates like this one draw from the 2012–2021 Strategic Plan and provide a sharpened focus that helps guide the Program in the nearer term. Annual strategic planning (for interagency priorities determined two years in advance) and ongoing sustained-assessment activities are other key elements of an integrated strategic framework for USGCRP. The guidelines for implementing the 2012–2021 Strategic Plan are detailed therein and briefly noted in Figure 31.

Figure 31: USGCRP Implementation Guidelines

- Advance a strong scientific foundation
- Phase in new activities thoughtfully
- Build/maintain a diverse portfolio that allows:
  - Consistent and freely available observations
  - Scientific exploration and science development for societal use
  - Leveraging of agency strengths and coordination across agencies
  - Transparent access to data and tools
  - Increasing interdisciplinary research, especially between natural and social sciences
  - Improving science translation and utilization
- Build collaborations that leverage USGCRP's science and increase its impact
- Enhance international partnerships
- Evaluate key aspects of performance
- Use adaptive management principles to improve performance

The USGCRP Interagency Priorities, shared annually with OSTP and OMB, spotlight specific areas within USGCRP that: 1) are responsive to the GCRA, current Strategic Plan, and Administration priorities; 2) evolve over several years as progress is made; 3) depend on progress in USGCRP's long-term investments; 4) are best accomplished by a collective, comprehensive multi-agency effort; and 5) may depend on unique capabilities of individual agencies in key areas. The priorities typically capitalize on—or help drive—advances in USGCRP core science capabilities in observations, modeling, process understanding, and making science actionable and accessible. Each priority is framed around areas of societal need, with an emphasis on emerging basic research areas, the harvesting of maturing science to inform decisions, and providing information to stakeholders. These areas are opportunities for the Program to improve its ability in some of the challenge areas identified in the Strategic Plan (e.g., integrating social-science needs into Program planning, broadening participation). These priorities help provide focus for IWG activities and collaboration. A team of SGCR and IWG members guide the evolution of the priorities over successive years.

USGCRP focal areas for Fiscal Years 2015, 2016, and 2017 are discussed in greater detail in Chapter II; related activities are discussed in Chapter III and accomplishments are highlighted in USGCRP's annual report to Congress, *Our Changing Planet*.

USGCRP's sustained-assessment process is a powerful tool for both strategic planning and tracking program performance (see Chapter III, Goal 3). The Program's 2016 *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* report brings a strong focus on modeling and understanding health impacts in the context of a changing climate. USGCRP is currently conducting special assessments on climate-change science, and

the state of the carbon cycle (see Chapter III, Figure 24), which will synthesize recent advances in research and understanding of impacts in these areas. Both will feed into NCA4. Internationally, USGCRP is participating in planning for the sixth Intergovernmental Panel on Climate Change Assessment Report and the special topics it will address, and other international efforts (see Chapter IV). These and other assessment reports will document scientific progress from USGCRP and other organizations, and identify research and capability needs.

The sustained-assessment process includes activities that support broader USGCRP goals, including a pilot indicators platform and the development of scenarios of likely future climate change and impacts in key sectors, drawing from USGCRP's Advance Science goal and providing resources to Program goals to Inform Decisions and Communicate and Educate (see Chapter III, Goal 3). It also includes processes that promote continuous and transparent participation of scientists and stakeholders across regions and sectors, enabling new information and insights to be synthesized as they emerge, and providing learning opportunities for the Program as a whole in strengthening stakeholder interactions. Key elements of this engagement include periodic Requests for Information from the public, a Federal Advisory Committee, interaction with the National Academies Committee to Advise USGCRP, and NCAnet (see Chapter III, Goal 3) in addition to routine and ongoing interaction through scientific meetings and ad hoc stakeholder forums.

Program Performance

Tracking program performance is important for demonstrating USGCRP's accomplishments and value, and guiding its evolution. As a multi-agency confederation based on joint priorities, it is inherently difficult to distinguish between the work that agencies would do independently and that done through the USGCRP consortium. In terms of performance, the Program is currently focusing attention on its successive National Climate Assessments (NCAs), which are the result of strong, ongoing interagency coordination and cooperation.

USGCRP is currently undertaking an external evaluation of NCA3. The framework for the evaluation draws from a 2014 Frameworks for Evaluating the National Climate Assessment community workshop that recommended quantitative and qualitative approaches to evaluating the impact of NCA3 products, including public events by its author team, and processes for stakeholder engagement, coordination, and co-production. The workshop recommendations are feeding into planning for NCA4, and the evaluation results will inform USGCRP's longer-term assessment planning. The Program also views the NCA3 evaluation as a learning tool for USGCRP in developing and using performance measures to guide future development. In addition, the National Academies' Committee to Advise USGCRP ("the Committee") is developing a review of Program accomplishments through the evaluation of assessments and their overall role in USGCRP, including lessons learned.

The Committee plays an important role in external evaluation and guidance for USGCRP. Formal mechanisms included its review of the 2012–2021 Strategic Plan, the NCA3, and the Climate Change and Health Assessment. Its reviews helped improve those publications and provided input that helps shape USGCRP's planning and direction-setting. The Committee also held a 2016 workshop to evaluate approaches for integrating a risk-based framework into parts of NCA4 (see Goal 3), and more broadly in subsequent years. In addition to the formal

reviews and workshops, the Committee meets with the SGCR one to two times a year. Recent and upcoming topics of those meetings include the Program's progress toward implementing its Strategic Plan, approaches towards this update of the Strategic Plan, and the role of broader engagement in helping USGCRP meet the Nation's needs in preparing (adapting and mitigating) for the impacts of climate change. The National Academies' recent report, *Enhancing Participation in the U.S. Global Change Research Program*, provides thoughtful examples of general strategies and specific actions that USGCRP can take to deepen its connections within the public and private sectors.

Collaborative Relationships

Interagency Collaboration

The USGCRP member agencies participate in programmatic areas related to their mission and strengths. Coordination across these areas, guided by USGCRP's Strategic Plan, creates a comprehensive framework implemented by the IWGs and the agencies. Each agency depends on the work of others, and all depend on the observing and modeling capability developed by a few agencies. Looking ahead, the SGCR is working to more systematically engage the non-research and development parts of its member departments or agencies, to bring that broader perspective into USGCRP planning.

