6

Vulnerability Assessment, Climate Change Impacts, and Adaptation Measures

Recent U.S. government-led scientific assessments of climate change impacts on the United States indicate that the nation is increasingly vulnerable to current and projected changes. It is also clear that there is more emphasis than ever on adaptation measures to increase the nation's resilience and take advantage of opportunities in the face of significant change.

During the past year, the U.S. government completed a major new climate change assessment, the U.S. Global Change Research Program's (USGCRP's) *Global Climate Change Impacts in the United States* (Karl et al. 2009). This assessment received a great deal of attention from large segments of the public and is now providing the basis for significant effort to incorporate climate change into decisions made by U.S. businesses, resource managers, and policymakers. This report is especially helpful because it assesses impacts on a regional and socioeconomic basis. Across nine regions and seven sectors it explains the current and potential U.S. impacts of climate change and illustrates adaptation measures already being adopted. As this chapter demonstrates, the motivation for adaptation is clear, and the movement to initiate and coordinate action is underway.

There has been early and significant investment by the Obama administration in developing the first overarching U.S. adaptation strategy. The Director of the Office of Science and Technology Policy highlighted the need for adaptation in recent testimony to the U.S. Senate:

[The reality of climate change] underlines the need to invest, in parallel with efforts to reduce emissions and increase the uptake of the main heat-trapping gases, in adaptation to the changes in climate that can no longer be avoided—e.g., breeding heat- and drought-resistant crop strains, bolstering defenses against tropical diseases, improving the efficiency of water use, managing ecosystems to improve their resilience, and management of coastal zones with sea-level rise in mind.[1]

Building on community, business, and resource management efforts to examine adaptation options, the President issued Executive Order 13514 on October 5, 2009.[2] In addition to reducing greenhouse gas (GHG) emissions, this order will seek to organize the national effort on climate change adaptation and ensure widespread and complementary programs across the U.S. government. The executive order states that federal agencies will participate actively in a new U.S. Interagency Climate Change Adaptation Task Force that is "developing the domestic and international dimensions of a U.S. strategy for adaptation to climate change." This strategy will contribute to the knowledge, capability, and resources to effectively respond to climate change.

Increasingly, activities to assess and address vulnerabilities are focusing on the specific information needed to make better decisions in the face of climate variability and change, and in particular to facilitate effective and appropriate adaptation initiatives. Recent scientific assessments have been more focused on defining the most relevant and useful information for decision makers and providing it in a way that is accessible for all. In other words, the process is changing to be more demand-driven, and not only identifies the expected climate impacts, but also looks at some key risks and opportunities. Some of the recent key findings follow.

GLOBAL CLIMATE CHANGE IMPACTS IN THE UNITED STATES

During the last three years (2006–2009), the U.S. government has completed a suite of focused assessments addressing high-priority climate research questions. In an open and transparent manner, this approach communicates scientific analyses to the public via a set of 21 Synthesis and Assessment Products (SAPs) developed by USGCRP (U.S. CCSP/GCRP 2006–2009). These SAPs were synthesized in a single national-scale assessment, *Global Climate Change Impacts in the United States* (GCCI), released in June 2009 (Karl et al. 2009). The report analyzed climate impacts and response options across nine U.S. regions and seven sectors, and identified the following 10 key findings:

1. Global warming is unequivocal and primarily human-induced. Global temperature has increased over the past 50 years. This observed increase is due primarily to human-induced emissions of heat-trapping gases.

2. Climate changes are underway in the United States and are projected to grow. Climate-related changes are already observed in the United States and its coastal waters. These include increases in heavy downpours, rising temperature and sea level, rapidly retreating glaciers, thawing permafrost, lengthening growing seasons, lengthening ice-free seasons in the ocean and on lakes and rivers, earlier snowmelt, and alterations in river flows. These changes are projected to grow.

3. Widespread climate-related impacts are occurring now and are expected to increase. Climate changes are already affecting water, energy, transportation, agriculture, ecosystems, and health. These impacts are different from region to region and will grow under projected climate change.

4. Climate change will stress water resources. Water is an issue in every region, but the nature of the potential impacts varies. Drought, related to reduced precipitation, increased evaporation, and increased water loss from plants, is an important issue in many U.S. regions, especially in the West. Floods, water quality problems, and impacts on aquatic ecosystems and species are likely to be amplified by climate change in most regions. Declines in mountain snowpack are important in the West and Alaska, where snowpack provides vital natural water storage.

5. Crop and livestock production will be increasingly challenged. Agriculture is considered one of the sectors most adaptable to changes in climate. However, increased heat, pests, water stress, diseases, and weather extremes will pose adaptation challenges for crop and livestock production.

6. Coastal areas are at increasing risk from sea level rise and storm surge. Sea level rise and storm surge place many U.S. coastal areas at increasing risk of erosion and flooding, especially along the Atlantic and Gulf Coasts, Pacific Islands, and parts of Alaska. Energy and transportation infrastructure and other property in coastal areas are very likely to be adversely affected.

