U.S. Global Change Research Program

OUR CHANGING PLANET

The U.S. Global Change Research Program for Fiscal Year 2022

A Report by the U.S. Global Change Research Program and the Subcommittee on Global Change Research, National Science and Technology Council

A Supplement to the President's Budget for Fiscal Year 2022

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Since 1989, the U.S. Global Change Research Program (USGCRP) has submitted annual reports to Congress called *Our Changing Planet*. The reports describe the status of USGCRP research activities, provide progress updates, and document recent accomplishments. This Fiscal Year 2022 edition of *Our Changing Planet* provides a summary of programmatic achievements, recent progress, and budgetary information for USGCRP. It thereby meets the requirements set forth in the U.S. Global Change Research Act of 1990 (Section 102, P. L. 101–606) to provide an annual report on Federal global change research priorities and programs. 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.

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U.S. GLOBAL CHANGE RESEARCH PROGRAM

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February 2022

Members of the Congress:

We face critical questions about how our Earth system is changing and how the United States and the world can respond. Researchers across the Federal Government are working to answer these questions, helping to provide the best available science to guide Americans as they prepare for a changing environment.

Congress created the U.S. Global Change Research Program (USGCRP) to coordinate efforts across 13 Federal agencies to observe, model, and analyze our changing planet. Making connections across these agencies—among scientists with expertise as varied as atmospheric chemistry, food security, sea ice change, soil science, and economics—allows the agencies' research capabilities to be more than the sum of their parts. This coordination and collaboration helps provide the foundation for a national response to climate change and other environmental changes that present increasing costs and challenges to the health and well-being of the American people.

As the impacts of climate and global change unfold around us, there is even higher demand for information that will help communities across the Nation understand the choices they face. By bringing together its member agencies to think strategically about how to address these demands, USGCRP is renewing efforts to ensure that climate and global change information is readily available to users, easy to understand and apply to decision-making, and responsive to user needs.

On behalf of USGCRP, I am pleased to transmit *Our Changing Planet: The U.S. Global Change Research Program for Fiscal Year* (FY) 2022. This report presents highlights of USGCRP's recent accomplishments that illustrate how it is meeting its mandate and achieving the goals outlined in the Program's Strategic Plan (2012–2021, updated 2017). The report also presents a summary of agency expenditures under USGCRP's budget crosscut, as required by the Global Change Research Act of 1990.

I appreciate the close cooperation of the participating agencies. The Office of Science and Technology Policy looks forward to working with members of the Congress to continue enhancing this essential national program.

Sincerely,

Jane Lubchenco
Deputy Director for Climate and Environment,
Office of Science and Technology Policy

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THE U.S. GLOBAL CHANGE RESEARCH PROGRAM

Changes to our global climate and environment driven by human activities are increasingly visible in communities across the United States. Coastal communities are experiencing more frequent and severe flooding due to sea level rise and storm surge. Large wildfires have become more common in the western United States and Alaska, driven in part by hotter and drier conditions. Reduced snowpack and earlier spring melt are affecting water resources in the western United States, and heavy rainfall and heat waves have become more frequent and intense across the country.[1] These trends are expected to continue and pose growing risks to health, food, water, energy, and transportation systems, and increasingly threaten the economy and the vitality of communities.[2]

As the climate continues to change and interact with other stressors, risks to all Americans are expected to rise, with disproportionate effects on populations that are already vulnerable. Communities, businesses, and government leaders across the country are considering how to reduce risks associated with climate change and other environmental changes in the years to come. Efforts to build more resilient infrastructure, protect natural resources and biodiversity, and support healthy communities rely on accessible, relevant scientific knowledge about how climate-related risks and other global changes affect valued resources and alter future conditions.

The U.S. Global Change Research Program (USGCRP) was created by Congress in the Global Change Research Act (GCRA) of 1990 to build a knowledge base for understanding and responding to climate change and other environmental changes affecting the total Earth system: the atmosphere, land, water, ecosystems, and people. USGCRP coordinates research across 13 Federal agencies (Figure 1) that conduct or use global change research, with an emphasis on research that can be used to answer critical questions about the changing Earth system and how the United States and the world can respond to those changes. See Appendix I. About USGCRP (p. 38) for details on program structure and the principal focus areas related to global change research for each member agency.

Figure 1 – U.S. Global Change Research Program Member Agencies (Top) *Department of Agriculture; Department of Commerce; Department of Defense; Department of Energy; Department of Health and Human Services; Department of the Interior* **(Bottom)** *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.*

Over the past three decades, USGCRP has coordinated Federal research on all aspects of global change, particularly climate change, providing the nation and the world with new understanding of the changing Earth system and its consequences for society. The Program summarized that knowledge in four National Climate Assessments that have informed national policymaking and provided useful scientific information to decision-makers. USGCRP has also promoted engagement on ambitious collaborative international research efforts and has supported U.S. engagement in international scientific assessments that provide the basis for global policymaking on climate and global change.

Global change science has evolved considerably over the past three decades, from a primary focus on understanding the physical Earth system to a broader inclusion of ecosystems, human systems, and their interactions in response to a changing environment. Today, growing recognition of the risks that climate

change poses to the United States and the world, along with increasing efforts to respond, has created new demands for information and opportunities to support public and private sector decision-makers as they integrate climate and global change information into their planning and operations and take actions to reduce risks with adaptation and mitigation activities.

Longstanding investments in Federal research capabilities coordinated through USGCRP provide the foundation for addressing evolving national needs, including climate-related risks that present increasing costs and challenges to the health and well-being of the American people. New and enhanced research is needed to inform strategies to effectively manage and reduce these risks in decades to come, presenting an opportunity for Federal science to sharpen its focus around changes that pose the greatest risks and opportunities for society, and ensure that this scientific foundation is accessible and relevant to decision-makers acting to build more resilient and prosperous communities.

IN THIS REPORT

The Fiscal Year 2022 edition of USGCRP's annual report to Congress, *Our Changing Planet*, presents recent Program accomplishments that illustrate how USGCRP is meeting its mandate under the GCRA and achieving the goals outlined in the Program's 2012–2021 Strategic Plan and its 2017 update. Highlighted activities represent interagency collaborations undertaken in calendar year 2020 that rely on coordinated investments of two or more member agencies and contribute to implementing USGCRP's strategic goals.

As required by the GCRA, this report also presents a summary of agency expenditures under USGCRP's budget crosscut (see Budgetary Information, p. 37). USGCRP's scope includes but is not limited to the range of agency programs implemented with funds included in the budget crosscut, and the efforts described in this document represent a subset of the overall accomplishments of the Program. Note that single agency investments, including many that enable interagency accomplishments, are not typically covered in this annual report.

IMPLEMENTING THE NATIONAL GLOBAL CHANGE RESEARCH PLAN

USGCRP's 2012–2021 National Global Change Research Plan (Strategic Plan) and its 2017 update provide a framework for advancing scientific understanding of the Earth system while strengthening capacity to answer questions critical to decision-making in a changing environment. The Program's four strategic goals, which respond to its mandate under the GCRA, are to advance global change science, inform decisions, conduct sustained assessments, and engage decision-makers and the public in support of these goals, including internationally. USGCRP is currently developing the 2022–2031 Strategic Plan for release this year.

While coordinating a broad spectrum of research relevant to global change, USGCRP finds value in emphasizing particular focus areas that are shared by multiple agencies. In Fiscal Year 2020, USGCRP identified three focus areas that reflect current Program priorities: the intersection of climate-related global change with coasts, human health, and the water cycle. These focus areas address topics of great societal relevance where coordinated Federal science can support important advances in understanding and inform efforts to build resilience to change. See Focus Areas (p. 18) for highlighted activities in each topic area.

This section highlights achievements that support implementation of USGCRP's goals and illustrate ongoing advances in the science of global change. Highlights are organized by overall science goals, focus areas, and program areas. Activities undertaken in previous years are available at globalchange.gov/explore.

Advancing Science

USGCRP's ongoing efforts to observe, model, and analyze the changing Earth system provide the knowledge base for a national response to climate change and other global changes. Federal investments in Earth observations, modeling, understanding Earth system processes, and understanding the connections between natural and human systems provide the scientific foundation for the decision support and assessment activities described in USGCRP's 2012–2021 Strategic Plan. Longstanding investments in Earth observations, modeling, and process studies also allow deployment of Federal assets and expertise to respond to new priorities and track how the global environment is responding to new conditions, such as the COVID-19 pandemic.

Observing Global Change

USGCRP agencies maintain long-term investments in multidisciplinary satellite, airborne, ground-based, and ocean-based observing systems. Information from these systems creates a record of change in Earth system processes over time that offers new understanding of their drivers and informs development of models that provide insight into future changes. USGCRP's Integrated Observations Interagency Working Group (ObsIWG) provides a forum for discussion, coordination, and implementation of integrated observational and monitoring capabilities for climate and global change. ObsIWG maintains a compendium of Federal Earth observation activities.

Both long-term observing networks and short-term experimental campaigns provide critical information for understanding Earth's climate system, how it interacts with other Earth system processes, and the current and future impacts on society. Coordinated interagency observing efforts, from focused field campaigns to long-running observation networks, enable insights that no single agency could produce.

Highlighted efforts this year include targeted observing campaigns investigating rapidly changing conditions in the Arctic (p. 5), the causes of an unexpected plume of methane, a potent greenhouse gas (p. 6), and the role of ocean ecosystems in the global carbon cycle (p. 7). Also highlighted are innovations in longer-term observing networks and capabilities, including measurement of how emissions of ozone-depleting substances are responding to global policy choices (p. 7), updates to an ocean float network to capture new indicators of ocean health (p. 8), and a multiyear campaign to help design new satellite measurements of changing snowpack (p. 9).

Understanding rapid change in the Arctic

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) project concluded a yearlong expedition into the Arctic ice pack, collecting data that aims to advance understanding, modeling, and prediction of Arctic environmental change.

Sea ice cover in the Arctic Ocean has shrunk dramatically over the past four decades as temperatures in the region have warmed at over twice the rate as the rest of the globe. This trend is expected to continue, resulting in nearly sea-ice free late summers in the Arctic by midcentury.[3] Arctic sea ice plays a key role in shaping climate within and beyond the region, and model limitations in reproducing Arctic climate changes are a central challenge in understanding and predicting global climate change.

The groundbreaking **MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate)** expedition aimed to close key data gaps that limit the ability to model climate processes in

The research icebreaker Polarstern, deployed as part of the MOSAiC expedition. Credit: Markus Rex.

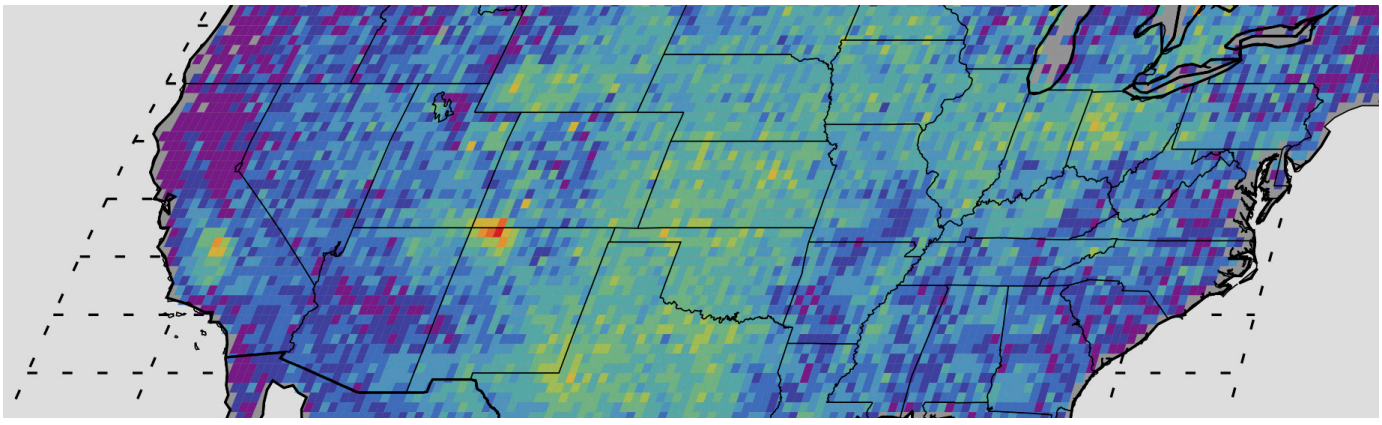
the region and globally. MOSAiC's main observatory, a research icebreaker ship, drifted with sea ice across the central Arctic from September 2019 to October 2020, collecting detailed data on the ocean, atmosphere, sea ice, and ecosystems, and how they interact. The international expedition involved hundreds of researchers from 20 countries, including scientific leadership and funding support from NSF, DOE, NOAA, and NASA.

The improved observations and understanding of the causes and consequences of rapid Artic change provided by MOSAiC data will support improved forecasts of sea ice and other critical environmental conditions that have both local impacts and influence lower latitude weather and climate extremes, as well as improved climate projections. Better understanding and predictive capabilities will directly inform regional Arctic issues such as fisheries management, protected and endangered species, mineral and energy exploration, shipping and transportation, and military exercises.

Investigating methane emissions in the San Juan Basin

A coordinated observing campaign uncovered the causes of an unexpected methane plume spotted by satellite.

Methane is a potent greenhouse gas emitted by both natural sources and processes (such as wetlands, geological seeps, and biomass burning) and human activities (including agriculture, waste and landfills, and fossil fuel extraction). Sources of regional and global methane pollution can be tracked through emission inventories, atmospheric in situ measurements, and remote sensing observations, allowing scientists to detect and study methane emissions and how they are changing.[4] A major fossil fuel-producing region in the U.S. Southwest came to national attention in 2014 when a satellite spotted an unexpectedly large methane plume over the region,[5] prompting scientists to investigate what became known as the largest local methane hotspot in the country.



This map shows how methane levels differ from average background levels for 2003 to 2009, as derived from remote sensing data from the European Space Agency's SCIAMACHY instrument. Purple and dark blue areas are below average, pale blue and green are close to normal, and yellows and red indicate higher-than-normal anomalies. Note that the San Juan Basin near the Four Corners region is the only red spot on the map. Credit: NASA/JPL-Caltech/University of Michigan.