Collaboration among USGCRP agencies, and with non-member Federal agencies, is critical to implementing the 2012–2021 Strategic Plan and helping the Nation prepare for and respond to climate-related global change and its impacts. *Our Changing Planet* annually showcases some of the outcomes from interagency cooperation, including those involving non-member agencies. Cooperation between the Federal Emergency Management Agency (FEMA) and the USGCRP agencies, for example, produced a sea-level rise tool for recovery after Superstorm Sandy and resilience preparedness exercises in different parts of the county. In identifying science needs for adaptation, USGCRP mines input from all Federal agencies that file Climate Change Adaptation Plans, not just USGCRP member agencies. Representatives from non-member agencies participate regularly in many USGCRP IWGs, bringing a more response-oriented perspective to the Program.

USGCRP is developing closer cooperation with other Subcommittees under the NSTC CENRS as a way of strengthening its connections with other Federal interagency groups (and their members) working in related areas. For example, USGCRP's Arctic priority is developed and tracked through the U.S. Arctic Executive Steering Committee in cooperation with the Interagency Arctic Research Policy Committee, building on the National Arctic Strategy. USGCRP is also working with the National Ocean Council and its subgroup, the Subcommittee on Ocean Science and Technology, in areas related to the Arctic; the ocean's role in climate; ocean acidification; the development of future sea-level rise scenarios for the U.S. coastline; and the incorporation of sea-level rise into Federal agency coastal flood hazard mapping tools. As another example, the National Plan for Civil Earth Observations, developed by OSTP through an interagency effort led by the U.S. Group on Earth Observations, places a high priority on sustaining observations for Earth systems research, directly supporting USGCRP's strategic goals. USGCRP is taking action to further strengthen these relationships, where they can result in more

cohesive Government preparation for climate change. Within the CENRS, the Program brings the longer time perspective of future climate change to the work of other Subcommittees.

External Relationships

As stated in the Strategic Plan, USGCRP is committed to better connecting its science and science products with science users. The Program aims to understand stakeholder needs, facilitate stakeholder uptake of USGCRP science and products, and foster co-development of scientific assessments and other products as appropriate, with the goal of establishing a bi-directional dialogue between science producers and users that feed into programmatic planning (see Figures 13 and 25). That said, the ever-growing call for climate and global change information, across all sectors and at scales from local to global, puts considerable pressure on Program resources.

In addressing that need, USGCRP is grounded in its strengths as an interagency research program, recognizing that it lacks the capacity to interact with all potential users. Rather, USGCRP information is often used by other government and non-governmental organizations to provide customized knowledge at the local and community levels (e.g., the Climate Data and Tools through the U.S. Climate Data Initiative (CDI), and FEMA Climate Resilience Exercises at the regional and community scales). Through the Resilience Dialogues, USGCRP is taking on a leading role in building on a pilot project that connected city planners with scientists via a web platform and webinars, to ensure the most appropriate science is shared and used, and to understand decision needs. In terms of providing science information, all USGCRP data are freely available to all users, and the Global Change Information System is increasing the discoverability of Federal climate data linked to science translation products like the NCA. USGCRP's new pilot indicators effort shows trends over time in key aspects of climate-related change, in formats intended for decision makers. USGCRP will explore adding new indicators to the initial pilot suite and will evaluate their utility for decision makers. USGCRP agency participation in Administration efforts like the Climate Data Initiative and Climate Resilience Toolkit is contributing to tools and data in targeted topics of particular societal interest, including climate change and human health, water, coastal flooding and resilience, and the Arctic.

USGCRP is able to interact with stakeholders and understand their needs primarily through two avenues: via the agencies and through the sustained-assessment enterprise. Member agencies feed their stakeholder interests and needs into the USGCRP strategic planning process, including this update and the development of annual interagency priorities, which include an element of actionable science and informing stakeholders. The regional science organizations of the USGCRP member agencies (e.g., DOI Climate Science Centers, NOAA Regional Integrated Science and Assessment program, and USDA Regional Climate Hubs) are playing an increasingly important pathway for stakeholder interaction. The NCA3, from the start, incorporated stakeholder engagement into the development of the report and its related products, and is expanding on this effort as part of the sustained-assessment process. NCAnet, a self-selecting and self-organizing group of collaborators, brings together more than 180 professional societies, non-governmental organizations, and other private and public sector organizations to discuss key regional and sectoral topics of interest to the members. They provide awareness of non-Federal science that is available, and of information needs outside the Government, all

of which feed into sustained assessment and planning for NCA4. They also enhance uptake of USGCRP products. Stakeholder engagement through the agencies and via the sustained assessment are important to USGCRP's engagement at the regional level, and with a number of agency regional groups participating in the NCA.

USGCRP recognizes that relationships beyond the public sector are becoming increasingly important, as many areas of business are moving to include global change information in their financial and business planning, a point made in a letter report from the President's Council of Advisors on Science and Technology. The Program is moving forward in this area, learning from experiences with the Climate Data Initiative. A next step for USGCRP is with the Resilience Dialogues and the private-public collaboration that supports the effort. Goals for any such partnerships undertaken by USGCRP would include: co-production of knowledge that is made universally and freely available; uptake of USGCRP knowledge by the private sector into translational science or tools that serve specific constituencies; and understanding science needs.

Appendix I. Program Activity Description by Agency/Department

This section summarizes the principal focus areas related to global-change research for each USGCRP member agency.