7. Threats to human health will increase. Health impacts of climate change include heat stress, waterborne and foodborne diseases, poor air quality, extreme weather events, and diseases transmitted by insects and rodents. Robust public health infrastructure could reduce the potential for negative impacts from climate change.

8. Climate change will interact with many social and environmental stresses. Climate change will combine with air and water pollution, population growth, overuse of resources, urbanization, and other social, economic, and environmental stresses to create larger impacts than from any of these factors alone.

[1] John P. Holdren, *Climate Services: Solutions from Commerce to Communities: Hearing before the United States Senate Committee on Science, Transportation, and Commerce*, 111th Cong., 1st Sess. (2009).

[2] "Federal Leadership in Environmental, Energy, and Economic Performance." *Federal Register*, Vol. 74, No. 194. See http://www.archives.gov/federal-register/executive-orders/2009-obama.html.

9. Thresholds will be crossed, leading to large changes in climate and ecosystems. There are a variety of thresholds in the climate system and ecosystems. These thresholds determine, for example, the presence of sea ice and permafrost, and the survival of species, from fish to insect pests, with implications for society. With further climate change, the crossing of additional thresholds is expected.

10. Future climate change and its impacts depend on choices made today. The amount and rate of future climate change depend largely on current and future human-caused emissions of heat-trapping gases and airborne particles. Responses involve reducing emissions to limit future warming, and adapting to the changes that are unavoidable.

The information in all of the SAPs as well as the GCCI is intended for use by a diverse group of decision makers, stakeholders, communicators (e.g., the media), and scientists. The material addresses the nation's needs for sound scientific information that decision makers can use to develop a better understanding of climate change impacts and vulnerabilities, as well as to develop and improve the design and implementation of adaptation measures. All of the SAPs and the GCCI were extensively reviewed by scientists, federal agency officials, stakeholders, and the general public. The SAPs build on and integrate cutting-edge research and application activities, advanced over the years by the interagency research efforts in climate and global change. More information about the SAPs and GCCI may be found in Chapter 8 of this report and at www.globalchange.gov.

The information highlighted in this chapter is taken principally from the GCCI report, which synthesizes much of the analysis in the SAPs and incorporates several other assessments. It provides analyses of ongoing and potential impacts of climate variability and change, adaptability of key systems, and measures that might be taken to reduce vulnerability, including examples of adaptation measures already in evidence. This chapter highlights ongoing U.S. efforts that are generating new insights into the potential impacts of climate change on key physical and biological processes (e.g., snowpack changes, streamflow, drought, extreme events) and changing resilience and vulnerability in a range of socioeconomic sectors (e.g., energy, agriculture, water resources, coastal systems, human health, and transportation).

SOME KEY U.S. VULNERABILITIES

Water and Energy

Climate change has clearly already altered, and will continue to alter, many aspects of the water cycle in the United States, affecting where, when, and how much water is available for all uses. Changes include widespread melting of snow and ice, increasing atmospheric water vapor, increasing evaporation, changing precipitation patterns and intensity, changing incidence of drought, rising water temperatures, reductions in river and lake ice, and changes in soil moisture and runoff. These changes have impacts across a vast range of socioeconomic activities, such as transportation, agriculture, energy production, industrial uses, and other needs, including human consumption (Karl et al. 2009).

Some examples of regional changes already observed include drying in the Southwest, a reduction of snowpack/snow-water equivalent in the West, an increase in the incidence of heavy precipitation events across most of the United States, increasing streamflow in the eastern United States, and reduced ice cover on the Great Lakes. All of these examples are projected to continue, along with additional emerging disruptions to the current state of the water cycle (Karl et al. 2009).

An illustration of impacts from one of these regional changes is the potential consequences of drying in the Southwest. Parts of the Southwest could see more than a 40 percent decrease in surface runoff by mid-century (even under a moderate future emissions scenario). This is occurring against a backdrop of rapid population growth in the region and in a climate that is already semi-arid. In this region (and in others), climate change places an additional stress on already overburdened water systems (Karl et al. 2009).

Many locations in the Southwest are likely to suffer from conflict over water resources by 2025, even in the absence of climate change (U.S. DOI/BOR 2005). Under drier conditions, these conflicts are likely to be more widespread or to occur sooner and with greater intensity. Water disputes already exist in several areas across the United States, including the Sacramento Bay Delta, the Rio Grande, the Klamath River in Oregon and California, the Colorado River, and the Apalachicola-Chattahoochee-Flint River system in the Southeast (Karl et al. 2009).

In addition to vulnerabilities in water supply for human consumption, water is used in the process of power production—for cooling thermal power plants, and for generating power in hydroelectric facilities. In addition, delivering and treating water require large amounts of energy; thus, the vulnerabilities of water and energy systems are tightly interconnected.