In 2015, researchers funded by NASA, NOAA, and NSF used ground and airborne instrumentation throughout the San Juan Basin to further study the plume, leading to new research published in 2020.[6] These detailed observations showed that the methane cloud was not a persistent, undiscovered emissions hotspot as initially believed. Instead, the plume was the result of nightly atmospheric conditions and local topography trapping industrial and natural methane emissions in the basin overnight, captured by a daily midmorning satellite overpass. Accumulated emissions were later flushed out by surface winds throughout the day, meaning that the plume was not as large and persistent as it initially appeared in satellite data.

The in situ ground and airborne measurement campaign was carried out by scientists from NOAA and the University of Colorado, Boulder, in collaboration with DOI, the Bureau of Land Management, state and local governments, the Southern Ute Indian Tribe Air Quality Program and Department of Energy, and the Navajo Nation Environmental Protection Agency. Results demonstrated that sustained, coordinated measurements are important for identifying the sources and impacts of apparent pollution spikes, particularly those that vary over time, and can help inform actions and policies to reduce emissions. Future satellite measurements of methane collected more frequently, such as hourly data from a geostationary satellite, could provide an improved picture of methane plumes that vary over time.

Measuring the strength of the ocean's biological carbon pump

Scientists are investigating the movement of carbon from the atmosphere to the deeper ocean via ecological processes.

Microscopic organisms known as phytoplankton in the upper ocean play a critical role in Earth's carbon cycle and climate, transporting carbon from the surface to the deeper ocean where it is stored for months to millennia. This movement of carbon—known as the biological carbon pump—represents a significant sink for atmospheric carbon dioxide, but measuring it remains a challenge. A better understanding of what influences the function of the ocean's biological pump, and how this may be altered under changing ocean conditions, is critical to predicting how oceans respond to and influence climate change.

The joint NASA-NSF **EXPORTS** **(EXport Processes in the Ocean from RemoTe Sensing)** field campaign is one of the most comprehensive studies on the biological carbon pump ever conducted. EXPORTS uses research vessels, underwater robotic platforms, and satellite imagery to study the role of ocean ecosystems in the global carbon cycle and its implications for Earth's climate. Results from the 2018 EXPORTS North Pacific field campaign, published in 2020, described how carbon flux varies over space and time and measured the strength of the biological carbon pump in an area characterized by its low ecosystem productivity.[7]

In addition, results highlight the importance of small organic particles in sustaining deep ocean communities and the critical role microorganisms play in removing and altering organic carbon as it sinks.[8] Data from the 2021 EXPORTS field campaign, deployed in the North Atlantic, will complement the 2018 findings. These results improve understanding of how the biological pump works, including how it may change in the future under different climate change scenarios, and could lead to more accurate climate models.

Springtime in the Bering Sea brings reduced sea ice cover and increased phytoplankton production. As the climate warms, productivity may contribute to oxygen depletion in these waters. The image is a composite of Aqua/MODIS data collected over two days in May 2021. Credit: NASA.

Supporting ozone layer recovery

Interagency observations and analyses show that emissions of the second-most important ozone-depleting substance are back on the decline after a recent surge.

Atmospheric measurements show that concentrations of ozone-depleting gases are declining in response to global controls on their production and use enacted under the Montreal Protocol of 1987 and its amendments. The decline since the early 1990s in the atmospheric concentration of trichlorofluoromethane (CFC-11), once widely used as a foaming agent and refrigerant, has been an important component of ozone layer recovery.

NOAA and NASA operate coordinated global observing networks that provide the primary data sets related to the ongoing monitoring of concentrations and emissions related to the Montreal Protocol. In 2018, researchers noted that the decline of CFC-11 concentration had slowed by about 50 percent after 2012,[9] suggesting increasing emissions and new unreported production despite the global ban. After the increase in emissions was detected, NOAA and NASA researchers worked in collaboration with the U.S. delegation to the Montreal Protocol, including EPA and DOS employees, to shed further light on the issue in support of emissions reductions.

Atmospheric concentrations of ozone-depleting gases are tracked at multiple remote sites across the globe, including the observatory at American Samoa (pictured), to determine if controls on these substances will allow recovery of the stratospheric ozone layer. Measurements at these sites previously indicated renewed increases after 2012 in emission and production of an ozone-depleting chemical banned by the Montreal Protocol. Recent findings reveal rapid declines in global and eastern Asian emissions of the potent ozone-depleting gas CFC-11, suggesting that the international response to redouble efforts to minimize emissions and production of this banned substance has been successful. Credit: G. Chensue/NOAA.

Measurements since the initial announcement in 2018 show a significant drop in global CFC-11 emissions from 2018 to 2019, comparable to the increase in emissions that occurred from 2012 to 2017.[10] The decline in global emissions suggests a substantial decrease in unreported CFC-11 production. A companion analysis showed a decline in regional emissions from eastern Asia during this time period.[11]

These results indicate that the long-term decline in CFC-11 emissions has been restored, and a substantial delay in ozone layer recovery from increased emissions has likely been avoided.

Tracking ocean change

New ocean sensors will expand the ability of the global Argo Program to monitor and forecast changes in ocean chemistry and marine ecosystem health.

The international **Argo Program** maintains a global fleet of nearly 4,000 ocean floats that help scientists understand how the ocean is changing over time. Underwater sensors provide data on trends related to climate change, including ocean temperature and heat content, salinity and freshwater content, sea level, and large-scale ocean circulation. Now, the program is innovating to

An Argo float equipped with newly developed oxygen sensors, pictured prior to deployment in the tropical Pacific Ocean, November 2020. Credit: NOAA.

improve measurements of ocean chemistry and other indicators important for management of marine ecosystems threatened by climate and global change.

Two new research projects, funded by NOAA and NASA, will partner with the private sector to improve floats equipped with sensors that can measure ocean acidity, oxygen and nitrate concentration, and phytoplankton productivity, important indicators of marine ecosystem health. The redesigned floats, known as BGC-Argo floats, will be deployed in the tropical Pacific Ocean to monitor variability in ocean biogeochemistry as a contribution to the Tropical Pacific Observing System, which supports forecasts of global shifts in climate and extreme weather associated with the El Niño–Southern Oscillation.

While NSF, NOAA, and NASA partners currently deploy floats with biogeochemical sensors as part of the Southern Ocean Carbon and Climate Observations and Modeling Project (SOCCOM) and the new NSF-funded Global Ocean Biogeochemistry Array (GO-BGC), more research is required to produce reliable floats that contain all needed sensors. These projects will improve sensor quality and float design and increase production of floats by introducing new vendors to the marketplace, with the eventual goal of establishing a sustained biogeochemical float array to monitor marine ecosystem health.

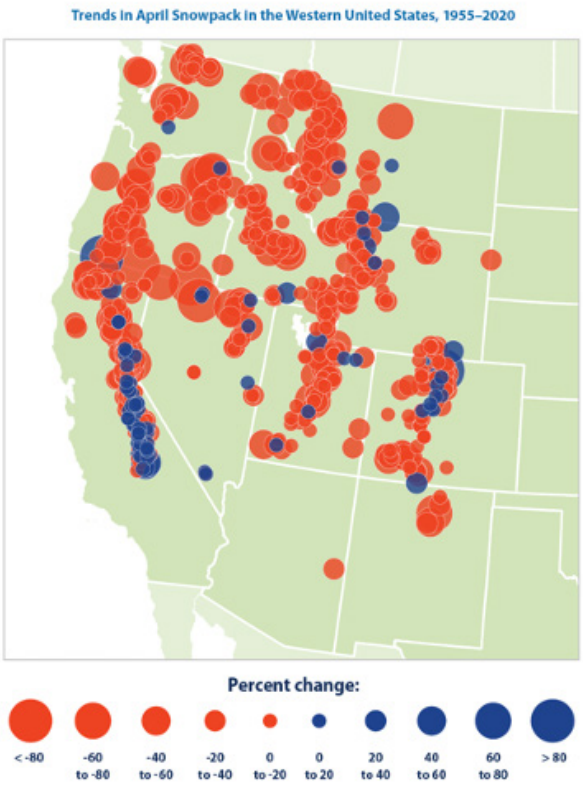
Monitoring snowpack change

A multiyear observing campaign is tracking changing snowpack in the western United States, laying the groundwork for a future snow satellite mission.

Snowpack plays a critical role in the water cycle and helps regulate Earth's climate. Storage of snow in the winter feeds spring snowmelt, bringing water to crops, people, and ecosystems downstream. Snowpack also feeds hydropower generation in the Southwest and Northwest, and snow-related tourism and recreation are important economic drivers in many regions.[12] Warmer winter temperatures and other climate-related changes are altering the timing, accumulation, and melt of snow. Large declines in snowpack in the western United States and shifts to more precipitation falling as rain rather than snow in many parts of the central and eastern United States are expected as the climate continues to warm,[13] and decision-makers need accurate snow information to respond to changing snow and water availability.

Remote sensing technologies allow scientists to monitor how snow cover is changing over time, but many aspects of snow cover are still difficult to measure. The **SnowEx** campaign is a multiyear effort to address key gaps in snow remote sensing knowledge, focusing on airborne campaigns and fieldwork in North America. Coordinated studies are underway to help determine which combination of instruments and techniques can deliver the needed information for researchers and decision-makers, and lay the groundwork for a future snow satellite mission.

SnowEx is led by NASA, with participation from NOAA, DoD, and the USDA Forest Service. In 2020, the U.S. Army Corps of Engineers, Engineer Research and Development Center-Cold Regions Research and Engineering Laboratory (ERDC-CRREL) deployed novel ground-based, mobile, and airborne sensing platforms to investigate the season's evolving snowpack in the western United States. Other coordinated airborne and field-based experiments tested instruments under a variety of snow conditions, including the ability to measure snow water equivalent (the amount of water held in a volume of snow), a critical indicator for water resources. This will augment the ground-based measurements of snowpack, such as from the snow telemetry (SNOTEL) network and other measurement stations (see figure).



These coordinated observations showed how changes in snowpack impact water management, water security, and hazard assessments in a changing climate, and will inform the design of a future snow satellite mission.

Trends in April snowpack in the western United States, 1955–2020, measured in terms of snow water equivalent from ground-based stations. Large and consistent declines in April snowpack have been observed over this time period, with an average decline of about 19 percent at the sites measured. Blue circles represent increased snowpack; red circles represent a decrease. Source: EPA, using data from the USDA Natural Resources Conservation Service.

Understanding Global Change Processes

USGCRP member agencies conduct natural, behavioral, and social science research to understand how environments and people respond to global change. The findings of basic research on global change processes strengthen understanding of the drivers of global change and the impacts on natural and human systems, including complex interactions among social and natural systems, and help reduce uncertainties in projections of future Earth system changes. Improved understanding of the interactions among human, behavioral, and natural systems responding to change also supports efforts to build resilience to change. This research relies on activities such as field, lab, and experimental studies; integrating socioeconomic data into models; and collecting qualitative and quantitative data on exposure and vulnerability to climate-related risks.

Understanding carbon cycle processes in the context of global change has been a longstanding focus for USGCRP. Human emissions of greenhouse gases, land use and deforestation, and other activities continue to alter the flow of carbon through different reservoirs in the Earth system, driving climate change and other processes of environmental change that profoundly impact society.[14] The U.S. Carbon Cycle Science Program, coordinated through USGCRP's Carbon Cycle Interagency Working Group, and USGCRP agencies are working to advance understanding of carbon cycle dynamics and their impact on the climate and society (p. 12 to p. 13).

Improving integration of social science approaches to understanding global change processes is another longstanding goal of the Program. USGCRP agencies continue to conduct and enhance interdisciplinary research into the complex interactions among human, behavioral, and natural systems responding to change (p. 14). USGCRP's Social Sciences Coordinating Committee also fosters integration of the methods, findings, and disciplinary perspectives of the social, behavioral, and economic sciences and interdisciplinary and

transdisciplinary approaches into USGCRP activities in support of the Program's strategic goals, including providing regular input on assessment activities (p. 31).

Research efforts to understand processes of global change highlighted this year are developing a more complete understanding of how clouds and interactions among the ocean and the atmosphere in the tropics influence global weather and climate (p. 11) and improving estimates of how future climate conditions affect the amount of carbon stored by ecosystems and in turn how changes in carbon sinks could affect future climate (p. 12 to p. 13). Other efforts are using social science approaches to learn from recent hurricanes and inform resilience measures (p. 14) and to understand how small business are disrupted by and resilient to weather and climate disasters and their interactions with other stressors, including the COVID-19 pandemic (p. 14).

Understanding air–sea processes

An interagency field campaign gathered data on interactions between the tropical ocean and atmosphere to improve weather and climate prediction.

Over the tropical ocean, interactions between winds and warm sea water form low-hanging clouds (known as shallow convective clouds) that act as the building blocks for storms. These clouds and air–sea interactions influence weather and climate conditions all over the world, but are poorly represented in models, in part due to a lack of detailed observations that are needed to understand and accurately simulate their behavior. In 2020, a NOAA-led field campaign in the tropical Atlantic Ocean gathered data that will advance understanding of how shallow convective clouds affect larger weather and climate patterns and support improved prediction of weather and climate.

ATOMIC, or the **Atlantic Tradewind Ocean-atmosphere Mesoscale Interaction Campaign**, launched from the island of Barbados in the Caribbean in January 2020, using multiple platforms to observe air–sea processes over six weeks. Data collected by piloted and autonomous vehicles, buoys, and radar provided a snapshot of how the ocean, atmosphere, and clouds work together to create weather and climate patterns. The research team will also compare measurements to long-term data from NOAA ocean observing sites. Data collected by NASA during the campaign, focused on how variations in salinity affect air–sea processes, are now publicly available via the Physical Oceanography Distributed Data Active Archive Center (PO.DAAC). The collection and use of these new data in process studies and model-based experiments are yielding new discoveries that will guide weather and climate model development.

ATOMIC is supported by NOAA with participation by researchers from NASA, NSF, U.S. universities, and the Caribbean Institute for Meteorology and Hydrology. The campaign is the U.S. contribution to the international EUREC4A field study investigating the role of clouds in climate change.