Department of Agriculture

The U.S. Department of Agriculture's (USDA's) Climate Change Research Program empowers land managers, policy makers, and its agencies with science-based knowledge to manage the risks and opportunities posed by climate change, reduce greenhouse gas (GHG) emissions, and enhance carbon sequestration. USDA's Climate Change Research Program includes contributions from the Agricultural Research Service (ARS), the National Institute of Food and Agriculture (NIFA), the Forest Service (USDA-FS), Natural Resources Conservation Service (NRCS), National Agricultural Statistics Service (NASS), and Economic Research Service (ERS). In addition to these agencies, programmatic and operational support for adaptation preparedness and resilience, greenhouse gas mitigation, and outreach and education are contributed by the Risk Management Agency (RMA) and Rural Development (RD), the Animal and Plant Health Inspection Service (APHIS), the Farm Service Agency (FSA), the Office of the Chief Economist (OCE), and Departmental Management Offices (DM). USDA has established Regional Climate Hubs for Risk Adaptation and Mitigation. Together the many USDA research and programmatic entities help ensure sustained food security for the Nation and the World. They maintain and enhance the health of U.S. forests, rangelands and natural resources while identifying ways to manage the risks and vulnerabilities ranging from temperature and precipitation extremes to the changing biology of pests, invasive species, increased wildfire intensity and extent, and diseases.

USDA develops GHG inventories and conducts assessments and projections of climate-change impacts on the natural and economic systems associated with agricultural production and forest and forest products. USDA also develops cultivars, cropping systems, and management practices to improve drought tolerance and build resilience to climate variability. The USDA Building Blocks for Climate Smart Agriculture and Forestry framework spans a range of technologies and conservation practices to reduce greenhouse gas emissions, increase carbon storage, and generate renewable energy. USDA both conducts research and promotes integration of USGCRP research findings into farm and natural resource management, and helps build resiliency to climate change by developing and deploying decision support through its Regional Climate Hubs network and delivers science-based region-specific information and technology. USDA maintains critical long-term data collection and observation networks, including the Long-Term Agro-ecosystem Research (LTAR) Network, the Snowpack Telemetry (SNOTEL) network, the Soil Climate Analysis Network (SCAN), the National Resources Inventory (NRI), and the Forest Inventory and Analysis (FIA). Finally, USDA engages in communication, outreach, and education through multiple forums, including its vast network of agricultural extension services, its field offices, and its Regional Climate Hubs.

Department of Commerce

The National Oceanic and Atmospheric Administration (NOAA) and the National Institute of Standards and Technology (NIST) comprise the Department of Commerce's (DOC's) participation in USGCRP.

NOAA's strategic climate goal is "an informed society anticipating and responding to climate and its impacts." NOAA's overall objective is to provide decision makers with a predictive understanding of the climate, to describe the state of the climate system and how it is evolving, and to communicate climate information so that people can make more informed decisions in their lives, businesses, and communities. These outcomes are pursued by developing complementary global *in situ* and satellite observing systems providing environmental data and product information for monitoring environmental changes, supporting research to understand these changes and their impacts, and supporting national weather and climate prediction services. Additionally, NOAA conducts research to understand climate processes, develops improved modeling capabilities, and develops and deploys climate educational programs and information services. NOAA aims to achieve its climate goal through the following strategic objectives:

- Improved scientific understanding of the changing climate system and its impacts;
- Assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions;
- Mitigation and adaptation efforts supported by sustained, reliable, and timely climate services; and
- A climate-literate public that understands its vulnerabilities to a changing climate and makes informed decisions.

NOAA is leading development of global ocean observing systems and products as well as atmospheric constituents and composition. Optimizing and improving such systems, e.g., through testing and incorporation of new technologies, is contributing towards new lines of research and information services. Authoritative records of environmental changes are routinely updated providing the nation with the latest information on short- and long-term trends and extremes. NOAA's complementary observing systems for weather, marine, ecosystems, and coasts also contribute towards NOAA's climate mission.

NIST works with other Federal agencies to develop or extend internationally accepted traceable measurement standards, methodologies, and technologies that enhance measurement capabilities for greenhouse gas emission inventories and measurements critical to advancing climate science research. NIST provides measurements and standards that support accurate, comparable, and reliable climate observations and provides calibrations and special tests to improve the accuracy of a wide range of instruments and techniques used in climate research and monitoring.

Department of Defense

The Department of Defense (DOD)—while not supporting a formal mission dedicated to global-change research—is developing policies and plans to manage and respond to the effects of climate change on DOD missions, assets, and the operational environment. Various research agencies within DOD sponsor and undertake basic research activities that concurrently satisfy both national security requirements as well as the strategic goals of USGCRP. These include the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Office, and the Defense Advanced Research Projects Agency. When applicable, the research activities of these agencies are coordinated with other Federally sponsored research via USGCRP and other entities.

Because the performance of DOD systems and platforms are influenced by environmental conditions, understanding the variability of the Earth's environment and the potential for change is of great interest to the Department. DOD is responsible for the environmental stewardship of hundreds of installations throughout the U.S., and must continue incorporating geostrategic and operational energy considerations into force planning, requirements development, and acquisition processes. DOD relies on the Strategic Environmental Research and Development Program, a joint effort among DOD, DOE, and EPA, to develop climate-change assessment tools and to identify the environmental variables that must be forecasted with sufficient lead time to facilitate appropriate adaptive responses. Each service agency within DOD incorporates the potential impact of global change into their long-range strategic plans. For example, the Navy's Task Force Climate Change assists in the development of science-based recommendations, plans, and actions to adapt to climate change. The U.S. Army Corps of Engineers Engineer Research and Development Center Cold Regions Research and Engineering Laboratory (CRREL) also actively investigates the impacts of climate trends for DOD and other agencies. The CRREL research program responds to the needs of the military, but much of the research also benefits the civilian sector and is funded by non-military entities including NSF, NOAA, NASA, DOE, and state governments.

Department of Energy

The Department of Energy's (DOE) Office of Science supports fundamental research to understand the energy-environment-climate connection and its implications for energy production, use, sustainability, and security—with particular emphasis on the potential impact of increased anthropogenic GHG emissions. The ultimate goal is to advance a robust predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the Nation's energy and environmental challenges.