Many of the effects of climate change have clear implications for the reliable production, transmission, and use of energy itself. For example, rising temperatures are likely to increase cooling needs and reduce heating needs in different parts of the country; changing precipitation patterns may positively or negatively affect the ability to produce hydropower; and increases in hurricane intensity could impact Gulf of Mexico energy production, refining, and transportation (Karl

et al. 2009). There may be changes in energy consumed for other climate-sensitive processes, such as pumping water for irrigation in agriculture (Peart et al. 1995; McCarthy et al. 2001). Depending on the magnitude of these possible energy consumption changes, it may be necessary to consider changes in energy supply or conservation practices to balance demand (Franco and Sanstad 2006; CEPA 2006).

Impacts due to climate change are more likely to be most apparent at the sub-national scale, such as the regional effects of extreme weather and reduced water availability, and increased cooling demands in areas where temperature and vulnerable populations are increasing. Overall, the national energy economy is large, and the energy industry has both the financial and the managerial resources to be adaptive (Karl et al. 2009). Of course, climate change effects on energy supply and demand will depend not only on climatic factors, but also on patterns of economic growth, land use, population growth and distribution, technological change, and social and cultural trends that shape individual and institutional actions (McCarthy et al. 2001).

Transportation

The U.S. transportation network is vital to the nation's economy, safety, and quality of life. Transportation accounts for approximately one-third of total U.S. GHG emissions. While it is widely recognized that emissions from transportation have impacts on climate change, climate will also likely have significant impacts on transportation infrastructure and operations (Karl et al. 2009; U.S. DOT 2006).

Examples of specific types of impacts include softening of asphalt roads and warping of railroad rails; damage to roads and opening of shipping routes in polar regions (McCarthy et al. 2001); flooding of roadways, rail routes, and airports from extreme events and sea level rise; and interruptions to flight plans due to severe weather (Karl et al. 2009).

Along the Gulf Coast alone, it is estimated that 3,864 kilometers (2,400 miles) of major roadways and 396 kilometers (246 miles) of freight rail lines are at risk of permanent flooding within 50–100 years as climate change and land subsidence combine to produce an anticipated relative sea level rise in the range of 1.2 meters (4 feet). In Alaska, the cost of maintaining the state's public infrastructure is projected to rise 10–20 percent by 2030 due to warming, costing the state an additional $4–$6 billion, with roads and airports accounting for about half this cost (Karl et al. 2009). In New York City, what is now a 100-year storm is projected to occur as often as every 10 years by late this century. Portions of lower Manhattan and coastal areas of Brooklyn, Queens, Staten Island, and Long Island's Nassau County would experience a marked increase in flooding frequency. Much of the critical transportation infrastructure, including tunnels, subways, and airports, lies well within the range of projected storm surge and would be flooded during such events (Karl et al. 2009).

Public Health

Climate change poses unique threats to human health, including direct threats from heat waves or storms, and indirect effects, such as heat-exacerbated air quality impacts on health, or climate-sensitive infectious diseases (Box 6-1; Karl et al. 2009). Given the complexity of the factors that influence human health, assessing health impacts related to climate change poses a significant challenge (NAS/NRC 2001). The extent and nature of climate change impacts on human health vary by region, by relative sensitivity of population groups, by the extent and duration of exposure to climate change itself, and by society's ability to adapt to or cope with the change (Rose et al. 2001).

The probability of exacerbated health risks due to climate change points to a need to maintain a strong public health infrastructure to help limit future impacts (Ebi et al. 2008). Several initiatives, especially in cities, have been implemented for reducing risk. Appropriate and focused weather and climate information from the U.S. government has been essential in these initiatives. For example, heat is already the leading cause of U.S. weather-related deaths, with more than 3,400 deaths reported between 1999 and 2003 from excessive heat. Projections for several cities indicate increasing risk of heat-related deaths with increasing temperatures, even when including the likelihood of some adaptation measures (Karl et al. 2009).

Warming will also make it more challenging to meet air quality standards that affect certain segments of the population, particularly those with existing lung conditions or those who spend more time outdoors. Under constant pollution emissions, by the middle of this century, Red Ozone Alert days (when the air is unhealthful for everyone) in the 50 largest cities in the eastern United States, are projected to increase by 68 percent due to warming alone (Karl et al. 2009).

Box 6-1 Endangerment and Cause or Contribute Findings for Greenhouse Gases[1]

In response to a U.S. Supreme Court decision requiring the U.S. Environmental Protection Agency (EPA) to determine whether greenhouse gases (GHGs) endanger human health or welfare, or whether the science is too uncertain to make a determination, the EPA Administrator proposed endangerment and cause or contribute findings under Section 202 (a) of the Clean Air Act in April 2009. The proposed findings then underwent a public comment period. The proposed findings stated that the total body of scientific evidence compellingly supports that GHGs threaten both public health and welfare and that emissions from U.S. vehicles cause or contribute to the problem. On December 7, 2009, EPA finalized the endangerment and the cause or contribute findings. The Administrator reached this conclusion after considering both current and projected future effects of climate change and the full range of risks and impacts to public health and welfare in the United States, as well as extensive public comments.