Deploying a Climate, Temperature, and Depth Rosette, which measures temperature and salinity of sea water at different depths, as part of the NOAA-led Atlantic Tradewind Ocean-atmosphere Mesoscale Interaction Campaign (ATOMIC). Credit: Richard Marchbanks, CIRES/NOAA.

Investigating how ecosystems respond to climate warming

Experimental warming of a peatland ecosystem showed a rapid shift towards net carbon loss to the atmosphere.

Peatlands cover only about 3 percent of Earth's land surface but store around 30 percent of global soil carbon. As the climate warms, these carbon stocks are vulnerable to release into the atmosphere as the greenhouse gases carbon dioxide and methane, contributing to a cycle of further warming and carbon release. The **SPRUCE (Spruce and Peatland Responses Under Changing Environments)** experiment, a DOE and USDA Forest Service initiative, is a 10-year study involving warming of an intact Minnesota black spruce peatland ecosystem that aims to improve understanding of carbon cycle dynamics in these landscapes under future climate scenarios.

Results emerging from SPRUCE show that experimental warming causes peatlands to shift from net carbon accumulation to carbon sources faster than anticipated.[15] This finding suggests that increased rates of global warming will have a significant impact on naturally stored carbon, with important feedbacks to the atmosphere that can drive further warming.

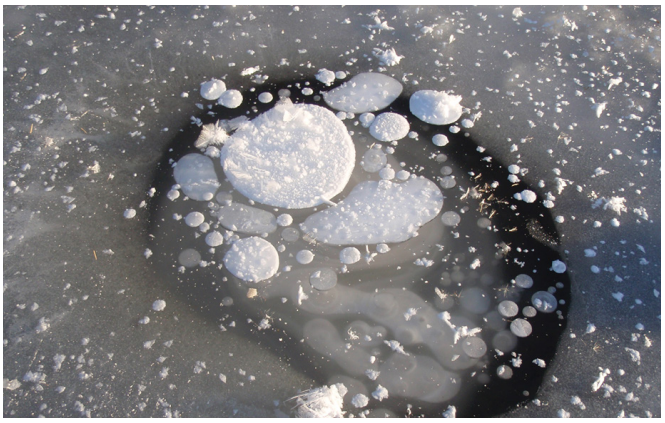
Scientists used SPRUCE (Spruce and Peatland Responses Under Changing Environments) experimental enclosures to record net carbon loss from warmed plots in the peatlands of Minnesota. Credit: Misha Krassovski, Oak Ridge National Laboratory/DOE.

Studying carbon cycle processes in northern aquatic ecosystems

Recent studies are improving the ability to quantify ecosystem carbon dynamics and greenhouse gas exchange in changing Arctic and boreal landscapes.

Northern high latitudes are warming at more than twice the global average, driving permafrost thaw, changes in surface water extent, increased wildfire, and other changes that affect how much carbon is stored in and emitted to the atmosphere by soils, vegetation, and inland waters.[16] Measuring the flow of carbon between ecosystems, landscapes, and the atmosphere—known as carbon flux—in the region and the potential impacts on global climate is an active area of research critical to understanding future climate change.

Since 2015, the U.S. Geological Survey (USGS) has conducted large-scale studies of carbon dynamics in stream, rivers, lakes, and wetlands across Alaska (including carbon dioxide and methane exchange with the atmosphere; inorganic carbon weathering and export; and dissolved organic matter amount, chemical composition, export, and storage) in partnership with the U.S. Fish and Wildlife Service, the Bureau of Land Management, NASA, and academic collaborators. A majority of this work is conducted on DOI lands, with funding from



Methane emitted from thawing permafrost below an Arctic thermokarst lake is trapped in bubbles as ice forms in the winter. Credit: Miriam Jones/USGS.

NASA's **Arctic-Boreal Vulnerability Experiment (ABoVE) Program**, a multiyear experiment that is using satellite, aircraft, and field data to understand the ecological impacts of a rapidly changing climate in Alaska and Northwestern Canada. Recent studies investigated how surface water influences carbon flux in the region and how aquatic ecosystem processes are being altered by climate change.

Wetlands, ponds, and lakes are the largest natural source of methane in the region but are poorly mapped, making estimates of carbon fluxes at the landscape scale a challenge. Researchers integrated airborne data collected by ABoVE aircraft flights, satellite data, and field measurements to identify different classes of landscape, ranging from permanently flooded to dry. Continued field data collection will measure how carbon flux varies across different types of landscapes and lakes, with the goal of upscaling greenhouse gas flux estimates for lakes and wetlands in Arctic-boreal environments.

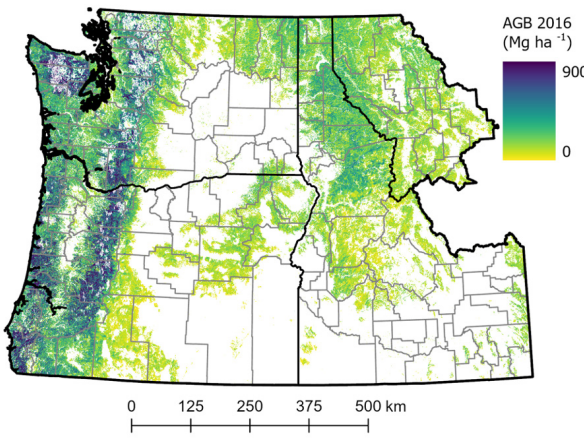
Changing climate and permafrost are altering the hydrologic connection of lakes and other water bodies with the landscape, affecting how organic carbon moves between ecosystems and the atmosphere. Recent results demonstrate that the reduced delivery of dissolved organic matter from terrestrial to aquatic ecosystems shifts the chemical composition of lake dissolved organic matter, with implications for lake productivity, light penetration, heat transfer, and their biogeochemical function.[17] Researchers also developed a novel methodology for estimating gross primary productivity (a measure of carbon uptake by photosynthesis) in lakes by combining satellite data of lake color with field water quality measurements.[18] This method can be used to assess change in ecological processes involving carbon cycling in hundreds of thousands of shallow lakes across northern high latitudes. Related investigations integrating field and remote sensing data are ongoing to quantify the effects of climate change on the water resources of boreal and Arctic regions.

Monitoring forest carbon storage

Mapping forest carbon stocks with in situ, airborne, and satellite data supports forest management in the western United States.

The **Carbon Monitoring System (CMS)**, a NASA-led effort also involving the USDA Forest Service (USDA-FS), NOAA, the USGS, and non-governmental scientists, focuses on improving the monitoring of carbon stocks and fluxes (or the movement of carbon between the oceans, atmosphere, land, and ecosystems) to support carbon management activities. A CMS study is helping the USDA-FS and other stakeholders monitor aboveground biomass (or organic matter) stored in U.S. forests.

Researchers from the USDA-FS Rocky Mountain Research Station used in situ tree measurements and airborne lidar (high-resolution digital elevation) datasets, contributed by USDA-FS managers and other stakeholders from across the western United States, to develop regional biomass maps. By then integrating satellite data and other geospatial data characterizing local and regional climates, researchers are able to map forest carbon stocks for the entire western United States on an annual basis. These maps are used to help support forest management decisions and carbon management practices for the USDA-FS and their stakeholders, including forest managers, regional planners, and policymakers.



Aboveground biomass (AGB) predicted annually (shown for 2016) across the northwestern United States from Landsat imagery, climate, and topographic metrics, at a spatial resolution of 30 meters shown in megagrams per hectare (Mg/ha). The AGB estimates used to train the model were developed from project-level field and airborne lidar datasets contributed by 29 public and private stakeholders from across the region. The annual AGB maps (available from 2000 to 2016) were calibrated using USDA Forest Service (FS) Forest Inventory and Analysis forest inventory plot data, such that they are unbiased and therefore suitable for regional forest planning and forest AGB Carbon Monitoring, Reporting, and Verification. Credit: USDA-FS.

Learning from climate disasters

Studies of vulnerability to hurricane impacts in agriculture and forestry support efforts to reduce risks from future storms.

Three storms in the 2017 hurricane season caused catastrophic damage to communities, livelihoods, and infrastructure in the U.S. Southeast and Caribbean, including billions of dollars in losses in the agriculture and forestry sector. Climate change and other stressors are expected to increase damages and disruptions from hurricanes in the future, driving research to improve understanding of sector-specific vulnerabilities to storms and how best to reduce the risks and costs from future hurricanes.[19] [20]

Scientists at the USDA Forest Service International Institute of Tropical Forestry have been investigating aspects of the 2017 hurricanes that affected Puerto Rico, the U.S. Virgin Islands, and the southeastern United States. Studies have included geospatial analyses of hurricane effects and surveys and interviews across a broad spectrum of people and agencies involved in forestry and agriculture. A study released in 2020 based on surveys of land managers found that long-term planning for hurricane events is still uncommon compared to shorter-term preparedness and recovery activities.[21] Other key findings include variability in social and ecological effects across sectors and geographies; an identification of the loss of power, water, and downed trees as key effects with cascading consequences; and a recognition of the importance of personal and organizational connectivity in effective planning, response, and recovery to hurricanes.

This work was accomplished with the USDA Caribbean Climate Hub and in collaboration with the USGS, USDA agencies, the National Weather Service, USDA Southeast Climate Hub, and several universities.

Dr. Nora Álvarez Berrios of the USDA Caribbean Climate Hub assessing hurricane-downed tropical hardwoods. Salvage of post-hurricane trees is a time-sensitive process requiring special efforts in planning and capacity to connect resources to markets. Credit: Eva Holupchinski/USDA Caribbean Climate Hub.

Exploring small and medium business resilience

Surveys of adaptation efforts adopted by businesses highlight opportunities for building resilience to complex climate events and other stressors.

Increases in the frequency and intensity of extreme climate and weather events put U.S. businesses at risk through closures, infrastructure damage, supply chain disruptions, and physical impacts on health and safety. The interaction among extreme events and other social and environmental stressors that affect U.S. businesses can lead to compound, simultaneous risks with impacts across multiple sectors that cause significant disruptions to livelihoods and the economy. NOAA's Regional Integrated Sciences and Assessments Program (RISA) and the National Institute of Standards and Technology's (NIST) Applied Economics Office are collaborating on a portfolio of social science projects exploring the ways small and medium businesses are resilient to and disrupted by the interaction of multiple hazards, known as complex events, focusing on how weather and climate events interact with other stressors, including the COVID-19 pandemic.

Building on regional case studies conducted collaboratively between RISA teams and NIST exploring small and medium business resilience to climate events, NIST and NOAA are undertaking a national-scale longitudinal survey highlighting paths to learning about resilience, novel approaches to

resilience and mitigation, inequities in impacts of complex events, and opportunities for recovery. This three-wave survey focuses on the ways small and medium businesses in areas subject to extreme climate and weather events are coping with COVID-19.

Early outcomes of Waves 1 and 2, completed in summer 2020 and winter 2020/2021, demonstrate that preparation for natural disasters (pre-pandemic) can help small and medium business resilience through the pandemic, and that minority-, women-, and veteran-owned businesses hit repeatedly by extreme events have significant challenges for recovery compared to others. Wave 3 data collection is scheduled to be completed by early 2022. These projects demonstrate the challenges to small and medium businesses for managing multiple events and the significance of long-term impacts on business recuperation, particularly in the context of social stressors and historical disenfranchisement.

Modeling and Predictability

Scientists use models to understand how different components of the Earth system interact, simulate past change, and project future change. Estimates of future conditions can be made over a range of timescales, from short-term climate predictions to long-term projections of future sea level rise and temperature change. Model information is used to inform planning and support efforts to manage future risks in sectors including agriculture, public health, and energy.

USGCRP fosters coordination across agencies and among modeling communities to support efforts to better model how natural and human systems interact, understand how to improve projections of future conditions, and develop information and understanding for local and regional decision making. USGCRP's Interagency Group on Integrative Modeling (IGIM) coordinates global change-related modeling activities across the Federal Government and provides guidance to USGCRP on modeling priorities. To improve the coordination and communication of national climate modeling goals and objectives, IGIM convenes an Annual U.S. Climate Modeling Summit that brings together representatives from U.S. climate modeling centers and operational climate prediction programs. The Sixth U.S. Climate Modeling Summit, held in June–July 2020, included a workshop on advancing how models represent interactions between clouds and aerosols, key to improving confidence in future projections and resolving discrepancies involving estimates of climate sensitivity.

Interagency modeling efforts highlighted this year include the development and use of a new seasonal-to-decadal climate prediction system (p. 15), a new assessment of how climate change is expected to influence tropical cyclones (p. 16), an updated historical reconstruction of the global climate (p. 17), model studies to understand the impacts of COVID-19 lockdown measures on Earth's atmosphere (p. 17), and efforts to improve how models represent and predict precipitation (p. 24).

Developing a new seasonal-to-decadal climate prediction system

A next-generation modeling system supports assessment of changing climate risks.

NOAA, the USGS, and Princeton University scientists contributed to the development of a new modeling system for seasonal-to-multidecadal climate predictions and projections, **SPEAR (Seamless System for Prediction and Earth System Research)**, at NOAA's Geophysical Fluid Dynamics Laboratory.[22] SPEAR combines a set of newly developed components that simulate the ocean, atmosphere, land, sea ice, and their interactions. The new system is used for real-time seasonal climate predictions as part of the North American Multimodel Ensemble, as well as for decadal predictions as part of a World Meteorological Organization international effort.

In making predictions, SPEAR uses a wide range of observed atmospheric and oceanic data for initial conditions to start the predictions, in combination with a new data assimilation system. SPEAR has

reduced error and increased accuracy for seasonal predictions, providing increasingly useful information for planning in many sectors. SPEAR is being tested for subseasonal prediction, which aims to fill the gap between short-term weather forecasts and long-term seasonal outlooks.

SPEAR is also used for making decadal and multidecadal climate change projections, with an emphasis on quantifying the changing risk of climate extremes, including extreme heat, floods, drought, and storms. The high spatial resolution of the model (50-km atmosphere/land grid) facilitates the simulation of regional climate and extremes. The output from a large suite of simulations with SPEAR, extending from 1921 to 2100, has been made publicly available. This data can be easily and freely downloaded, facilitating planning and assessment of changing climate risks on the regional scale over the 21st century.