Two DOE research areas focus on areas of uncertainty in Earth System Models: Atmospheric System Research (science of aerosols, clouds, and radiative transfer); and Terrestrial Ecosystem Science (role of terrestrial ecosystems and carbon cycle observations). DOE supports climate model codes designed for Leadership Class Computational Facilities, including the Accelerated Climate Model for Energy. DOE also collaborates with NSF to develop the widely used Community Earth System Model, supports methods to obtain regional climate information, integrates analysis of climate-change impacts, and analyzes and distributes large climate datasets through the Program for Climate Model Diagnosis and Intercomparison and the Earth

System Grid. DOE also supports the Atmospheric Radiation Measurement Climate Research Facility, an interagency scientific user facility that provides the research community with unmatched measurements permitting the most detailed high-resolution, three-dimensional documentation of evolving cloud, aerosol, and precipitation characteristics in climate-sensitive sites around the world.

DOE also conducts applied climate-related research, centered in DOE's Office of Energy Policy and Systems Analysis and Office of Policy and International Affairs. These programs develop and utilize energy-economic models, including Integrated Assessment Models, to evaluate policies and programs that enable cost-effective GHG reductions and accelerate the development and deployment of clean energy technologies. This includes supporting work to characterize climate-change impacts for use in policy analysis, vulnerability and adaptation assessments, and agency rulemakings. DOE also conducts assessments of climate change on electric grid stability, water availability for energy production, and site selection for the next generation of renewable energy infrastructure.

Department of Health and Human Services

The U.S. Department of Health and Human Services (HHS) supports a broad portfolio of research and decision support initiatives related to environmental health and the health effects of global climate change, primarily through the National Institutes of Health and the Centers for Disease Control and Prevention. Research focuses on the need to better understand the vulnerabilities of individuals and communities to climate-related changes in health risks such as heat-related morbidity and mortality, respiratory effects of altered air contaminants, changes in transmission of infectious diseases, and impacts in the aftermath of severe weather events, among many others. Research efforts also seek to assess the effectiveness of various public-health adaptation strategies to reduce climate vulnerability, as well as the potential health effects of interventions to reduce GHG emissions.

Specifically, HHS supports USGCRP by conducting fundamental and applied research on linkages between climate change and health, translating scientific advances into decision-support tools for public-health professionals, conducting ongoing monitoring and surveillance of climate-related health outcomes, and engaging the public-health community in two-way communication about climate change.

Department of the Interior

The U.S. Geological Survey (USGS) conducts global-change research for the Department of the Interior (DOI) and constitutes DOI's formal participation in USGCRP.

USGS scientists work with other agencies to provide policy makers and resource managers with scientifically valid information and predictive understanding of global change and its effects with the ultimate goal of helping the Nation understand, adapt to, and mitigate global change.

Specifically, the USGS Climate and Land Use Change Research and Development Program supports research to understand processes controlling Earth system responses to global change

and model impacts of climate and land-cover change on natural resources. The USGS Land Change Science and Land Remote Sensing programs (such as the Landsat satellite mission and the National Land Cover Database) provide data that is used to assess changes in land use, land cover, ecosystems, and water resources resulting from the interactions between human activities and natural systems. The science products and datasets from these programs are essential for DOI's biological carbon sequestration project (LandCarbon), which is conducting quantitative studies of carbon storage and GHG flux in the Nation's ecosystems.

USGS also leads the regional DOI Climate Science Centers that provide science and technical support to other bureaus as well as region-based partners, such as Landscape Conservation Cooperatives (LCCs), that are dealing with the impacts of climate change on fish, wildlife, and ecological processes. The LCCs complement and work closely with the CSCs, focusing on convening partners, developing shared plans, and delivering applied tools for addressing climate change and other landscape-scale stressors.

Department of State

Through the Department of State (DOS) annual funding, the U.S. is the world's leading financial contributor to the United Nations Framework Convention on Climate Change (UNFCCC) and to the Intergovernmental Panel on Climate Change (IPCC)—the principal international organization for the assessment of scientific, technical, and socioeconomic information relevant to the understanding of climate change, its potential impacts, and options for adaptation and mitigation. Recent DOS contributions to these organizations provide substantial support for global climate observation and assessment activities in developing countries. DOS also works with other agencies in promoting international cooperation in a range of bilateral and multilateral climate-change initiatives and partnerships.

Department of Transportation

The Department of Transportation (DOT) conducts research to examine potential climate-change impacts on transportation, methods for increasing transportation efficiency, and methods for reducing emissions that contribute to climate change. DOT's Center for Climate Change and Environmental Forecasting coordinates transportation and climate-change research, policies, and actions within DOT and promotes comprehensive approaches to reduce emissions, address climate-change impacts, and develop adaptation strategies. DOT also contributes directly to USGCRP's National Climate Assessment through focused research such as the Center's Gulf Coast Studies. The Gulf Coast Phase 2 study, completed in FY 2015, developed tools to assist transportation agencies in performing climate change and extreme weather vulnerability assessments and build resilience.

The Federal Aviation Administration (FAA) works closely with USGCRP and its participating agencies to identify and address key scientific gaps regarding aviation climate impacts and to inform mitigation solutions. Other DOT initiatives to address climate change and improve the sustainability of the U.S. transportation sector follow:

- The Federal Highway Administration and other DOT agencies are undertaking climate impact and adaptation studies (including vulnerability and risk assessments), working with science agencies to develop regional climate data and projections, conducting methodological research, supporting pilot programs, and providing assistance to transportation stakeholders including state and local agencies. DOT has requested additional funding in FY 2016 for these purposes. The Federal Transit Administration (FTA) completed seven Climate Change Adaptation Pilot studies to advance the state of the practice in adapting transit assets and operations to the impacts of climate change.
- The FAA manages the Continuous Lower Energy, Emissions, and Noise program as a government–industry consortium to develop technologies for energy efficiency, noise and emissions reduction, and sustainable alternative jet fuel. FAA also participates in the Commercial Aviation Alternative Fuels Initiative, a public–private coalition to encourage the development of sustainable alternative jet fuel.