[1]Further information can be found at http://www.epa.gov/climatechange/endangerment.html.

Studies analyzed by the U.S. Environmental Protection Agency (EPA) show that climate change causes increases in summertime ozone concentrations over substantial regions of the country (U.S. EPA/ORD 2009). For those regions that showed climate-induced increases, the increase in the maximum daily 8-hour average ozone concentration—a key metric for regulating U.S. air quality—was in the range of 2–8 parts per billion, averaged over the summer season. The increases were substantially greater than this during the peak pollution episodes that tend to occur over a number of days each summer. Several studies suggest that climate change may increase the frequency of high-ozone events (Bell et al. 2007; Leibensperger et al. 2008). Even when considering future scenarios with large decreases in air pollution emissions, climate change partly offsets the benefit of the emission reductions (Jacob and Winner 2009). Accordingly, climate change represents a significant penalty for air quality managers working to achieve ozone air quality goals and raises concerns about adverse health outcomes.

Ecosystems

Climate is an important factor influencing the distribution, structure, function, and services of ecosystems. Ongoing climate changes are interacting with other environmental changes to affect biodiversity and the future condition of ecosystems (e.g., McCarthy et al. 2001; Parmesan and Yohe 2003; Karl et al. 2009). Many factors affect biodiversity, including climatic conditions; the influence of competitors, predators, parasites, and diseases; disturbances, such as fire; and other physical factors. Human-induced climate change, in conjunction with other stresses, is exerting major influences on natural environments and biodiversity, and these influences are generally expected to grow with increased warming (Karl et al. 2009).

Climate change is already affecting many U.S. ecosystems, including wetlands, forests, grasslands, rivers and lakes, and coastal and nearshore environments, and has led to large-scale changes in the range of species and timing of seasons and migration. Invasive weed species have also increased, as have some insect pests and pathogens. Nearshore ecosystems are under stress not only from increasing temperatures, but also from the increased acidity in the ocean. U.S. desert and dry lands are likely to become hotter and drier, feeding a self-reinforcing cycle of invasive plants, fire, and erosion. In the future, these effects are likely to increase (Karl et al. 2009).

Coasts

Approximately one-third of the U.S. population lives in counties immediately bordering the nation's ocean coasts. In addition to accommodating major cities, the coastal zone supports recreation, fishing, energy, industry, and critical transportation infrastructure. Coastal and ocean activities contribute more than one trillion dollars to the national gross domestic product (Karl et al. 2009).

Increasing vulnerability at the coast will result from extreme events and sea level rise, and also from population changes, building practices, beach management, increasing nitrogen runoff, and many other socioeconomic factors. Sea levels have been rising by 2–3 millimeters (0.078–0.117 inches) per year along most of the U.S. coast (Zervas 2001). However, due to the feedback loops of climate change, that rise is projected to accelerate in the coming decades. Accounting for local subsidence, coastal scientists are considering the possible impacts of a 0.9-meter (3-foot) rise in sea level (or more in some locations) over the next century (Titus et al. 2009; Karl et al. 2009).

Key concerns associated with these changes include land loss, increased flooding of low-lying coastal communities, coastal erosion, barrier island migration, wetland loss, and increased salinity of aquifers and estuaries, especially during droughts. Various health impacts, including those associated with population displacement, are among the secondary effects of these changes. This increasing societal vulnerability is leading some insurance companies to raise rates or deny property coverage to communities along the Gulf and Atlantic coasts (Mills 2005).

SAMPLE U.S. RESEARCH, ASSESSMENTS, AND ACTIVITIES PERTAINING TO VULNERABILITY, IMPACTS, AND ADAPTATION

Many of the key U.S. vulnerabilities discussed above are being addressed across the government and within communities through specific programs at a variety of different geographic scales. Following is a sample cross-section of the programs being carried out by the United States at the international, federal, state, regional, and local levels to assess the impacts of and reduce vulnerability to climate change. A goal of the new U.S. Interagency Climate Change Adaptation Task Force is to create a coherent, comprehensive program of activities that allows synergies among these many and varied programs.

International Activities

NASA, USAID, and NOAA Hubs

The National Aeronautics and Space Administration (NASA), the U.S. Agency for International Development (USAID), and the National Oceanic and Atmospheric Administration (NOAA) are working to develop regional hubs around the world to apply remotely sensed information to development assistance. Based on the successful SERVIR (Regional Visualization and Monitoring System) hub in Central America, this activity will link available data streams to new applications, develop tools, and build local human and institutional capacity to use this information. These systems will sup-

port decision making in a number of areas, including climate change, land management, urban planning, food security, agriculture, and disaster mitigation.