Assessing the effects of climate change on tropical cyclones

New research shows that the destructive power of individual tropical cyclones is likely to increase over this century.

New research led by NOAA scientists found that as global temperatures and global average sea level continue to rise throughout this century, the destructive power of individual tropical cyclones (including hurricanes, tropical storms, and typhoons) is likely to increase.[23] The assessment, conducted by a World Meteorological Organization science team, evaluated modeling studies of how tropical cyclone activity is expected to change in response to 2°C (3.6°F) of human-caused climate change.

Much of the heat trapped by increasing atmospheric greenhouse gas levels from human activities has been absorbed by the ocean, causing oceans to warm and sea level to rise. Under 2°C (3.6°F) of warming, modeling results show that sea level rise over the coming century will lead to more severe storm surge inundation and flooding from tropical cyclones, assuming no other changes. Damage risk from storms will likely be further heightened by higher tropical cyclone intensities as well as increased tropical cyclone rainfall rates due to a warmer, moister atmosphere. Together, these changes will likely increase the potential damage from individual storm events, and the changes are projected to accelerate, particularly under high future emission scenarios. Changes in future tropical cyclone frequency, size, and storm tracks are still uncertain, and could reduce or further exacerbate these risks.

Hurricane Harvey led to widespread flooding and knocked out power to 300,000 customers in Texas in 2017, with cascading effects on critical infrastructure facilities such as hospitals, water and wastewater treatment plants, and refineries. The photo shows Port Arthur, Texas, on August 31, 2017—six days after Hurricane Harvey made landfall along the Gulf Coast. Credit: Staff Sgt. Daniel J. Martinez, U.S. Air National Guard.

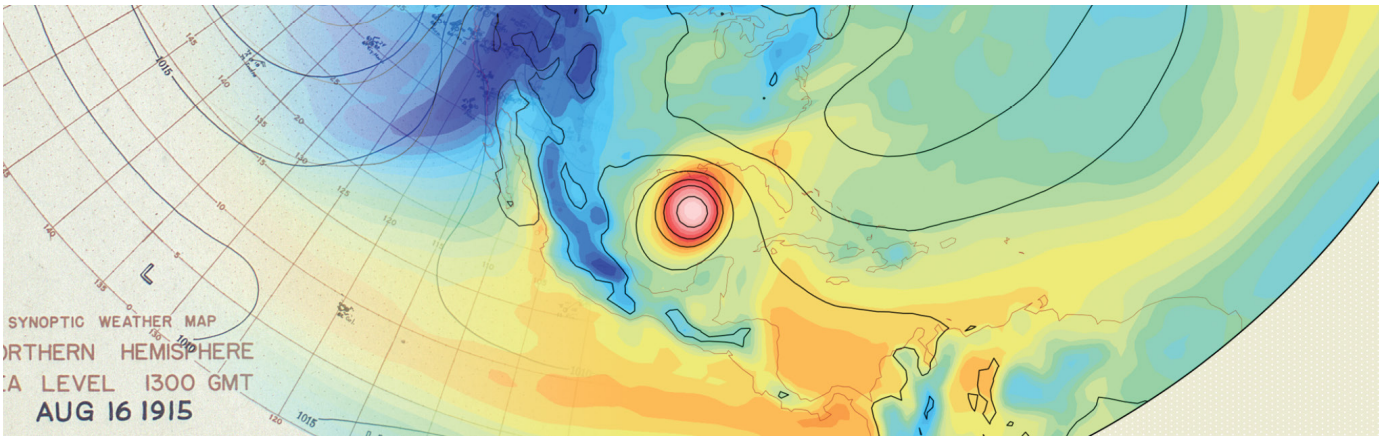
Updating a high-resolution reconstruction of the global climate

A reconstruction of daily weather back to 1806 puts current climate trends into historical perspective.

Historical weather reconstructions, or reanalyses, combine weather model output and observations from many sources to estimate the state of the atmosphere at a particular instant in time, over the entire globe. Reanalyses provide the context for understanding how weather and climate events and trends are changing over time and support improved prediction of future changes.

An interagency partnership between NOAA and DOE supported an updated version of the **20th Century Reanalysis Project (20CRv3)**, a unique high-resolution reconstruction of the global climate that uses surface observations to estimate daily weather back to 1806 on a 75-km grid. The 20CRv3 is able to accurately reconstruct individual weather events, variability in precipitation from year to year, and recent long-term trends in atmospheric temperature. The extension of 20CRv3 back to 1806 means that individual weather events and trends can now be placed into a consistent 210-year context—allowing scientists to understand, for example, how the frequency and intensity of severe winter storms are varying and changing over time.

20CRv3 is led by NOAA and the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, supported by DOE.



This illustration depicts a reconstruction of global weather patterns on August 16,1915, as the Galveston hurricane was about to make landfall on the Texas coast. Credit: 20th Century Reanalysis Project.

Measuring the atmospheric impacts of COVID-19-related emissions reductions

Researchers used interagency modeling and observational capabilities to understand the impacts of reduced pollution related to the COVID-19 pandemic on Earth's energy balance.

Lockdown measures enacted to control the spread of COVID-19 led to a worldwide reduction in emissions of tiny atmospheric particles known as aerosols. Through their interactions with solar energy and clouds, aerosols play a significant role in shaping Earth's energy balance (or the balance between incoming energy from the sun and outgoing energy from the Earth) and climate that is still inadequately understood. NOAA and NASA researchers used multi-agency observational and modeling capabilities to investigate the climate effects of this sharp drop in aerosol pollution, which provided an opportunity to test how well models simulate interactions between aerosols, clouds, and solar energy.

Satellite observations showed a 7% decline in the amount of solar energy reflected back to space at the top of Earth's atmosphere and a 32% drop in aerosol concentrations over the East Asian Marginal Seas in March 2020, coinciding with COVID-19 lockdown measures. Using model simulations, researchers separated the impacts of weather from the impacts of aerosols on the amount of solar energy reflected to space. Results showed that pandemic-related emissions reductions account for about one-third of the drop in solar clear-sky reflection (or the fraction of the sun's energy that is reflected back into space under cloud-free conditions).[24] The rest of the reduction was attributed to weather variability and long-term emissions trends.

Multi-agency observational and modeling capabilities were critical to monitoring and understanding impacts on Earth's energy balance from reduced aerosol pollution. The framework developed in this research can be used to study the atmospheric impacts of the ongoing pandemic in other parts of the world and to enhance the predictive capabilities of climate and weather models.

Focus Areas

While coordinating a broad spectrum of research relevant to global change, USGCRP finds value in emphasizing particular focus areas that are shared by multiple agencies. In Fiscal Year 2020, USGCRP identified three focus areas that reflect current Program priorities: the intersection of climate-related global change with coasts, human health, and the water cycle. These topics represent areas where coordinated Federal science can support key advances and inform efforts to build resilience in critical sectors.

USGCRP's existing interagency groups serve as the home for coordinating the scoping and implementation of activities in support of each of these focus areas. Focus area activities integrate across USGCRP's strategic goals and program areas, from core scientific capabilities to decision support, scientific assessment, and engagement with science users and the public. For each focus area, this section highlights activities carried out by interagency groups as well as other interagency activities that address scientific and decision-support needs.

Coasts

U.S. coastal infrastructure, communities, resources, and property are increasingly threatened by climate-related changes including sea level rise, high-tide flooding, marine heat waves, coastal erosion, higher storm surge, and more intense precipitation events, with cascading effects on the larger economy.[25] Climate-related impacts on the coastal zone are shaped by many factors, both human and natural, including climate system changes, changes in ecosystem services, changes in human systems, and the complex interactions among them. USGCRP is facilitating research across agencies to improve understanding of processes that affect the range and timing of these impacts and to support development of information and tools to help coastal communities plan adaptation strategies.

In early 2020, USGCRP's Coasts Interagency Group identified three initial workstreams: coastal inundation, coastal integrated hydro-terrestrial modeling, and coastal science and decision-making. These workstreams support and promote interagency collaboration via monthly meetings and targeted workshops, and may lead to the development of products that benefit from multi-agency input.

Coordinating effective Federal responses to sea level rise requires aligning the research products of science-producing agencies with the needs of agencies that use science to carry out their missions. The coastal inundation workstream is scoping agency needs and science capabilities to improve existing tools and platforms to communicate future coastal inundation and flooding to affected communities. White papers are being developed to address themes from the interagency discussions.

The interagency Sea Level Rise Task Force, under the auspices of the USGCRP coastal inundation workstream and the Subcommittee on Ocean Science and Technology, has begun updating the 2017 interagency sea level rise technical report, which provided regional sea level rise projections for the Fourth National Climate Assessment. A draft report and accompanying dataset will summarize the latest guidance and projections of future sea level rise to both underpin discussions of coastal impacts in NCA5 and update the broader multi-agency approach to managing sea level rise.

Modeling the complex changes and interactions among physical, environmental, and human systems along the U.S. coastline is a key research frontier with significant potential to inform and shape management of coastal regions, resources, and infrastructure. In November 2020, the coastal integrated hydro-terrestrial modeling workstream brought together the Federal modeling community and academic researchers in a series of workshops to envision new pathways for understanding climate impacts and compound stressors on coastal communities. Sessions were attended by participants from eleven Federal agencies and many academic labs and centers specializing in modeling the interaction among human activities and environmental systems. In addition to a workshop report, the workshop led to the formation of three interagency teams that are coordinating targeted activities around modeling, data/observations, and use cases.

Other interagency efforts highlighted this year are building coastal resilience in the Chesapeake Bay (p. 19), informing coastal resilience efforts through a modeling framework providing insight on coastal hazards (p. 20), and helping land managers assess risks to coastal wetlands through satellite data products (p. 21).

Building coastal resilience in the Chesapeake Bay

Nature-based restoration efforts on Swan Island aim to protect coastal communities from erosion and storm surge while restoring ecosystems.

Coastal islands and marshes in the Chesapeake Bay provide habitat for many species and protect coastal communities from wave energy. Within the last half century, the effects of shoreline erosion, land subsidence, and sea level rise have accelerated the rate of island submergence and degradation of ecosystems in the region. In one example, the Smith Island complex, of which Swan Island is a part, has eroded at rates of up to 2 meters per year over the past 75 years.[26] Nature-based restoration efforts have the potential to reduce erosion in coastal communities, increase resilience to sea level rise, and provide new habitat for wildlife.

A multi-agency partnership is working to restore marshlands on Swan Island and fill knowledge gaps on the resilience and ecological benefits of island restoration efforts.

The U.S. Army Corps of Engineer's Baltimore District restored Swan Island with dredged sediment from a nearby navigation channel and planted native salt marsh and dune plants throughout 2019. With support from USACE's **Engineering With Nature® (EWN®)** Program, USACE and partners (including NOAA, the U.S. Fish and Wildlife Service, and the Maryland Department of Natural Resources) are

studying the ability of this restoration to reduce storm and flood risk to a nearby community and support healthy ecosystems. The collection of physical and ecological data will be used to quantify benefits derived from the project and inform the management and design of future nature-based restoration projects within the Chesapeake Bay and beyond.

Swan Island in 2019 after placement of dredged sediments as part of a nature-based restoration effort to protect nearby coastal communities from erosion and provide new habitat for wildlife. Credit: NOAA.

Understanding coastal hazards

A modeling framework provides insight on future coastal flooding risks to guide resilience efforts.

Sea level rise and other climate-related changes are increasing risks from the impacts of storms on coastal communities, infrastructure, and ecosystems. To support efforts to build resilience to climate variability and change, the U.S. Army Corps of Engineers Engineer Research and Development Center-Coastal and Hydraulics Laboratory (ERDC-CHL) developed the **Coastal Hazards System (CHS)** as a framework to quantify risks from coastal hazards and flooding events caused by hurricanes and other extreme storms that can be expected to occur in the future.[27]

The CHS provides information on risks from coastal hazards, such as expected storm surge along coastal Louisiana from a 100-year storm, based on high-resolution modeling of coastal storm dynamics. Currently, the CHS covers all U.S. hurricane-prone coastlines along the Gulf of Mexico, the Atlantic seaboard, Puerto Rico, and the U.S. Virgin Islands, as well as regions affected only by extratropical storms, such as the Great Lakes.

The CHS includes a database and web-based data repository and visualization system available to the public. The Nuclear Regulatory Commission, FEMA, the USGS, state and local governments, private industry, and academia, and others use CHS to develop long-term strategies to enhance resiliency and increase sustainability in high-risk coastal communities and natural ecosystems.

The aftermath of a category 4 hurricane, Mexico Beach, FL. Credit: K.C. Wilsey/FEMA.

Assessing the health of coastal wetlands nationwide

Satellite data products are helping land managers quickly evaluate the health of vulnerable coastal wetlands.

Salt marshes protect communities and infrastructure from storms, filter pollution, and provide habitat for fish and shellfish. These coastal wetlands and the ecosystem services they provide are increasingly threatened by rising sea levels, erosion, and land use change, and land and resource managers need tools to track changes and trends in their health and extent. Satellite data products provide one method for quickly evaluating marsh vulnerability to environmental change and can help inform efforts to restore and protect coastal wetlands.

Salt marsh resilience can be evaluated through a metric called the UnVegetated-Vegetated marsh Ratio (UVVR), developed by the USGS, which measures how much vegetation a marsh area contains and provides an indicator of its overall health.[28] Using Landsat 8 satellite imagery, USGS scientists mapped the UVVR at a 30-meter resolution for the coastal wetlands of the contiguous United States for 2014–2018.[29] This product enables DOI, state managers, and other users to get broad assessments of the most vulnerable marshes without requiring site-specific studies.

Regular delivery of updated UVVR assessments supports marsh restoration efforts by the National Park Service, the U.S. Fish and Wildlife Service (USFWS), and state agencies. The new data products and national map of UVVR complement detailed mapping by the USFWS' National Wetland Inventory program and can also be combined with the Coastal National Elevation Database to generate national estimates of marsh lifespan under varying sea level rise scenarios. UVVR data is available in the USGS Coastal Change Hazards Portal.

Salt Marsh at Chassahowitzka National Wildlife Refuge. Credit: Amber Breland/USFWS.