Environmental Protection Agency

The core purpose of the Environmental Protection Agency's (EPA's) global-change research program is to develop scientific information that supports policy makers, stakeholders, and society at large as they respond to climate change and associated impacts on human health, ecosystems, and socioeconomic systems. EPA's research is driven by the Agency's mission and statutory requirements, and includes: (1) improving scientific understanding of global change effects on air quality, water quality, ecosystems, and human health in the context of other stressors; (2) assessing and defining adaptation options to effectively prepare for and respond to global change risks, increase resilience of human and natural systems, and promote their sustainability; and (3) developing an understanding of the potential environmental and human health impacts of GHG emission reduction technologies and approaches to inform mitigation solutions. EPA Program Offices and Regions leverage this research to support mitigation and adaptation decisions and to inform communication with external stakeholders and the public.

EPA relies on USGCRP to develop high-quality scientific models, data, and assessments to advance understanding about physical, chemical, and biological changes to the global environment and their relation to drivers of global climate change. Satellite and other observational efforts conducted by USGCRP agencies are crucial to supporting EPA's efforts to understand how land-use change, population change, climate change, and other global changes are affecting ecosystems, and the services they provide. EPA's global-change research applies and extends these results using regional and local air quality, hydrology, and sea-level rise models to better understand the impacts of climate change to specific human health and ecosystem endpoints in ways that enable local, regional, and national decision makers to develop and implement strategies to protect human health and the environment. In turn, EPA's research provides USGCRP agencies with information and understanding about the connections between global change and impacts at local, regional, and national scales, as well as how mitigation and adaptation actions may influence global changes.

EPA's research informs approaches to prepare for, adapt to, and minimize the impacts of climate change, including extreme weather events, wildfire, and rising sea levels, and their impacts on human health and well-being and social and economic systems. Other EPA program

activities include the development and application of economic and biophysical models to generate projections of potential future greenhouse gas emissions trajectories and mitigation scenarios. EPA also applies long-term datasets and analytical tools to communicate observed climate change indicators and conduct economic and risk modeling to examine and project analyze impacts and economic damages associated with global mitigation scenarios. EPA collaborates with other agencies and numerous stakeholders to develop the Inventory of U.S. Greenhouse Gas Emissions and Sinks, which is submitted to the United Nations in accordance with the Framework Convention on Climate Change. Lastly, EPA efforts include technical evaluation of biogenic emissions fluxes associated with biomass use for energy.

National Aeronautics and Space Administration

NASA's global change activities have four integrated foci: satellite observations, research and analysis, applications, and technology development. Satellites provide critical global atmosphere, ocean, land, sea ice, and ecosystem measurements. NASA's 22 on-orbit satellite missions (as of July 2016) measure numerous variables required to enhance understanding of Earth interactions. NASA is now routinely providing data from satellites launched in the 12-month period from February 2014 to January 2015: including precipitation data from the Global Precipitation Measurement (GPM), carbon dioxide data from the Orbiting Carbon Observatory-2 (OCO-2), and soil moisture data from the Soil Moisture Active Passive (SMAP), as well as wind and aerosol/cloud data from two payloads aboard the International Space Station (ISS), RapidScat and Cloud-Aerosol Transport System, respectively. NASA is also contributing to ocean and atmosphere observations with satellites launched by interagency partners (Jason-3, Deep Space Climate Observatory). NASA has delivered two payloads for planned late 2016 launch to the ISS: the Lightning Imaging Sensor, and the Stratospheric Aerosol and Gas Experiment-III. In November 2016, NASA will launch the Cyclone Global Navigation Satellite System constellation of eight nanosatellites to study winds associated with tropical storms and severe weather systems. In 2016, NASA selected two additional satellite missions as part of its Earth Venture–Instrument series of missions: 1) the Multi-Angle Imager for Aerosols, which will provide observations of small atmospheric aerosol particles to be combined with health information to determine the toxicity of different particulate matter types in airborne pollutants over the world's major cities; and 2) Time-Resolved Observations of Precipitation structure and storm intensity with a Constellation of Smallsats, which will develop and launch a constellation of CubeSats to study the development of tropical cyclones through rapid-revisit sampling.

The Administration's FY 2017 budget also enables NASA to continue its program in sustainable land imaging (in coordination with the U.S. Geological Survey) and in long-term monitoring responsibility for environmental parameters not directly in support of weather forecasting, such as solar radiation, Earth radiation budget, ozone vertical profile, and sea-surface height.

NASA's program advances observing technology and leads to new and enhanced space-based observation and information systems. The Earth science research program explores interactions among the major components of the Earth system—continents, oceans, atmosphere, ice, and life—to distinguish natural from human-induced causes of change and to understand and predict the consequences of change. NASA makes significant investments to assure the quality and integration of data through calibration and validation efforts that include satellite,

surface, and airborne measurements, as well as data intercomparisons. NASA also carries out observationally driven modeling projects that include data assimilation, reanalysis, process representation, initialization, and verification. Six significant new multi-year airborne campaigns initiated in 2015 began deployment in 2016. They address major global environmental issues: sources and sinks of atmospheric carbon in the continental United States; the role of the ocean in melting of ice sheets at the coast of Greenland; the effects of biomass burning in Africa on cloud structure off its western coast; the latitudinal variation of radiatively- and chemically-active trace constituents in the upper troposphere over the Atlantic and Pacific oceans; and the seasonal variation of biological productivity in the North Atlantic ocean and its implications for the overlying atmosphere. Applications projects extend the societal benefits of NASA's research, technology, and spaceflight programs to the broader U.S. public through the development and transition of user-defined tools for decision support, and are focused on such areas as water resources, health/air quality, and ecological forecasting. The Earth science technology program enables previously infeasible science investigations, improves existing measurement capabilities, and reduces the cost, risk, and/or development times for Earth science instruments. During the FY 2016/FY 2017 time frame it will launch several small satellites as part of its InSpace Validation of Earth Science Technologies.