USAID Climate Change Program[3]

USAID, often in partnership with other agencies, leads a number of activities to help build developing country capacity to understand climate change and adapt to its impacts. This includes supporting innovative applications and tools for climate and weather observation, and developing guidance on how to build the resilience of projects designed to promote economic development. USAID works to make data and guidance readily accessible and useful for development decisions at the community, national, and regional levels. USAID also provides support for cutting-edge research to develop more climate change-resilient agricultural inputs, and provides capacity building in disaster preparedness and risk reduction. USAID's approach places particular emphasis on partnerships with the private sector and on working with local and national authorities, communities, and nongovernmental organizations.

Recent climate change adaptation projects supported by USAID include:

- Community-based drought preparedness planning in Cambodia, East Timor, and Vietnam.
- An early-warning system to ensure that drought and other threats to the well-being of East African pastoralists' free-ranging livestock can be detected and addressed in a timely manner.
- A three-year initiative to help vulnerable communities in the seven Zambezi river basin countries use conservation-based farming techniques, soil conservation, water-harvesting techniques, and reforestation to adapt to climate-related threats.
- Research into the development of heat-tolerant wheat and flood-tolerant rice varieties in South Asia, where farmers are already seeing the impacts of higher temperatures and more severe flooding on crop yields.
- Community training to help farmers in Malawi diversify their livelihoods and adopt new agriculture conservation practices that reduce soil erosion, improve water quality, and sequester carbon in the soil.
- A Collaborative Research Support Program that is identifying ways to build the resilience of Andean small-holder production systems and their capacity to adapt to climate change.
- Dissemination of micro-irrigation technologies, such as foot pumps, in Mali, to address rainfall variability and increase water use efficiency.

USAID recognizes that adapting to climate change requires a hierarchy of linked efforts. USAID is working to make Earth observation information readily accessible and applicable to development decisions, including developing innovative applications and appropriate tools, and communicating that information to stakeholders and decision makers. Through interaction with local partners and with new tools, USAID can better understand how environmental changes may affect sectors critical for development. Once those impacts are understood, stakeholders need to assess and agree on preferred adaptation options. Then, on-the-ground actions can be implemented to build the resilience of projects designed to promote economic development.

USAID is also supporting a three-year initiative implemented by the International Federation of Red Cross and Red Crescent Societies and the United Nations World Meteorological Organization, to help vulnerable communities in the seven Zambezi river basin countries use conservation-based farming techniques, soil conservation, water-harvesting techniques, and reforestation to adapt to climate-related threats.

Activities at Local to National Scales

USGCRP Assessments[4]

USGCRP, an interagency body of 13 agencies, has published a suite of 21 SAPs over the past three years (U.S. CCSP/GCRP 2006–2009). USGCRP is the focal point for the development of the detailed assessments referred to in this chapter. Each of the 21 reports focused on particular elements of climate change and U.S. vulnerabilities, and many assessment efforts of individual agencies are incorporated into these USGCRP assessments. In the spring of 2008, a technical scientific assessment was produced to provide an ongoing summary of the work (CENR 2008). In June 2009, the comprehensive national-scale GCCI assessment was released, which incorporated the results of all 21 SAPs and included a specific focus on adaptation information (Karl et al. 2009). The assessment is being discussed at dozens of local, regional, and national meetings and stakeholder forums, and is being built on to provide a foundation for more focused scientific information to support adaptation and decision making.

NASA Applied Sciences Program

This program benchmarks practical uses of NASA-sponsored observations from Earth observation systems and predictions from Earth science models. NASA implements projects that carry forth this mission through partnerships with public, private, and academic organizations working toward developing innovative approaches for using Earth system science information to provide decision support that can be adapted in applications worldwide. This program focuses on applications of national priority, such as agriculture, water resources, and air quality, and expands and accelerates the use of knowledge, science, and technologies resulting from the NASA goal of improving predictions in the areas of weather, climate, and natural hazards.[5]

[3] See http://www.usaid.gov/our_work/environment/climate/.

[4] See http://www.globalchange.gov/publications/reports.

[5] See http://science.hq.nasa.gov/earth-sun/applications/index.html.

EPA Global Change Research Program

EPA's Global Change Research Program (GCRP) is an assessment-oriented program that emphasizes understanding the potential consequences of climate variability and change on U.S. human health, ecosystems, and socioeconomic systems. This program has four areas of emphasis: human health, air quality, water quality, and ecosystem health. In an attempt to capitalize on expertise in the academic community, a significant portion of EPA's GCRP resources is dedicated to extramural research grants administered through the STAR (Science To Achieve Results) grants program, which supports science related to assessments of the consequences of global change and human dimensions research.[6] Another sample of research and assessment is available in the form of the Sanctuaries Condition Reports published by NOAA's Office of National Marine Sanctuaries.