Health

Changes in climate affect the incidence and severity of public health impacts such as temperature-related illnesses and mortality, respiratory diseases, waterborne and vector-borne diseases, and mental health impacts. These impacts increasingly threaten the health and well-being of the American people, particularly populations that are already vulnerable.

Recent extreme heat and wildfire events, outbreaks of climate-sensitive infectious diseases, and other impacts are driving demand for more information and tools for communicating the connections between climate change and health. USGCRP, through its Crosscutting Group on Climate Change Human Health (CCHHG), is coordinating efforts to advance the science of predictive models for projecting changes in climate-sensitive conditions and diseases and develop and deploy other climate-relevant decision support tools to protect Americans' health (p. 22). In collaboration with USGCRP's International Activities Interagency Working Group (IAIWG), the CCHHG also helped mobilize support for international and U.S.-based research teams investigating the public health implications of climate-related changes (p. 22). Finally, the CCHHG created a compendium of federally funded research activities on climate change and health published since 2016 that will help inform authors of the Fifth National Climate Assessment and interagency research planning (p. 22).

Informing heat health decisions

A heat health forecast tool aims to help communities better prepare for and respond to extreme heat events.

The CCHHG, led by NOAA and the Centers for Disease Control and Prevention (CDC), with input from the National Institutes of Health and other agencies, developed a **Climate and Health Monitor and Outlook Heat Forecast Product** for the continental United States based on NOAA seasonal forecasts. The heat health forecast tool displays the rate of heat-related illness by region for a given week and is designed to help communities better prepare for and respond to extreme heat events. CDC is incorporating the forecast tool into its Environmental Health Tracking Portal.

Supporting international health and climate research

USGCRP agencies mobilized support for research on the health implications of climate change.

As part of its mandate to promote international cooperation in global change research, USGCRP engages with the Belmont Forum, an international partnership that catalyzes funding for research in support of resilience and sustainability. USGCRP member agencies (including NOAA, NSF, USDA, and the National Institutes of Health) participated in the scoping, call text writing, review, and funding of nine research proposals on climate, environment, and health supported through the Belmont Forum. The projects will provide crucial new understanding of the health implications of the impacts of climate change and variability on the food supply, chronic exposure to increases in heat and humidity, and changes in the distribution and incidence of a range of infectious diseases and emergence of novel pathogens.

Developing a new resource on Federal climate change and health research

A new resource ensures that Federal health and climate research is accessible to inform the Fifth National Climate Assessment.

In 2020, the CCHHG began an effort to identify and organize information on federally funded research activities on climate change and human health since 2016. This group, co-led by EPA and NASA, collated this information into a **Federal climate change and health research compendium** document to

help inform authors of the Fifth National Climate Assessment, as well as agency research planning. Nine Federal agencies contributed to the compendium, which includes sections on air quality, temperature, extreme events, water-related illness, and other research areas (such as rainfall, drought, and chemical exposures following natural disasters).

Water

The quality and quantity of water available to people and ecosystems are being affected by climate change, increasing risks and costs to agriculture, energy production, industry, recreation, and the environment.[30] Future warming will add to the stress on water supplies, and the demand for information from water-dependent sectors is a key driver of research on how climate variability and change will affect the water cycle.

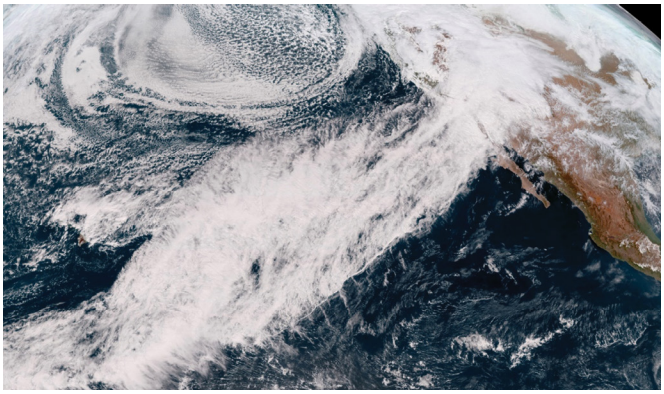
USGCRP coordinates research to better observe, model, and predict changes in the global water cycle and their impacts on society. USGCRP's Integrated Water Cycle Group and the U.S. Global Energy and Water Exchanges Program Office (U.S. GEWEX) are exploring activities related to changing precipitation patterns and their predictability and the interaction between the water cycle and a changing climate on regional scales, including an effort to support improvements in the ability to represent precipitation processes in regional and global climate models (p. 24). USGCRP agencies also continue to enhance observing systems that track key components of the water cycle (p. 9).

Other efforts highlighted this year include the development of tools to inform decision-making and enhance collaboration among decision-makers working to build resilience to climate-related impacts (p. 24), new national-scale drought information (p. 25), and a knowledge-sharing network of drought management practitioners (p. 25).

Improving precipitation prediction

Collaboration across modeling, observational, and process research communities aims to improve how models represent and predict precipitation.

Many extreme events and related impacts are associated with the intensity, duration, and frequency of precipitation, including drought, flooding, wildfire, and severe storms. Understanding when, where, and how much precipitation will fall can help decision-makers and planners in agriculture, emergency management, energy, and other sectors prepare for and reduce costs from potential impacts. While models are skilled at simulating global and regional temperature, precipitation-related processes are not captured as well, and producing accurate forecasts and realistic projections with enough lead time to support decision-making is an ongoing science challenge.



An atmospheric river stretching across the Pacific Ocean captured on February 14, 2019, by NOAA's GOES-17 satellite. Atmospheric rivers carry huge amounts of moisture from the tropics northward, often resulting in heavy rainfall and high-elevation snow along the West Coast of North America during winter. Improved prediction of atmospheric rivers will support timelier, more accurate flood watches and warnings. Credit: NOAA.

Recognizing the need for improved skill in precipitation prediction, NOAA and DOE led a workshop in November–December 2020 that focused on advancing understanding of precipitation predictability and physical processes key to precipitation biases (or systematic model errors). The workshop brought together the observational, modeling, and research communities to identify sources of predictability that span weather to climate time scales, identify which physical processes could be better represented in models to improve the accuracy of future predictions, evaluate which existing and desired observing systems are needed to address shortcomings, and suggest which Federal and international collaborations would be appropriate to accelerate progress.

Addressing water supply challenges in the American West

Collaborative studies among scientists and decision-makers are identifying strategies to meet current and future water demands.

The western United States faces growing water challenges. Drought, population change, aging infrastructure, and ecosystem needs all strain existing water and power infrastructure, and future climate change is expected to further increase stress on water supplies. Through the **WaterSMART Basin Study Program**, the Bureau of Reclamation works with states, tribes, non-governmental organizations, other Federal agencies, and local partners to identify strategies to adapt to and mitigate

Water recycling and reuse offsets the demand for imported water in Southern California, such as the diversion of Colorado River Water through the All-American Canal. Credit: Andrew Pernick/Bureau of Reclamation.

current or future water supply and demand imbalances, including the impacts of climate change and other stressors on water and power facilities. Since 2009, Reclamation has funded 27 Basin Studies in 15 western states, 18 of which are now complete.

Each Basin Study examines projections of future supply and demand by river basin, analyzes infrastructure performance in the face of changing supplies, and develops strategies to meet current and future demands. Basin Studies have involved coordination with other Federal agencies, including the USGS, EPA, DOE, and DoD. These collaborative efforts aim to support decision-makers as they plan for and implement measures to meet current and future water demands.

Providing national-scale drought information

New data products integrate multiple sources of soil moisture information to improve drought monitoring and prediction.

Drought is one of the most destructive and costly natural disasters, resulting in diminished agricultural production, reduced water resources, and deadly heatwaves. NOAA and the National Integrated Drought Information System have supported interagency activities to develop a **national-scale drought product** that integrates multiple sources of soil moisture information to improve drought monitoring and prediction. These activities represent collaborative efforts among NOAA, NASA, the USGS, USDA, and the academic community to provide accurate and timely drought information and forecasting in order to facilitate decision-making and management.

Sharing knowledge on drought resilience

The Drought Learning Network supports knowledge exchange on drought management in the U.S. Southwest.

The **Drought Learning Network (DLN)** brings together drought management leaders and resource managers to support knowledge sharing and improve collaboration around building resilience among communities impacted by drought in the U.S. Southwest, one of the hottest and driest regions of the world. The DLN was created by drought management leaders from the USDA Southwest Climate Hub, the National Drought Mitigation Center, and NOAA's National Integrated Drought Information System to help capture lessons learned from previous droughts and assist resource managers in responding to future events.

The network now has more than 70 members representing diverse agencies. In the first year, the DLN hosted more than 22 virtual workshops and webinars, developed two surveys about climate data preferences of resource managers, and published case studies on conservation and drought preparedness efforts. In 2021, there are five teams working on priority challenges of the DLN, including Indigenous collaboration, drought in agriculture, drought impact reporting, and sharing management practices.

Corn shows the effect of drought in Texas. Credit: Bob Nichols/USDA.

Informing Decisions

USGCRP research creates the foundation for delivering useful climate and global change information. USGCRP member agencies support decision-makers through activities such as conducting natural, behavior, and social science research to understand how people and environments respond to change; engaging with stakeholders to understand their needs and foster the use of information; and informing decision makers on projected changes.

USGCRP coordinates and integrates many efforts across the Federal Government to provide access to authoritative, freely available assessments, datasets, and tools that inform decisions under changing environmental conditions. Interagency science contributes to the development of information tools for managing climate-related risks and opportunities in sectors such as agriculture, transportation, and water resources, including the provision of information at regional scales useful for decision-making. USGCRP's Federal Adaptation and Resilience Group provides a forum for members to learn and collaborate across agencies on topics including the economics of adaptation, climate-resilient infrastructure, and adaptation and natural resource management.

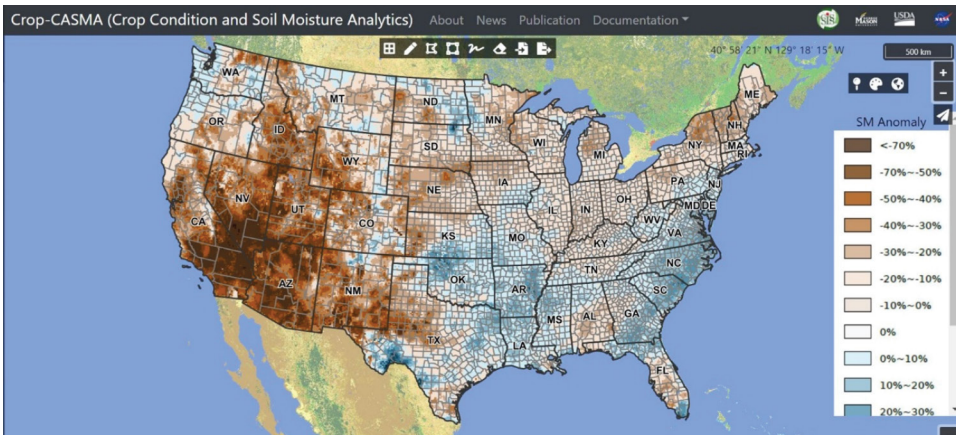
Interagency efforts highlighted this year include the development of a tool to bring satellite data on field conditions to agricultural users (p. 27), an assessment of the latest science on managing invasive species in U.S. forests and rangelands (p. 28), and a collaborative effort among scientists and land managers to design climate change adaptation strategies (p. 28). Also highlighted are an assessment of science informing conservation strategies for ecosystems and species affected by climate change (p. 29) and a synthesis of research on the environmental drivers of the COVID-19 pandemic that informed Federal responses (p. 29).

Informing agricultural operations

A new tool makes satellite data on field conditions available to producers.

Soil moisture data are used to plan crop planting, forecast yields, track droughts or floods, and improve weather forecasts, and can also be used to track changing conditions for U.S. agriculture over time. A new tool developed by USDA makes soil moisture data from NASA available to farmers, researchers, and other users.

The **Crop-CASMA (Crop Condition and Soil Moisture Analytics)** tool uses high-resolution satellite data from NASA's Soil Moisture Active Passive (SMAP) mission to map soil moisture across the United States. Crop-CASMA provides access to data that can help producers plan spring plantings, guide predictions of moisture conditions and water availability, track damage after natural disasters, and



Crop-CASMA provides access to high-resolution soil moisture data from NASA's Soil Moisture Active Passive (SMAP) mission and the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument in a user-friendly format. Source: USDA-NASS and the Center for Spatial Information Science and Systems at George Mason University.

monitor crop health and field conditions. The tool is formatted to be accessible to the public, including farmers, researchers, and students. Crop-CASMA was developed by USDA's National Agricultural Statistics Service in collaboration with NASA and George Mason University.

Supporting management of invasive species in forests and rangelands

A new scientific assessment provides information on the spread and control of invasive species for land managers.

The spread of invasive species is recognized as a major driver of biodiversity loss and a source of substantial economic and environmental damage. Global environmental changes, including climate change and land use change, continue to influence how invasive species spread and interact with ecosystems, presenting new and ongoing challenges for land managers. A recent USDA Forest Service (USDA-FS) assessment presents the latest natural and social science research on the ecology, impacts, and practical tools for management of invasive species affecting America's forests and grasslands, including research on the interactions between invasive species and climate change.[31]

The emerald ash borer is the most devasting invasive forest insect pest in North America and threatens the nation's ash resource. Credit: Deborah L. Miller/USDA Forest Service, Northern Research Station.

The scientific synthesis serves as a resource for land managers looking for information on current and future threats from invasives, the most important invasive species and issues in each region of the country, and what is known about control of invasive species. The assessment is the product of over 100 authors from the USDA-FS; other Federal agencies including the U.S. Fish and Wildlife Service, the U.S. Geological Survey, DoD, and DOT; and university, non-governmental, and tribal land partners.

Co-designing climate change adaptation strategies with land managers

The Climate Change Response Framework provides landowners with adaptation options to address climate change risks to forests.