National Science Foundation

The National Science Foundation (NSF) addresses global-change issues through investments that advance frontiers of knowledge, provide state-of-the-art instrumentation and facilities, develop new analytical methods, and enable cross-disciplinary collaborations while also cultivating a diverse, highly trained workforce and developing educational resources. In particular, NSF global-change programs support the research and related activities to advance fundamental understanding of physical, chemical, biological, and human systems and the interactions among them. The programs encourage interdisciplinary approaches to studying Earth system processes and the consequences of change, including how humans respond to changing environments and the impacts on ecosystems and the essential services they provide. NSF programs promote the development and enhancement of models to improve understanding of integrated Earth system processes and to advance predictive capability. NSF also supports fundamental research on the processes used by organizations and decision makers to identify and evaluate policies for mitigation, adaptation, and other responses to the challenge of a changing and variable environment. Long-term, continuous, and consistent observational records are essential for testing hypotheses quantitatively and are thus a cornerstone of global-change research. NSF supports a variety of research observing networks that complement, and are dependent on, the climate monitoring systems maintained by its sister agencies.

NSF regularly collaborates with other USGCRP agencies to provide support for a range of multidisciplinary research projects and is actively engaged in a number of international partnerships.

Smithsonian Institution

Within the Smithsonian Institution, global-change research is primarily conducted at the National Air and Space Museum, the National Museum of Natural History, the National Zoological Park, the Smithsonian Astrophysical Observatory, the Smithsonian Environmental Research

Center, and the Smithsonian Tropical Research Institute. Research is organized around themes of atmospheric processes, ecosystem dynamics, observ¬ing natural and anthropogenic environmental change on multiple time scales, and defining longer-term climate proxies present in the historical artifacts and records of the museums as well as in the geologic record. Most of these units participate in the Smithsonian's Global Earth Observatories, examining the dynamics of forests (ForestGEO, formerly SIGEO) and coastal marine habitats (MarineGEO) over decadal time frames.

The Smithsonian Grand Challenge for Understanding and Sustaining a Biodiverse Planet brings together researchers from around the Institution to focus on joint programs ranging from estimating volcanic emissions to ocean acidification measurement. Smithsonian paleontological research documents and interprets the history of terrestrial and marine ecosystems from 400 million years ago to the present. Other scientists study the impacts of historical environmental change on the ecology and evolution of organisms, including humans. Archaeobiologists examine the impact of early humans resulting from their domestication of plants and animals, creating the initial human impacts on planetary ecosystems.

These activities are joined by related efforts in the areas of history and art, such as the Center for Folklife and Cultural History, the National Museum of the American Indian, and the Cooper Hewitt, Smithsonian Design Museum to examine human responses to global change, within communities, reflected in art and culture, food, and music. Finally, Smithsonian outreach and education expands our scientific and social understanding of processes of change and represents them in exhibits and programs, including at the history and art museums of the Smithsonian. USGCRP funding enables the Smithsonian to leverage private funds for additional research and education programs on these topics.

U.S. Agency for International Development

The U.S. Agency for International Development (USAID) supports programs that enable decision makers to apply high-quality climate information to decision making. USAID's climate-change and development strategy calls for enabling countries to accelerate their transition to climate resilient, low emissions economic development through direct programming and integrating climate-change adaptation and mitigation objectives across the Agency's development portfolio. USAID is the lead contributor to bilateral development assistance, with a focus on capacity building, civil society building, and governance programming, and creating the legal and regulatory environments needed to address climate change. USAID leverages scientific and technical resources from across the U.S. Government (for example, from NASA, NOAA, USDA, USGS) as it applies its significant technical expertise to provide leadership in development and implementation of low-emissions development strategies, creating policy frameworks for market-based approaches to emission reduction and energy sector reform, promoting sustainable management of agriculture lands and forests, and mainstreaming adaptation into development activities in countries most at risk. USAID has long-standing relationships with host country governments that enable them to work together to develop shared priorities and implementation plans. USAID's engagement and expertise in agriculture, biodiversity, infrastructure, and other critical climate-sensitive sectors provide an opportunity to implement innovative cross-sectoral climate-change programs. Finally, USAID bilateral programs work in key political and governance areas where multilateral agencies cannot.

Appendix II. Acronym List

AACA	Adaptation Actions for a Changing Arctic
ABoVE	Arctic Boreal Vulnerability Experiment
ACAPEX	CalWater2/ARM Cloud-Aerosol Precipitation Experiment
AMAP	Arctic Monitoring and Assessment Programme
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
ARS	Agricultural Research Service
ASIWG	Adaptation Science Interagency Working Group
AUV	Autonomous underwater vehicle
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
CATS	RapidScat and Cloud-Aerosol Transport System
CCAP	Climate Change Adaptation Plans
CCSP	U.S. Carbon Cycle Science Program
CDAT	Chemical Data and Tools
CDC	Centers for Disease Control and Prevention
CDI	Climate Data Initiative
CENRS	Committee on Environment, Natural Resources, and Sustainability
CLIVAR	Climate Variability and Predictability
CMIP	Coupled Model Intercomparison Project
COP	Conference of Parties to the UNFCCC
CRT	Climate Resilience Toolkit
DISCOVER-AQ	Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality

DNA	Deoxyribonucleic Acid
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
DOT	Department of Transportation
DYNAMO	Dynamics of the Madden-Julian Oscillation
ENSO	El Nino/Southern Oscillation
EO	Executive Order
EOP	Executive Office of the President
EPA	Environmental Protection Agency
ESM	Earth System Models
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
ForestGEO	Smithsonian's Global Earth Observatories examining the dynamics of forests (formerly SIGEO)
FTA	Federal Transit Administration
FY	Fiscal Year
G7	the Group of Seven (United States, Canada, France, Germany, Italy, Japan, and the United Kingdom)
GCB	Global Carbon Project
GCI	Global Change Information
GCIS	Global Change Information System
GCM	General Circulation Model
GCP	Global Carbon Project
GCRA	Global Change Research Act of 1990
GEO	Group on Earth Observations