NOAA Office of National Marine Sanctuaries

The Office of National Marine Sanctuaries (ONMS) manages marine areas in both nearshore and open ocean waters that range in size from less than 2.59 square kilometers (1 square mile) to almost 362,600 square kilometers (140,000 square miles). To study marine ecosystems and the human influences that affect them, in 2001 ONMS began to implement System-Wide Monitoring (SWiM). Part of SWiM includes the preparation of Condition Reports that summarize the resources in each sanctuary, pressures on those resources, the current condition and trends, and management responses to the pressures that threaten the integrity of the marine environment. Specifically, the reports include information on the status and trends of water quality, habitat, living resources, and maritime archaeological resources and the human activities that affect them. They also consider ways to observe and respond to climate-related changes in sea level, water temperature, ocean acidity, coral bleaching, invasive species, and diseases.[7]

USGS Climate Effects Science Network[8]

The U.S. Geological Survey (USGS) Climate Effects Science Network (CESN) is coordinated through all U.S. Department of the Interior (DOI) resource management bureaus. CESN integrates climate and environmental change data sets with conceptual and digital models across disciplines, including remote sensing, geography, geology, biology, and hydrology, to better understand the impacts of climate on natural resources, agriculture, and human populations on episodic to decadal and millennial time scales, local to global spatial scales, and weather to climate process scales. The goal of CESN is to develop a systems-level understanding of biogeochemical processes resulting from changes in climate, to link these changes to the sustainability of ecosystems, wildlife, subsistence cultures, and societal infrastructure, and to apply the knowledge gained for decision support. In 2008, USGS initiated pilot-integrated research in northern Alaska, where permafrost thaw and sea-ice melting are resulting in rapid and poorly understood changes to regional ecosystems.

U.S. National Integrated Drought Information System

More than a dozen U.S. federal agencies or offices collaborate in the U.S. National Integrated Drought Information System (NIDIS) effort to provide risk and drought management information.[6] Some of the agencies include NOAA, the U.S. Department of Agriculture (USDA), DOI, the U.S. Department of Transportation (DOT), and the U.S. Department of Energy. NIDIS was formally launched in 2006 and has significant milestones to increase capabilities in every year. It is designed to develop the leadership and networks to implement an integrated drought monitoring and forecasting system at federal, state, and local levels and to foster and support a research environment focusing on risk assessment, forecasting, and management. A key piece of the NIDIS activity will be an early-warning system for drought to provide accurate, timely, and integrated information. All of this information is incorporated into interactive systems, such as the Web portal, which provides not only timely access to the early-warning capabilities, but also a framework for public awareness and education about droughts.[9]

NSF Decision Making Under Uncertainty Centers[10]

Under the leadership of the U.S. National Science Foundation (NSF) five interdisciplinary research teams are studying important aspects of problems associated with understanding climate-related decisions under uncertainty. The increased knowledge generated by recent scientific research on the causes and consequences of climate change and variability has led to a growing need to better understand how decision makers choose among alternative courses of action. These teams are expected to produce new insights of interest to the academic community, generate significant educational benefits, and develop new tools that will benefit decision makers and a range of stakeholders. Research centers are located at Arizona State, Carnegie-Mellon, and Columbia universities. Other interdisciplinary teams are conducting research at the University of Colorado at Boulder, and Rand Corporation in Santa Monica, California.

USDA/NRCS National Water and Climate Center

The National Water and Climate Center (NWCC) leads the development and transfer of water and climate information and technology through natural resource planning support, data acquisition and management, technology innovation and transfer, partnerships, and joint ventures.[11] The NWCC develops and manages key observation and monitoring networks called SNOTEL (SNOpack TELemetry) and SCAN

[6] See http://cfpub.epa.gov/gcrp/about_ov.cfm.

[7] See http://sanctuaries.noaa.gov/science/condition/welcome.html.

[8] See http://www.usgcrp.gov/usgcrp/agencies/interior.htm.

[9] See http://www.drought.gov.

[10] See http://www.nsf.gov/news/news_summ.jsp?cntn_id=100447.

[11] See http://www.wcc.nrcs.usda.gov/.

(Soil Climate Analysis Network). These networks provide automated comprehensive snowpack, soil moisture, and related climate information designed to support natural resource assessments. They collect and disseminate continuous, standardized soil moisture and other climate data in publicly available databases and climate reports. Uses for these data include inputs to global circulation models, verifying and ground truthing satellite data, monitoring drought development, forecasting water supply, and predicting sustainability for cropping systems.