Climate change increases uncertainty about future conditions affecting land and natural resources, creating new challenges for land managers working to sustain healthy ecosystems and ecosystem services. In 2020, the Northern Institute of Applied Climate Science (NIACS) and the USDA Northern Forests Climate Hub worked side-by-side with land managers to advance regionally specific climate change adaptation strategies. The NIACS Climate Change Response Framework was used to provide landowners with regional forest vulnerability assessments and

An emerald ash borer trap being used to monitor populations of the insect across the Pokagon Reservation. Credit: Vic Bogosian.

adaptation options to address climate change risks and sensitivities. The Framework is a collaborative effort among scientists, managers, and landowners to address the major challenges that U.S. land managers face when considering how to integrate climate change considerations into their planning and management. Recent work includes development of new menus of adaptation strategies and approaches for areas including forest carbon management, recreation, and health.

NIACS is a collaborative initiative among the USDA Forest Service, universities, conservation organizations, and forest industry to provide information on managing forests for climate change adaptation and carbon sequestration. NIACS's Federal partners include the U.S. Geological Survey, the U.S. Fish and Wildlife Service, the National Park Service, and the Bureau of Indian Affairs.

Understanding climate change refugia

A journal special issue highlights advances in the science of protecting species and ecosystems from climate change impacts.

An increasingly important climate change adaptation strategy is to focus conservation on climate change refugia, or areas that are relatively buffered from contemporary climate change. Protection and management of climate change refugia can help shelter native species and ecosystems from current climate change impacts and provide longer-term havens that protect valued ecological and sociocultural resources. The U.S. Geological Survey and EPA, along with Federal, state, and other partners, are supporting advances in scientific understanding of refugia that enable researchers and resource managers to put this understanding into practice. A 2020 journal special issue highlighted advances in refugia science that reflect improved incorporation of ecological complexity and the shift towards practical application in conservation strategies.[32]

The Arctic ground squirrel faces threats from habitat loss and climate changes, such as temperature increases in shifts in the timing of snow melt. Credit: Toni Lyn Morelli/Northeast Climate Adaptation Science Center.

Translating research on the environmental drivers of COVID-19 to support decision-making

Interagency science informed the synthesis of actionable research to support Federal responses to the COVID-19 pandemic.

In March 2020, DoD began working with interagency partners to synthesize actionable research on potential environmental drivers impacting the life and spread of the COVID-19 virus. From this collective research, representatives from the Air Force Directorate of Weather worked with DoD's operational climate services unit, the 14th Weather Squadron in Asheville, NC, to produce actionable products for senior DoD leaders on potential environmental drivers of COVID-19, as well as an assessment of potential extreme weather and climate events that could impact DoD's response. Through USGCRP's CCHHG, the Air Force Directorate of Weather coordinated with the Centers for Disease Control and Prevention, Johns Hopkins University, NOAA, and other medical subject matter experts in academia and the U.S. Government. Finally, representatives from the Air Force Directorate of Weather participated on a science panel at a World Meteorological Organization virtual symposium on climatological, meteorological, and environmental factors in the COVID-19 pandemic in August 2020.

Conducting Sustained Assessments

As directed by the Global Change Research Act, USGCRP produces regular assessments of current scientific understanding on global change, including projections of future climate conditions and ongoing and potential impacts on society in the United States. USGCRP approaches assessment as a sustained process that enables scientists and stakeholders to address issues of emerging importance on an ongoing basis while improving the thoroughness of the quadrennial National Climate Assessment (NCA). Development of the Fifth National Climate Assessment (NCA5) is underway, and USGCRP's interagency groups continue to develop products and tools and provide guidance that contribute to the assessment process. USGCRP's Sustained Assessment Working Group focuses on improving the production efficiency of the NCA, including aspects of the assessment process, scenario products and data tools, indicators, research needs and gaps, special reports, evaluation, and engagement with assessment contributors and users.

Improved integration of social science approaches in climate and global change research is an ongoing goal for USGCRP, and the Program's Social Sciences Coordinating Committee has provided valuable input on incorporating social science perspectives in NCA5 (p. 31). USGCRP and its member agencies also regularly update climate change indicators that expand the ability of USGCRP agencies to provide the latest information to users between quadrennial assessments. USGCRP's Indicators Interagency Working Group leverages existing agency research, data, and indicators in support of sustained assessment activities (p. 32). Indicators produced by USGCRP agencies, including a recent set of indicators on climate and agriculture (p. 33), contribute to the NCA and support decision-making in particular sectors.

USGCRP assessment reports evaluate existing literature, which typically uses scenarios for future change developed by the global scientific community. USGCRP and its member agencies also consider and use federally developed scenario products in the research they support that contribute to the NCA and other assessment reports. The interagency Sea Level Rise Task Force, under the auspices of the USGCRP Coasts Group and the Subcommittee on Ocean Science and Technology, is updating regional sea level rise projections that will underpin discussions of coastal impacts in NCA5 and update the broader multi-agency approach to managing sea level rise (See Coasts, p. 18).

Finally, USGCRP's Climate Change and Human Health Group is creating a compendium of Federal research on climate change and human health that will help inform NCA5 authors (p. 22).

Improving social science inputs to the National Climate Assessment

Interagency efforts ensure that social science expertise helps shape the Fifth National Climate Assessment.

USGCRP's Social Sciences Coordinating Committee (SSCC) provides regular input into USGCRP's sustained assessment process, including ongoing engagement with the academic social sciences community and recommendations for the further integration of social science topics into National Climate Assessments.

Fifth National Climate Assessment (NCA5) Webinar for Social Scientists

In October 2020, the SSCC hosted a public webinar for social scientists that outlined the different mechanisms for engaging in the development of NCA5. The webinar drew over 140 attendees, and together with other SSCC-led outreach, resulted in over 200 NCA5 author nominations with social science expertise, far exceeding the number of social scientist nominations in past assessments.

Memo to the NCA5 Federal Steering Committee (FSC)

Building off the mandate of the Global Change Research Act and substantial public and scientific

input, the SSCC submitted a memo to the NCA5 FSC that made recommendations on how to further integrate the social sciences into NCA5. One major recommendation was a separate chapter on human social systems, which is being developed for NCA5.

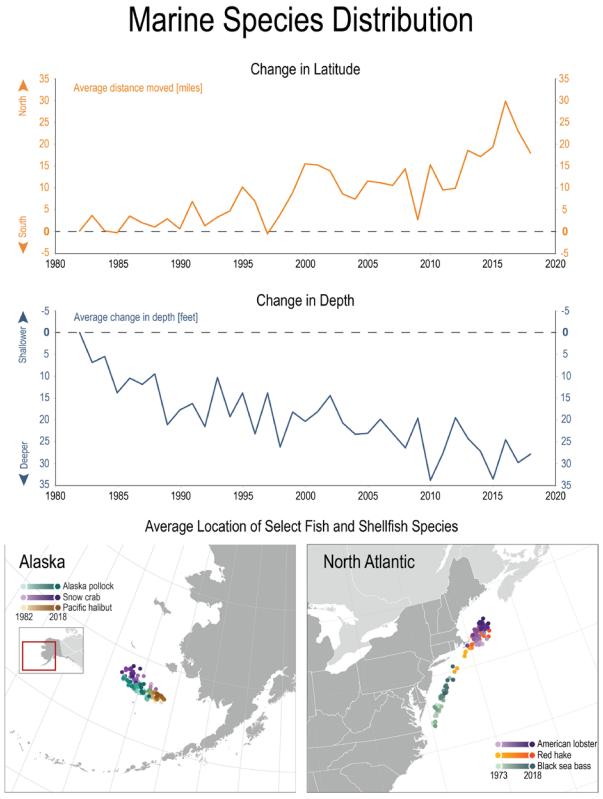
Communicating climate change

New climate indicators and communications efforts tell the story of climate change through federally supported observations.

Climate indicators show trends over time in important aspects of our environment, such as greenhouse gas levels in the atmosphere and the start of spring each year. Indicators are based on long-term, consistently collected data and can be used to assess risks and vulnerabilities from a changing climate and to inform response actions. IndIWG developed an interagency web platform for USGCRP to highlight federally supported climate-relevant indicators and is continuing to support the development and inclusion of new indicators.

New indicator publication: marine species distribution

As climate change drives ocean warming, populations of some marine species are adapting by shifting northward or to deeper waters that have a more suitable temperature, with implications for U.S. fisheries and consumers. EPA and NOAA partnered in the development of an indicator examining changes in the location of fish, shellfish, and other marine species along U.S. coasts that is now part of EPA's climate change indicators, the Fourth National Climate Assessment, and the USGCRP Indicator Platform. A related peer-reviewed publication on the climate impacts to U.S. marine fisheries was also published in 2020, finding that warming ocean temperatures could lead to annual losses in the range of hundreds of millions of dollars to U.S. commercial fisheries by the end of the century.[33]



*The graphs show the annual change in latitude (orange line; movement in miles) and depth (blue line; depth change in feet) of 140 marine species along the northeastern U.S. coast and in the eastern Bering Sea. Changes in the centers of biomass have been aggregated across all 140 species. The maps show the annual centers of biomass for three species (Alaska pollock, snow crab, and Pacific halibut) in the eastern Bering Sea from 1982 to 2018 (**Left**) and for three species (American lobster, red hake, and black sea bass) along the northeastern U.S. coast from 1973 to 2018 (**Right**). Dots are shaded from light to dark to show change over time. Data sources: Rutgers University and NOAA NMFS.*

Federal workshop on forest-related climate indicators

Indicators of climate impacts for forests such as change in forest structure and composition or disturbance from wildfire and forest insects and diseases can help forest managers understand how climate drives changes in forests and how to manage for these changes over time. IndIWG co-chairs and members of the working group organized and hosted a 3-day workshop with over 30 scientists from the USDA Forest Service and academia to help identify and discuss indicators related to forest disturbances. Follow-up from the workshop includes advancing indicators on forest disturbances including wildfires, insect and disease mortality, drought, flooding, and others.

New science communication overview of indicators

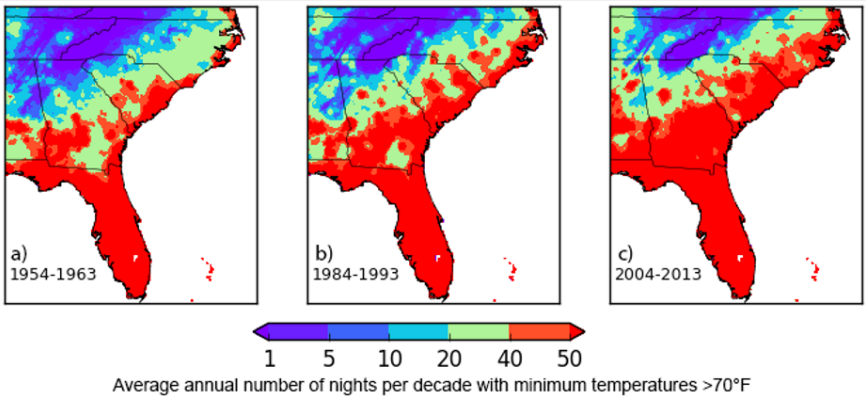
The USDA Forest Service, the EPA, and USGCRP partnered to develop a new communication tool that allows users to explore the story of climate change through federally supported observations. The interactive Story Map features multiple agency indicators, some of which are hosted on USGCRP's Indicator Platform. The Story Map is also featured in EPA's main climate change website.

Tracking the impacts of climate change on agriculture

A new set of agricultural and climate data products provides the basis for communicating the impacts of climate change on U.S. agricultural lands.

The recent **USDA Climate Change Indicators for Agriculture report** provides national, regional, and local information to support effective decision-making by U.S. agricultural producers, resource managers, policy makers, and other users.[34] This set of indicators identifies high-priority agricultural and climate data products while providing the basis for tracking the impacts of climate change on American working lands, in support of adaptive operational responses. The report categorizes physical, crop and livestock, biological, phenological, and socioeconomic indicators for a wide range of U.S. geographical areas, production types, and systemic outcomes. The indicators are currently being further developed into a queryable, geographically explicit, real-time decision support system for resource management.

The report was produced through a collaboration among USDA, Colorado State University, Florida State University, Cornell University, the National Center for Atmospheric Research, and NSF.



Average annual number of nights with minimum temperatures greater than 70°F, averaged over three decades across the southeastern United States. Each decade—(a) 1954–1963, (b) 1984–1993, and (c) 2004–2013—shows an increased area where the average number of nights with minimum temperatures above 70°F occurred; these temperatures exceed the thermoneutral zone for cattle, sheep, and goats, above which heat stress can occur. (Based on data from Livneh et al. 2015.) Source: USDA.

Coordinating International Global Change Research

As directed by the Global Change Research Act, USGCRP works to improve coordination of U.S. activities with the programs of other nations and international organizations in order to promote international cooperation on global change research and build global change research capacity in developing countries. To advance these goals, USGCRP maintains and develops international partnerships that support the priorities and objectives of the USGCRP community, link to USGCRP's program areas, and build on existing agency investments and resources. USGCRP's International Activities Interagency Working Group (IAIWG) works with member agencies to promote and contribute to international and intergovernmental cooperation on global change research and engages with international organizations and initiatives in a variety of ways.

This section highlights an effort to support building capacity in tropical forested countries to monitor carbon storage in ecosystems (p. 35). USGCRP agencies also participate in global observing campaigns and networks (e.g., p. 5, p. 8, p. 8, p. 11) and modeling efforts (e.g., p. 15) that are supportive of the Program's mandate to promote international coordination around global change research.

In addition, in 2020, USGCRP helped mobilize support for international and U.S.-based research teams investigating the public health implications of climate-related changes through the Belmont Forum, an international partnership that catalyzes funding for research in support of resilience and sustainability (p. 22).

Improving monitoring of forest carbon stocks

SilvaCarbon leverages state-of-the-art science and technology to advance the generation and use of information in managing forest and terrestrial carbon.

Tropical deforestation and forest degradation are major sources of greenhouse gas emissions, and sustainable management of tropical forest resources is an important opportunity for climate change mitigation. Many tropical forested countries have committed to providing accurate, transparent information about landscape changes and changes in forest carbon stocks and emissions, but need technical assistance to accomplish their goals.