GEOSS	Group on Earth Observation System of Systems
GEWEX	Global Energy and Water Cycle Exchanges project
GFCS	Global Framework for Climate Services
GLOBE	Global Learning and Observations to Benefit the Environment
GPM	Global Precipitation Measurement
HHS	Department of Health and Human Services
IAM	Integrated Assessment Model(ing)
IAV	Impacts, Adaptation, and Vulnerability Model(ing)
IARPC	Interagency Research Policy Committee
ICESat	Ice, Cloud, and Land Elevation Satellite
ICSU	International Council on Science
IGBP	International Geosphere-Biosphere Program
IHDP	International Human Dimensions Programme
IOC	International Oceanic Commission
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISSC	International Social Science Council
IWG	Interagency Working Group
LiDAR	Light Detection and Ranging
MarineGEO	Marine Global Earth Observatories Network
MATCH	Metadata Access Tool for Climate and Health
MIP	Model Intercomparison Project
NACP	North American Carbon Program
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCA	National Climate Assessment

NCA3	Third National Climate Assessment
NCA4	Fourth National Climate Assessment
NCAnet	National Climate Assessment network
NCO	National Coordination Office
NGEE-Arctic	Next-Generation Ecosystem Experiments Arctic
NGEE-Tropics	Next-Generation Ecosystem Experiments Tropics
NGO	Non-Governmental Organization
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
Obs4MIPS	Observations for Model Intercomparison Projects
OCP	*Our Changing Planet*
OMB	Office of Management and Budget
OMG	Oceans Melting Greenland
OSTP	Office of Science and Technology Policy
PCAP	President's Climate Action Plan
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PECAN	Plains Elevated Convection at Night
PREP	Partnership for Resilience and Preparedness
RCP	Representative Concentration Pathway
SERVIR	Regional Visualization and Monitoring System
SGCR	Subcommittee on Global Change Research
SMAP	Soil Moisture Active Passive
SOCCR-2	Second State of the Carbon Cycle Report

SOST	Subcommittee on Ocean Science and Technology
SSCC	Social Sciences Coordinating Committee
START	global change SysTem for Analysis, Research, and Training
UAS	Uninhabited Aerial System
UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
USGEO	U.S. Group on Earth Observations
WAIS	West Antarctic Ice Sheet
WCRP	World Climate Research Program
WGI, WGII, WGIII	Working Group one, two, and three (of the IPCC)
WMO	World Meteorological Organization

Appendix III. Glossary of Terms

Adaptation: adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.

Adaptation science: scientific research that directly contributes to enabling adjustments in natural or human systems to a new or changing environment in a way that exploits beneficial opportunities or moderates negative effects.

Adaptive capacity: the potential of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, take advantage of opportunities, and cope with the consequences.

Adaptive management: a structured process of flexible decision-making that incorporates learning from outcomes and new scientific information. The process facilitates decision-making by resource managers to manage and respond to climate-change impacts.

Aerosols (atmospheric): fine solid or liquid particles, emitted by human activities or occurring naturally, suspended in the atmosphere. Depending on their composition, aerosols can cause both atmospheric cooling by scattering incoming radiation or by affecting cloud cover, or warming by absorbing radiation.

Biodiversity: the variety of life, including the number of plant and animal species, life forms, genetic types, habitats, and biomes (which are characteristic groupings of plant and animal species found in a particular climate).

Biogeochemical cycles: fluxes, or flows, of chemical elements among different parts of the Earth: from living to non-living, from atmosphere to land to sea, from soils to plants.

Black carbon: the most strongly light-emitting component of particulate matter emitted into the atmosphere by incomplete combustion of fossil fuels, biofuels, and biomass.

Blue carbon: carbon captured and stored by living organisms in oceans and coastal ecosystems.

Carbon cycle: circulation of carbon atoms through the Earth systems as a result of photosynthetic conversion of carbon dioxide into complex organic compounds by plants, which are consumed by other organisms, and return of the carbon to the atmosphere as carbon dioxide as a result of respiration, decay of organisms, and combustion of fossil fuels.

Carbon sequestration: storage of carbon through natural or technological processes in biomass or in deep geological formations.

Climate change: changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and changes to other features of the climate system.

Climate forecast: a probabilistic estimation of the future conditions of the climate system on a seasonal or inter-annual time scale, derived from a climate model. Climate forecasts are driven by the observed state of the climate system, typically sea-surface temperatures. See also: climate prediction.

Climate intervention: intentional modifications of the Earth system, usually technological, as a means to reduce future climate change.

Climate model: a numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. Climate models are applied, as a research tool, to study and simulate the climate, and for operational purposes, including monthly, seasonal, and interannual climate predictions.

Climate prediction: a probabilistic estimation of the future conditions of the climate system on a seasonal or inter-annual time scale, derived from a climate model. Climate predictions are driven by the observed state of the climate system, typically sea-surface temperatures.

Climate projection: a simulated response of the climate system to a scenario of future emissions or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions in that projections depend upon the emissions scenario used, which is based on assumptions concerning potential future socioeconomic and technological pathways.

Climate variability: natural changes in climate that fall within the observed range of extremes for a particular region, as measured by temperature, precipitation, and frequency of events. Drivers of climate variability include the El Niño Southern Oscillation and other phenomena.

Cryosphere: areas of snow, ice, or permafrost in the Earth system.

Data assimilation: the process of combining observations from a variety of sources to estimate the state of components of the Earth system in a consistent manner, in order to initialize an Earth system model.

Drought: a period of abnormally dry weather marked by little or no rain that lasts long enough to cause water shortage for people and natural systems.

Earth System: Earth's interacting "spheres," including: air (atmosphere), water (hydrosphere), life (biosphere), land (geosphere), ice (cryosphere), and human activities, and their interactions and feedbacks to one another.

Earth System Model: mathematical models that simulate the physics, chemistry, and biology that influence the climate system

Ecosystem: all the living things in a particular area as well as components of the physical environment with which they interact, such as air, soil, water, and sunlight.

Ecosystem services: the benefits produced by ecosystems on which people depend, including, for example, fisheries, drinking water, fertile soils for growing crops, climate regulation, and aesthetic and cultural value.