Regional Activities

NOAA Regional Integrated Sciences and Assessments Program

One of the key questions NOAA faces is how to improve the link between climate sciences and society. The Regional Integrated Sciences and Assessments (RISA) program is helping to realign the nation's climate research to better serve society. NOAA's RISA program supports research that addresses complex climate-sensitive issues of concern to decision makers and policy planners at a regional level. RISA research team members are primarily based at universities, though some are based at government research facilities, nonprofit organizations, or private-sector entities. Research areas include the fisheries, water, wildfire, and agriculture sectors, coastal restoration, and climate-sensitive public health issues.[12] The program currently supports eight regional centers. A new RISA initiative, the Southern Climate Impacts Planning Program, was initiated in 2009 in the Gulf Coast region.[13]

NOAA Regional Climate Centers

NOAA's six Regional Climate Centers (RCCs) are a federal-state cooperative effort designed to provide regional and local expertise and assistance to a wide range of customers.[14] The RCCs are engaged in the timely production and delivery of useful climate data, information, and knowledge for decision makers and other users at local, state, regional, and national levels. The RCCs support NOAA's efforts to provide operational climate services, while leveraging improvements in technology and collaborations with partners to expand quality data dissemination capabilities.

DOI Practitioner Development Program

In partnership with many stakeholders and several federal agencies (including NOAA, EPA, the Department of Defense [DOD], and USDA), the DOI Bureau of Reclamation (BOR) has implemented the Basin Study Program, which will incorporate the latest science, engineering technology, climate models, and innovative approaches to water management in the western United States.[15] The program will serve as a part of BOR's Water Conservation Initiative and as a key element in implementing the Secure Water Act. To integrate climate change into water management activities and to help improve methods of water resources planning, these partners are working together to develop and provide a Climate Change Integration Technical Training Program for western water practitioners, planners, technical specialists, and decision makers. This effort also exposes practitioners to emerging methods as they become available.

DOI Climate Change Response Centers

Under a new secretarial order, DOI has launched a coordinated strategy to address the current and future impacts of climate change on land, water, and other natural and cultural U.S. resources. A cornerstone of this strategy is the implementation of eight Climate Change Response Centers located across the country. A network of Landscape Conservation Cooperatives will also work at landscape scales to foster partnerships and assess climate impacts on such issues as wildlife migration, invasive species, and wildfire risk. This 2009 initiative will support and promote adaptation responses.

State Activities

California Climate Change Center[16]

The California Climate Change Center is investigating the range of possible changes to the state's climate and the likelihood and rate of progression of such changes.[17] Using the results of this work, the Center is assessing the potential future economic and ecological consequences of climate change for California, and examining a range of impacts and adaptation options (e.g., agriculture and water resources), as well as mitigation strategies. The center manages a robust research program with a dynamic community of California researchers from various scientific disciplines and a worldwide network of peers collaborating on climate change issues of interest to California.

SAMPLE U.S. ASSESSMENT AND ADAPTATION ACTIVITIES IN SPECIFIC SECTORS

The sample sector- and region-specific impact summaries and adaptation projects included in this section demonstrate the variety and scale of information and methods utilized within the United States. The examples are illustrative of key areas of investigation, and are not intended to be a comprehensive listing of all efforts across the nation.

Water Resources

Working Toward a Drought-Resilient U.S. Southwest

A NOAA RISA program based at the University of Arizona, titled the Climate Assessment for the Southwest (CLIMAS),[18] is developing and utilizing new information on drought to increase societal resilience to this recurrent phenomenon. The impacts of U.S. drought during the last five to seven years have included

[12] See http://www.climate.noaa.gov/cpo_pa/risa/.

[13] See http://www.southernclimate.org.

[14] See http://www.ncdc.noaa.gov/oa/climate/regionalclimatecenters.html.

[15] See http://www.usbr.gov/WaterSMART/docs/Basin%20Study%20Program.pdf.

[16] See http://www.doi.gov/archive/climatechange/SecOrder3289.pdf.

[17] See http://www.climatechange.ca.gov/research/index.html.

[18] See http://www.ispe.arizona.edu/climas/.

sustained and significant economic losses, significantly reduced reservoir levels, water emergencies, and widespread and severe wildfires. Creating a more drought-resilient society requires a fundamental shift from crisis management to risk management. Investigators studying the impacts of drought are studying the historical record, evolving demographics and population growth, water law, and ecosystem management. For example, investigators are working to develop methods to utilize seasonal climate and streamflow forecasts more effectively to mitigate the impact of drought on water supplies. It is expected that knowledge of this type will become even more valuable in the coming decades, if climate model projections of increasing aridity in continental interiors prove accurate.

Developing Strategies for Improving Water Management

If the allocation of water is already a concern in many locations around the country, the added challenges of climate change pose increased risk and vulnerability for some of these locations. An interagency report, released in 2009 by DOI, DOD, and NOAA, explored strategies to improve water management by tracking, anticipating, and responding to climate change (Brekke et al. 2009). This report describes the existing and still needed science crucial to addressing the many impacts of climate change on water resource management. It provides adaptation and planning options for water resource practitioners.