SilvaCarbon provides coordinated technical support from multiple U.S. Government agencies (including USAID, DOS, USDA, the USGS, EPA, NASA, NOAA, and SI) to build capacity in tropical forested



SilvaCarbon provides targeted capacity-building support to help countries meet their long-term needs for improved data and information related to forest and terrestrial carbon. This includes hands-on training and technical assistance on remote sensing tools and methods, ground-based forest inventories, and data integration for accurate, transparent emissions estimation and reporting. ***(Left)*** *forest inventory field training in Vietnam.* ***(Middle)*** *remote sensing data time-series analysis training in the Congo Basin.* ***(Right)*** *carbon flux tower field training in the Andean Amazon. Source: USAID.*

countries to measure, monitor, and report on forest and terrestrial carbon. By providing remote sensing and ground-based forest inventory expertise and trainings, SilvaCarbon helps countries adopt nationally appropriate tools and methods that integrate satellite data with field data for more cost-effective and systematic monitoring of forest carbon stocks and emissions.

SilvaCarbon has worked with 25 tropical forested countries to build forest and landscape monitoring capacities, promote collaboration and knowledge sharing, and facilitate technical coordination globally. SilvaCarbon is the primary U.S. contribution to the international Global Forest Observations Initiative, an international consortium working to increase availability and use of remote sensing data and tools for national forest monitoring.

Recent SilvaCarbon support resulted in the development of a REDD+ Registry for Zambia. SilvaCarbon also supported Fiji, Indonesia, Lao PDR, Nepal, and Vietnam in signing the Emission Reduction Purchase Agreement with the Forest Carbon Partnership Facility. In addition, with SilvaCarbon technical assistance, El Salvador submitted its first and Peru and Honduras submitted their second Forest Reference Levels. Finally, the SilvaCarbon Women in Forest Carbon Initiative was launched to better address gender disparities in the field of forest and carbon monitoring.

BUDGETARY INFORMATION

The budget crosscut represents the funds self-identified by USGCRP agencies as their expenditures in support of USGCRP research activities. In addition, USGCRP leverages other agency activities not represented in the budget crosscut to accomplish its mission. For example, many of the satellite systems and surface-based observing networks that are foundational to USGCRP research were originally implemented by their sponsoring agencies for operational purposes, and thus typically are not included in the research crosscut.

Fiscal Year (FY) 2022 USGCRP Budget Crosscut by Agency

Funding amounts are shown in millions of dollars ($M) and are rounded to the nearest millions (totals reflect the rounded sum of the unrounded agency amounts).

Agency	FY 2020 Enacted ($M)	FY 2021 Enacted ($M)	FY 2022 President's Budget ($M)
Department of Agriculture	111	128	405
Department of Commerce	306	444	731
Department of Energy	256	305	366
Department of Health and Human Services	10	19	154
Department of the Interior	38	207	461
Department of Transportation	0	1	52
Environmental Protection Agency	18	20	51
National Aeronautics and Space Administration	1,469	1,617	1,827
National Science Foundation	246	521	762
Smithsonian Institution	8	8	13
TOTAL (USGCRP)	**2,461**	**3,270**	**4,822**

APPENDIX I. ABOUT USGCRP

Program History

The U.S. Global Change Research Program (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate a "comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

USGCRP coordinates and integrates global change research across 13 Federal agencies and engages with international partners to promote cooperation around global change research. The Program emphasizes research that can be used to answer critical questions about the changing Earth system and how the United States and the world can respond to those changes. USGCRP's legal mandate is available on the USGCRP website.

As mandated by Congress, USGCRP develops a new strategic research plan every ten years, with triennial revisions and updates. The 2012–2021 Strategic Plan and its 2017 update are being implemented by the collective efforts of USGCRP's member agencies. Development of the 2022-2031 Strategic Plan is underway.

USGCRP's annual report to Congress, *Our Changing Planet*, presents highlights of the Program's accomplishments each year that illustrate how USGCRP is meeting its mandate under the GCRA and achieving the goals outlined in the Program's Strategic Plan.

Program Structure

USGCRP is steered by the Subcommittee on Global Change Research (SGCR) of the National Science and Technology Council's Committee on Environment, which is overseen by the White House Office of Science and Technology Policy. The SGCR coordinates interagency activities through the USGCRP National Coordination Office and interagency groups.

Interagency groups are USGCRP's primary vehicle for implementing and coordinating global change research activities within and across agencies. They are designed to bring agencies together to plan, develop, and implement coordinated activities, and to identify and address gaps in the Program's plans. The groups span a range of interconnected climate and global change issues and address major components of the Earth's environmental and human systems, as well as cross-disciplinary approaches for addressing these issues. They allow Federal scientists and program managers to communicate with each other on emerging directions within their agencies, their stakeholder needs, and best practices learned from agency activities. Together, these functions allow the agencies to work in a more coordinated and effective manner.

Member Agencies

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) global change research activities reflect the challenges posed to agriculture, forests, and natural resources by climate change, and the promise of addressing the climate challenge from within the land sector. USDA's research aims to understand the role of agricultural and forest systems in contributing climate change, the risks and vulnerabilities facing these sectors, opportunities to reduce emissions and increase sequestration, and strategies to enhance productivity while building resilience to climate change. USDA's global change research is focused on the development and evaluation of innovative practices and technologies, monitoring networks, and a range of analyses and modeling efforts to investigate outcomes of climate scenarios and adoption of climate-smart practices. USDA partners with research institutions and the private sector to ensure that useful and useable data are collected across landscapes to observe effects and responses to climate change. The outcomes of these wide-ranging scientific activities are synthesized to be region- and context-specific to support USDA's delivery of programs and assistance that best enable farmers, ranchers, land managers, and rural communities to make decisions in a changing climate.

Within USDA, climate change research activities harness the combined strengths of the Agricultural Research Service (ARS), the Forest Service (FS), the National Institute of Food and Agriculture (NIFA), the Economic Research Service (ERS), the National Agricultural Statistics Service (NASS), and the Natural Resources Conservation Service (NRCS). The Department's scientific reach extends beyond the direct Federal investment to include its network of Land Grant and Minority Serving Colleges and Universities, Cooperative Extension, an active extramural research enterprise, and the USDA Climate Hubs.

The USDA Climate Hubs provide regionally relevant science-based tools and information for agricultural producers and natural resource managers to support adaptation and mitigation efforts and increase resilience in a changing climate. The Hubs' outreach, education, and extension activities provide a conduit for the latest USGCRP-supported research and facilitate the implementation of cutting-edge science for enhanced decision-making and risk management. The Hubs are an important example of USDA's cross-organizational regional collaborations, placing technical solutions in the hands of farmers, ranchers, forestland owners, and resource managers to achieve better management, climate, and socio-economic outcomes.

Selected areas of priority USDA research and development for climate-smart practices and technologies, nature-based climate solutions, and user-driven scientific research include

- The effects of climate change on crop and livestock production, and the adaptive management capacity to manage outcomes
- The potential within agriculture and forestry for greenhouse gas emissions mitigation
- Wildfire mitigation and response
- The implications of climate change on agricultural markets
- Drought resilience and risk management
- Maintaining and enhancing soil resources

- Developing new varieties of plants and animals that can adapt to changing climate conditions
- Observational monitoring networks, such as the Soil Climate Analysis Network (SCAN), the Snowpack Telemetry Network (SNOTEL), and the Forest Inventory and Analysis (FIA) Program
- Techniques and technologies to ensure efficient water delivery

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.

From daily weather forecasts, severe storm warnings, and climate monitoring to fisheries management, coastal restoration, and supporting marine commerce, NOAA's products and services support economic vitality and affect more than one-third of America's gross domestic product. NOAA's dedicated scientists use cutting-edge research and high-tech instrumentation to provide citizens, planners, emergency managers, and other decision-makers with reliable information they need, when they need it.

NOAA's mission to better understand our natural world and help protect its precious resources extends beyond national borders to monitor global weather and climate and work with partners around the world.

NOAA holds key leadership roles in shaping international ocean, fisheries, climate, space, and weather policies. NOAA's many assets—including research programs, vessels, satellites, science centers, laboratories, and a vast pool of distinguished scientists and experts—are essential, internationally recognized resources. NOAA works closely with other nations to advance our ability to predict and respond to changes in climate and other environmental challenges that imperil Earth's natural resources, human life, and economic vitality.

NIST's measurement science research supports enhanced, internationally accepted, and traceable measurement standards, methodologies, and technologies that provide accurate greenhouse gas emissions and uptake data and analyses to support mitigation management and the advancement of climate science research. NIST provides measurements and standards for consistent, 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) recognizes that global changes in the environment, such as climate change, impact DoD operations and installations. In alignment with the National Defense Strategy (NDS), the DoD Directive 4715.21 Climate Change Adaptation and Resilience, and the Department's 2019 Arctic Strategy, DoD seeks to understand, prepare, and respond to the impact of global environmental changes. DoD's research, development, test, and evaluation (RDT&E) activities as well as interagency and international collaboration through the USGCRP

play a critical role in DoD's efforts to address global environmental change. DoD manages and executes RDT&E activities across the Services that respond to specific national security requirements and may also be leveraged to address the strategic goals of the USGCRP. DoD's global change RDT&E efforts focus on building awareness of the changing operational physical environment through observations and predictive models and enhancing operations in those changing environments via mitigation, adaptation, and resilience.

The Navy is exploring new platforms for sustained observational capability in the Arctic as well as developing global weather, ocean, and sea ice prediction models at the seasonal (months) timescale. The Navy and the Air Force collaborate with U.S. interagency partners on the National Earth System Prediction Capability, the next generation of predictive models for the entire Earth system. The Air Force leverages National and allied partners' seasonal and climate model projections to provide value-added products for DoD and the Intelligence Community. DoD is expanding and modifying an Army tool for installations to assess exposure to climate and weather impacts. The Army continues to focus on addressing Arctic mobility and infrastructure challenges. The Strategic Environmental Research and Development Program (SERDP), the Department's joint environmental science and technology program, invests in research to enhance DoD's overall resilience to environmental threats and climate change impacts. Finally, the Department more broadly sponsors basic research in a number of potentially relevant areas such as marine meteorology, physical oceanography, polar science and engineering, biogeochemical sciences, and terrestrial science and phenomenology.

Department of Energy

The Department of Energy's (DOE) Office of Science supports fundamental research to address key uncertainties in regional to global-scale Earth system change arising from the interactions and interdependencies of the atmospheric, terrestrial, cryospheric, oceanic, and human-energy components of the Earth system. DOE's research strives to understand and anticipate how environmental and compounding stressors can influence the pattern and magnitude of weather and other extremes, and how these in turn influence the robustness and resilience of U.S. energy infrastructures. Supporting its major role in Earth system prediction, DOE supports long-term field experiments to advance process and systems level understanding; scale-aware parameterizations that can be incorporated into multi-scale models; and advanced software tailored to models that can be ported to DOE's fastest supercomputers. DOE also invests in novel machine learning and uncertainty quantification methodologies that allow model products to be more useful to DOE stakeholders. To assist the scientific community in carrying out research, DOE commits significant resources to archiving and management of extensive observed and model-generated datasets for easy retrieval and processing.

There are three areas of DOE research that contribute to the Department's efforts to advance the science of Earth system change: (a) Atmospheric System Research (science of aerosols, clouds, precipitation, and radiative transfer); (b) Terrestrial Ecosystem Science (role of terrestrial ecosystems and coupled biogeochemical cycles); and (c) advanced modeling that combines development, simulation and analysis. DOE maintains its own suite of advanced modeling platforms, including the Energy Exascale Earth System Model (E3SM), which currently uses DOE's advanced high performance pre-exascale computers; DOE also collaborates with NSF to support the widely used Community Earth System Model. Using the DOE-supported Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the DOE- and NASA-supported Earth System Grid Federation, DOE analyzes and distributes large Earth System Model output, with data analytics capabilities available to researchers. The Department also supports the Atmospheric Radiation Measurement (ARM) Research Facility, a

scientific user facility based on three permanent observatories and three mobile observatories that in turn provides the research community with unmatched measurements permitting the most detailed high-resolution, three-dimensional documentation of evolving cloud, aerosol, precipitation, and radiative transfer characteristics in climate-sensitive sites around the world.

DOE also conducts related applied research involving energy technologies, energy analysis, and prototype infrastructures. The research and analyses undertaken by these offices often requires the development and application of companion models to those used in the Office of Science, e.g., models of energy systems and infrastructures; economics; technology impact; and risk assessment. The applied offices also maintain and update datasets to explore such topics as electric grid stability, water availability for energy production, and siting of 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 (NIH) and the Centers for Disease Control and Prevention (CDC). 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 air contaminants affected by climate change, 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 variability and 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 an understanding of global change and its impacts with the ultimate goal of helping the Nation understand, adapt to, and mitigate global change.

Specifically, the USGS supports research to understand the physical, chemical, and biological components of the Earth system, the causes and consequences of climate and land use change, and the vulnerability and resilience of the Earth system to such changes. The USGS Land Change Science and National Land Imaging programs (such as the Landsat satellite mission and the National Land Cover Database) provide data that are used to assess changes in land use, land cover, ecosystems, and water resources resulting from the interactions between human activities and natural systems.

USGS also leads the regional DOI Climate Adaptation Science Centers, which deliver science to help fish, wildlife, water, land, and people adapt to a changing climate.

Department of State

The Department of State (DOS) contributes to the Intergovernmental Panel on Climate Change (IPCC), which assesses scientific, technical, and socioeconomic information relevant to the understanding of climate change, its potential impacts, and options for adaptation and mitigation. DOS, with the assistance of USGCRP, coordinates U.S. reviews of IPCC reports to ensure that the reports are a comprehensive, objective, and balanced assessment of the subject matter; nominates U.S. scientists to serve as authors; and represents the United States at IPCC meetings. DOS also works with other agencies in promoting international cooperation in a range of bilateral and multilateral science initiatives and partnerships.

Department of Transportation

The Department of Transportation (DOT) coordinates with USGCRP and its participating agencies to inform transportation system mitigation and resilience solutions. DOT initiatives to improve the resilience and sustainability of the U.S. transportation sector include the following:

- The Federal Aviation Administration (FAA) is working on many fronts to address concerns related to climate change. The FAA is working through their university partners to understand the impacts of aviation activity on climate change and are following a holistic plan to reduce those impacts with other federal agencies through new technologies, sustainable aviation fuels, and improved operational procedure concepts. The FAA is also working to evaluate and mitigate the risks of sea level rise and other impacts of climate change on FAA infrastructure and the ability to safely operate the National Airspace System. FAA is leading an effort to develop an implementation plan for a national airport strategy to provide a top-down framework for investments in airport infrastructure, including resilience.