El Niño-Southern Oscillation (ENSO): natural variability of sea-surface temperatures and the air pressure of the overlying atmosphere in the tropical Pacific Ocean. The warm phase of ENSO, El Niño, is associated with high air surface pressure in the western tropical Pacific and warm sea-surface temperatures in the eastern tropical Pacific, while the cold phase, La Niña, is associated with low air surface pressure in the western tropical Pacific and cool sea-surface temperatures in the eastern tropical Pacific. Each phase generally lasts for 6 to 18 months. ENSO events occur irregularly, roughly every 3 to 7 years. The extremes of this climate pattern's oscillations can cause extreme weather (such as floods and droughts) in many regions of the world.

Emissions scenarios: quantitative illustrations of how the release of different amounts of climate-altering gases and particles into the atmosphere from human and natural sources will produce different future climate conditions. Scenarios are developed using a wide range of assumptions about population growth, economic and technological development, and other factors.

Extreme events: a weather event that is rare at a particular place and time of year, including, for example, heat waves, cold waves, heavy rains, periods of drought and flooding, and severe storms

Feedback: the process through which a system is controlled, changed, or modulated in response to its own output. Positive feedback results in amplification of the system output; negative feedback reduces the output of a system.

Food security: when all people at all times have both physical and economic access to sufficient food to meet their dietary needs for a productive and healthy life.

Forcing: factors that affect the Earth's climate. For example, natural factors such as volcanoes and human factors such as the emission of heat-trapping gases and particles through fossil fuel combustion.

Global change: changes in the global environment that may alter the capacity of the Earth to sustain life. Global change encompasses climate change, but it also includes other critical drivers of environmental change that may interact with climate change, such as land-use change, the alteration of the water cycle, changes in biogeochemical cycles, and biodiversity loss. [Synonymous with global environmental change].

Global Circulation Models (GCMs): mathematical models that simulate the physics, chemistry, and biology that influence the climate system.

Global warming: the observed increase in average temperature near the Earth's surface and in the lowest layer of the atmosphere. In common usage, "global warming" often refers to the warming that has occurred as a result of increased emissions of greenhouse gases from human activities. Global warming is a type of climate change; it can also lead to other changes in climate conditions, such as changes in precipitation patterns.

Greenhouse gases: gases that absorb heat in the atmosphere near the Earth's surface, preventing it from escaping into space. If the atmospheric concentrations of these gases rise, the average temperature of the lower atmosphere will gradually increase, a phenomenon known as the greenhouse effect. Greenhouse gases include, for example, carbon dioxide, water vapor, and methane.

Indicator: an observation or calculation that allows scientists, analysts, decision makers, and others to track environmental trends, understand key factors that influence the environment, and identify effects on ecosystems and society.

Land cover: the physical characteristics of the land surface, such as crops, trees, or concrete.

Land use: activities taking place on the land surface, such as growing food, cutting trees, or building cities.

Mitigation: measures to reduce the amount and speed of future climate change by reducing emissions of heat-trapping gases or removing carbon dioxide from the atmosphere.

Model Intercomparison: a standard experimental protocol for studying the output of Earth System models.

Observations: systematic measurement of variables reflecting the state of the Earth system, from ground, airborne, aquatic, or space-based sensors.

Ocean acidification: the process by which ocean waters have become more acidic due to the absorption of human-produced carbon dioxide, which interacts with ocean water to form carbonic acid and lower the ocean's pH. Acidity reduces the capacity of key plankton species and shelled animals to form and maintain shells.

Paleoclimate: the climate that existed during the period before modern record-keeping. Paleoclimate can be measured with "natural thermometers" such as ice cores or tree rings.

Permafrost: ground that remains at or below freezing for at least two consecutive years.

Phylogeny: the evolutionary history of an organism.

Preparedness: actions taken to build, apply, and sustain the capabilities necessary to prevent, protect against, and ameliorate negative effects.

Reanalysis: a systematic approach to producing consistent data sets for climate monitoring and research. Reanalyses combine historical observed data spanning an extended period, using a single assimilation scheme to produce consistent spatial and temporal coverage.

Resilience: the capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.

Resolution: in climate models, the physical distance (meters or degrees) between each point on the grid used to compute the equations that represent the state of the system. Temporal resolution refers to the time step or time elapsed between each model computation of the equations.

Risk: threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).

Risk assessment: studies that estimate the likelihood of specific sets of events occurring and their potential positive or negative consequences.

Risk management: planning to manage the effects of climate change to increase positive impacts and decrease negative impacts.

Risk-based framing: planning based on the pros and cons of a given set of possibilities; includes assessment of a risk in terms of the likelihood of its occurrence and the magnitude of the impact associated with the risk.

Scenario: sets of assumptions used to help understand potential future conditions such as population growth, land use, and sea-level rise. Scenarios are neither predictions nor forecasts. Scenarios are commonly used for planning purposes.

Sink: a natural or technological process that removes carbon from the atmosphere and stores it.

Stakeholder: an individual or group that is directly or indirectly affected by or interested in the outcomes of decisions.

Storm surge: the sea height during storms such as hurricanes that is above the normal level expected at that time and place based on the tides alone.

Stressor: something that has an effect on people and on natural, managed, and socioeconomic systems. Multiple stressors can have compounded effects, such as when economic or market stress combines with drought to negatively impact farmers.

Teleconnection: recurring and persistent, large-scale pattern of atmospheric pressure and circulation anomalies that spans vast geographical areas and influence temperature, rainfall, storm tracks, and jet stream location/intensity.

Tipping point: the point at which a change in the climate triggers a significant environmental event, which may be permanent, such as widespread bleaching of corals or the melting of very large ice sheets.

Uncertainty: an expression of the degree to which future climate is unknown. Uncertainty about the future climate arises from the complexity of the climate system and the ability of models to represent it, as well as the inability to predict the decisions that society will make. There is also uncertainty about how climate change, in combination with other stressors, will affect people and natural systems.

Validate: to establish or verify accuracy. For example, using measurements of temperature or precipitation to determine the accuracy of climate model results.

Vulnerability: the degree to which physical, biological, and socio-economic systems are susceptible to and unable to cope with adverse impacts of climate change.

Vulnerability assessment: an analysis of the degree to which a system is susceptible to or unable to cope with the adverse effects of climate change.