- The Federal Highway Administration (FHWA) and the Federal Transit Administration (FTA) are working with States, public transportation agencies, and metropolitan areas to improve the condition and increase the resilience of the Nation's Highways and public transportation systems, respectively, and to reduce greenhouse gas emissions. FHWA and FTA are supporting transportation agencies through ongoing programs that include: assessing vulnerabilities; considering resilience in the transportation planning process; incorporating resilience in asset management plans; addressing resilience in project development and design; optimizing operations and maintenance practices; and deploying alternative fuel vehicle infrastructure. FTA and FHWA are also working to ensure that resilience is considered when rebuilding damaged transportation infrastructure after a natural disaster.

- The Maritime Administration (MARAD) Ports Team is developing a framework for an asset management tool called the "Waterfront Asset Management Tool" (WFAM) to inform port planning and decision making. This asset management tool can be used by public and privately owned ports to identify infrastructure vulnerabilities, establish risk-based asset management plans and prioritize infrastructure expenditures to improve resiliency and mitigate risks that threaten operational stability. The MARAD Ports Team

is also working with the University of Arkansas' Maritime Transportation Research and Education Center (MarTREC) to develop a geospatial "data hub" data repository that will provide a template for mechanisms and processes to compile, standardize, synchronize and integrate disparate data sources related to maritime transportation and demonstrate large-scale data storage and visualization tools that can be used to improve resiliency, planning, investment and operational decisions.

- The Pipeline and Hazardous Materials Safety Administration (PHMSA) Offices of Pipeline Safety (OPS) and Hazardous Materials (OHMS) are conducting research projects that address safety, environmental sustainability, and climate change. OPS is conducting research to promote safer systems for underground gas storage and liquefied natural gas facilities, as well as research related to the use and transport of hydrogen and hydrogen/natural gas blended fuels by pipeline. In addition, OPS is hoping to reduce methane emissions by sponsoring advanced research in methane detection and leak control. OHMS also focuses on hazardous materials packaging, particularly ways to reduce risks related to the transport of lithium batteries, and new packaging needed to address hazards associated with emerging energy technologies.

- The Office of International Transportation and Trade engages bilaterally and multilaterally to foster a zero-emission global transformation that addresses climate mitigation, adaptation, and resilience through standards, policies, strategies, research, trade promotion, and technical cooperation and assistance.

- The Office of the Assistant Secretary for Research and Technology is working in partnership with FHWA and DOT's Office of Intelligence, Security, and Emergency Response to ensure that the costs and benefits of resilience are incorporated into the transportation infrastructure planning process. The goal is to develop nationally replicable modelling tools capable of estimating the regional-scale impacts of natural and man-made disasters on the transportation system. These tools will enhance pre-event planning and disaster recovery capabilities.

- DOT is committed to meeting the Biden-Harris Administration's climate change goals, including the national target of net-zero greenhouse gas emissions by 2050. To that end, DOT has re-instituted and expanded the DOT Climate Change Center (CCC) to build on existing efforts to ensure intermodal coordination and collaboration on climate change activities across the Department. The CCC regularly convenes senior career staff and climate change experts from each of DOT's Operating Administrations, as well as external stakeholders including other federal agencies and the international community, to coordinate research, policies, and actions to reduce greenhouse gas emissions and make our transportation systems more resilient.

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 to protect human health and the environment 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 sustainable mitigation solutions. EPA Program Offices and Regions leverage this research to support mitigation and adaptation decisions, as well as 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. These connections 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, understand, and minimize the vulnerabilities to and 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 activities include applying long-term datasets, analytical tools, and models to examine and communicate observed climate change indicators and project impacts and economic damages associated with global mitigation scenarios. EPA's technical assistance and analytical expertise supports State and local decision-makers seeking to identify, prioritize, and implement adaptation work within their environmental programs.

National Aeronautics and Space Administration

NASA's global change activities span the entire Earth Science Division, from satellite observations and technology development to research and analysis, informing real-life applications of NASA science. These program elements advance our capacity to observe and explore the interactions among the major components of the Earth system—including the atmosphere, ocean, land, ice, and human communities.

As of June 2021, NASA's portfolio included 22 on-orbit missions, the combined measurements of which enhance our understanding of our changing planet. These included new satellite missions and recently launched or newly selected instruments aboard the International Space Station. Several of these came through NASA's Earth Venture portfolio, which consists of science-driven, competitively selected, cost-capped missions. In addition, NASA has made significant use of its airborne platforms and sensors together with surface-based measurements in targeted campaigns.

In tandem with these missions and measurements, NASA supports applications projects to extend the societal benefits of its research, technology, and spaceflight programs to the broader public. These include the development and transition of user-defined tools for decision support for water resources, health and air quality, ecological forecasting, disasters, food security, and more. Moreover, NASA's Earth Science Technology Office funds, develops, and demonstrates a broad range of cutting-edge technologies to enable new capabilities and reduce costs, risks, and development times for new Earth science instruments. NASA Earth science satellite data are made widely and freely available through the Earth Science Data System.

To help us understand rising sea levels, NASA recently launched Sentinel-6 Michael Freilich, a joint U.S.-European effort. Rising seas are one of the most distinctive and potentially devastating effects of Earth's warming climate. The Copernicus Sentinel-6/Jason-CS (Continuity of Service) mission consists of two identical satellites that will be launched five years apart. The first spacecraft is Sentinel-6 Michael Freilich, named for the former director of NASA's Earth Science Division, Michael Freilich. He was a pioneer in oceanography from space and dedicated his life to better understanding the Earth, with the goal of improving the lives of those who call it home. Sentinel-6 Michael Freilich launched from Vandenberg Air Force Base in California aboard a SpaceX Falcon 9 rocket on Nov. 21, 2020. Science data began being released to the research and applications communities on June 21, 2021.

In the past year, major mission-related milestones have included the following:

- In February 2020, NASA selected Libera as its first Earth Venture Continuity Mission and will maintain the decades-long climate data recorded from NASA's suite of Clouds and the Earth's Radiant Energy System (CERES) instruments. Libera will be integrated with the Joint Polar Satellite System (JPSS-3) spacecraft to meet three overarching goals: provide seamless continuity of the Earth Radiation Budget (ERB) Climate Data Records (CDRs); develop a self-contained, innovative and affordable observing system; and provide new and enhanced capabilities that support extending ERB science goals.

- In September 2020, NASA confirmed the Polar Radiant Energy in the Far InfraRed Experiment (PREFIRE) mission. PREFIRE will document, for the first time, variability in spectral fluxes from 5-45 μm on hourly to seasonal timescales.

- In February 2021, NASA also selected the cost-effective launch services for the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission, expected to launch in 2022 on three separate rockets to achieve high temporal resolution. TROPICS is designed to provide rapid-refresh microwave measurements over the tropics that can be used to observe the thermodynamics of the troposphere and precipitation structure for storm systems at the mesoscale and synoptic scale over the entire storm lifecycle. NASA launched a test satellite, or pathfinder, ahead of the TROPICS mission in June 2021.

- In June 2020 NASA confirmed the Earth Surface Mineral Dust Source Investigation (EMIT), which will map the surface mineralogy of arid dust source regions via imaging spectroscopy in the visible and short-wave infrared (VSWIR). The maps of the source regions will be used to improve forecasts of the role of mineral dust in the radiative forcing (warming or cooling) of the atmosphere. It is scheduled to launch to the International Space Station in 2022.

NASA's next major launch is the Landsat 9 mission, a joint activity with the U.S. Geological Survey. Scheduled to launch late in September 2021, Landsat 9 will help continue the multi-decadal record (since 1972) which has proven critical to studies of land cover/land use change and support research and applications in areas such as tropical deforestation and global forest dynamics, urban expansion, water use, coral reef degradation, glacier and ice-shelf retreat, natural and man-made disasters, and climate change.

In addition, NASA has announced the intention to move forward with the Earth System Observatory. This observatory is comprised of an integrated set of missions that includes the Designated Observables identified by the National Academies of Science, Engineering, and Medicine (NASEM) in their 2017 Decadal Survey for Earth Science, *Thriving on our Changing Planet: A Decadal Strategy for Earth Observation from Space*, as well as the NASA-Indian Space Research Organization Synthetic Aperture Radar (NISAR) mission. Individually, these missions

deliver important environmental measurements. Taken together, as a single Observatory, these missions will provide unprecedented ability to study Earth's interacting components and the relationship of human-induced and naturally occurring processes in shaping Earth's present and future. In addition, the NASA Earth System Observatory will include a new, competed Earth System Explorer line involving competitive opportunities for medium-sized instruments and missions.

This understanding of how our planet's complex systems work together will improve our capability to predict how the distributed variable effects of climate change may play out around the world. Critical to the Earth System Observatory is the work NASA continues through its Program of Record, as recommended by NASEM. These missions include

- The Surface Water and Ocean Topography (SWOT) mission set to launch in 2022, a partnership with France, Canada, and the United Kingdom to survey the world's oceans and terrestrial surface water;
- The Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) satellite scheduled for launch in 2023; and
- The Climate Absolute Radiance and Refractivity Observatory Pathfinder scheduled for launch to the International Space Station in late 2023, as well as others selected and/or agreed upon previously.

NASA continues to conduct numerous field campaigns using surface-based measurements, aircraft, and ships. While field-based activities were limited in much of 2020 and 2021 due to the COVID-19 pandemic, significant in-field presence included test and/or data acquisition deployments occurred. Several significant airborne campaigns selected as part of the Third Earth Venture Suborbital solicitation were able to obtain data during 2021, including Dynamics and Chemistry of the Summer Stratosphere (DCOTTS), Delta-X, Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE), the Delta-X campaign, and Sub-Mesoscale Ocean Dynamics Experiment (S-MODE). Another field campaign, the ship-based EXport Processes in the Ocean from Remote Sensing (EXPORTS) campaign, provided critical information for quantifying the export and fate of upper ocean net primary production using satellite observations and state-of-the-art ocean technologies. As part of an international and intergovernmental collaboration, NASA participated in the Michigan-Ontario Ozone Source Experiment (MOOSE) and plans to conduct the Convection Processes Experiment–Aerosols and Winds (CPEX-AW), coordinated with the European Space Agency (ESA) to study atmospheric dynamics while underflying ESA's Aeolus satellite in collaboration with ESA-supported investigators. Future campaigns also include the joint NASA-NSF Asian Summer Monsoon Chemical and CLimate Impact Project (ACCLIP) deploying from South Korea and NASA's contribution to the DOE-led Tracking Aerosol Convection interactions ExpeRiment–Air Quality (TRACER-AQ) campaign over Houston.

Federal partners for current and future campaigns include DOE, the National Park Service, the U.S. Geological Survey, the Bureau of Land Management, USDA Forest Service, U.S. Fish and Wildlife Service, NSF, EPA, National Center for Atmospheric Research, NOAA, Naval Research Lab, and the Office of Naval Research.

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 multi-disciplinary research projects and is actively engaged in a number of international partnerships.

Smithsonian Institution

Within the Smithsonian Institution (SI), 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, observing 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 also brings together researchers from around the Institution to focus on joint programs aimed at estimating volcanic emissions, understanding and sustaining biodiversity, monitoring animal migrations, characterizing working landscapes and seascapes, or studying emerging infectious diseases in wildlife and humans. 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, the Anacostia Community Museum, the National Museum of African American History and Culture, and the Cooper Hewitt Museum of Design to examine human responses to global change, within communities, reflected in art and culture, food, and music. Finally, Smithsonian outreach and education programs expand our scientific and social understanding of processes of change and represent 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, education, and outreach programs on these topics.

U.S. Agency for International Development

The U.S. Agency for International Development (USAID) carries out climate change and development work in four main areas: energy, sustainable landscapes, climate resilience, and climate risk management. USAID supports global research and analysis and partners bilaterally with dozens of countries to build capacity, address governance, and create the legal and regulatory environment needed to address climate change and development. This work is integral to helping countries pursue economic growth, stability, and self-reliance.

Energy: USAID helps partner countries build strong energy sectors that can attract private investment and power global economic and social development. USAID's efforts support least-cost modern energy solutions. In many countries, renewable energy is now the least-cost solution that maximizes development impact.

Sustainable landscapes: USAID supports research on estimating and accounting for land-based carbon stocks and greenhouse gas fluxes, and on governance and finance in the land sector, all with a focus on developing countries. USAID also supports partner countries in meeting their commitments to reduce land-based greenhouse gas emissions, often through activities that promote conservation, restoration, and sustainable use of forests, agriculture, and other lands. By improving landscape management, USAID helps to curb destruction and degradation, improve livelihoods, and increase resilience.

Climate resilience: USAID works with partner countries to build climate resilience and disaster preparedness to weather and climate-related shocks and stresses such as droughts, floods, and shifting rainfall patterns. Improved weather and climate information, informed land use planning, and smart infrastructure design are some ways communities can prepare for these risks and avoid setbacks. Thinking ahead and proactively managing risks help sustain livelihoods and maintain critical services, reducing the need for costly disaster response.

Climate risk management (CRM): CRM is an internal USAID practice to assess, address and manage climate risk in new strategies, projects, and activities across USAID's development portfolio, safeguarding U.S. investments through informed decision-making.

With over seventy overseas missions, USAID enables decision-makers to apply high-quality climate information to their decision-making and enables countries to accelerate their transition to climate resilient, sustainable economic development. USAID achieves these objectives through direct programming and integration of climate change adaptation and mitigation activities into the broader development portfolio.

USAID leverages scientific and technical resources from across the U.S. Government, private sector partners, and nongovernmental organizations and science institutes to develop and implement low-emissions development strategies, creating policy frameworks for market-based approaches to emission reduction and energy sector reform, promoting sustainable management of agricultural lands and forests, protecting biodiversity, and mainstreaming adaptation into development activities in countries most at risk to advance resilient and sustainable development.

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