In addition, federally funded researchers are working with water and ecosystem managers as new insights and techniques become available, allowing incorporation of scientific data and information into near- and long-term planning. Interagency and partnership projects are occurring for the Colorado River, in the Columbia River Basin, and in California and many other locations.[19]

Evaluating Hydroclimatic Conditions in the Pacific Northwest

The Climate Impacts Group (CIG) at the University of Washington is using emerging knowledge to help inform decision making related to changing hydroclimatic conditions in the Pacific Northwest. CIG is utilizing its hydrologic modeling and prediction capabilities to evaluate water resource issues, including the consequences of alternative water and hydroelectric power management strategies for salmon restoration efforts and the consequences of changing water demands and changes in land cover for regional water resources.[20] CIG is one of seven similar RISA programs funded by NOAA's Climate Program Office. These programs are designed to provide the nation with experience-based knowledge about how to develop climate services.[21] They are an important element of the USGCRP's efforts to support decision making on climate-related issues.

Planning for Climate Change in New York City

New York City is an example of adaptation in the face of water resource concerns. The city's Department of Environmental Protection (DEP), which provides water for 9 million people in the New York City metropolitan area, is beginning to alter its planning to take into account the effects of climate change—sea level rise, higher temperatures, increases in extreme events, and changing precipitation patterns—on the city's water systems. Examples of measures that have emerged from the comprehensive assessment and evaluation process include relocating critical control systems to higher floors in low-lying buildings or to higher ground, building flood walls, and modifying infrastructure design criteria. The DEP is also establishing a system for reporting the impacts of extreme weather on the city's watershed and infrastructure (Karl et al. 2009).

Assessing Groundwater Availability

The depletion of groundwater at a variety of scales and the compounding effects of recent droughts emphasize the need for an updated status on the availability of the nation's groundwater resources. Assessments of the current state of the highest-stressed groundwater flow systems are necessary tools for characterizing the availability of groundwater. The USGS Groundwater Resources Program[22] is taking advantage of the quantitative work previously conducted by the Regional Aquifer-System Analysis Program and information available from USGS, DOI (e.g., BOR, the National Park Service [NPS], Bureau of Land Management [BLM]) and other federal agencies (e.g., EPA and NOAA), states, tribes, and local governments to provide an updated quantitative assessment of groundwater availability in areas of critical importance. The assessments currently underway and continuing into 2010 and beyond will (1) document the effects of human activities on water levels, groundwater storage, and discharge to streams and other surface-water bodies; (2) explore climate variability impacts on the regional water budget; and (3) evaluate the adequacy of data networks to assess impacts at a regional scale.

Developing a National-Scale View of Water Quality Impacts from Climate Change

EPA is using high-resolution simulations of future climate change over the contiguous United States from the North American Regional Climate Change Assessment Program and land-use scenarios from EPA's Integrated Climate and Land Use Scenarios project to develop hydrologic and water quality change scenarios for 20 major drainage basins across the United States. These scenarios will be based on watershed simulations conducted with the HSPF (Hydrologic Simulation Program–Fortran) and SWAT (Soil and Water Assessment Tool) watershed models, and will focus on the response of stream flow,

[19] See, for example, http://pubs.usgs.gov/circ/1331/Circ1331.pdf and http://wwa.colorado.edu/colorado_river/.

[20] See http://www.cses.washington.edu/cig/res/hwr/hwr.shtml.

[21] See http://www.climate.noaa.gov/cpo_pa/risa/.

[22] See http://water.usgs.gov/ogw/gwrp/.

nitrogen, phosphorus, and suspended sediment to a range of projected changes in climate and land use.

Ecosystems

Enhancing Ecosystem Management Strategies

The extent to which ecosystem conditions will be affected in the future will depend on the magnitude of climate change, the degree of sensitivity of the ecosystem to that change, the availability of adaptation options for effective ecosystem management, and the willingness to deploy those options. USGCRP addressed management strategies for facilitating ecosystem adaptation to climate variability and change in several state-of-the-art reports focused on federal lands (Baron et al. 2008; Backlund et al. 2008; Fagre et al. 2009). The goal of these adaptation strategies is to reduce the risk of adverse outcomes through activities that increase the resilience of ecological systems to climate change, and to take advantage of positive outcomes (Turner et al. 2003; Tompkins and Adger 2004; Scheffer et al. 2001; Baron et al. 2008). Because some changes in the climate system are likely to persist into the future regardless of emissions reduction, adaptation is an essential response for future protection of climate-sensitive ecosystems.

Adaptation options for enhancing ecosystem resilience include changes in processes, practices, or structures to reduce anticipated damages or enhance beneficial responses associated with climate variability and change. In some cases, opportunities for adaptation offer stakeholders multiple beneficial outcomes, such as the addition of riparian buffer strips that, for example, manage pollution loadings from agricultural land into rivers or provide a protective barrier to increases in both pollution and sediment loadings that may be associated with future climate or other environmental change (Baron et al. 2008).

Identifying Necessary Information and Tools

A range of adaptation options is possible for many ecosystems, but a lack of information or resources may impede successful implementation. In some cases, managers may not have the knowledge or information they need to address climate change impacts. In other instances, managers may understand the issues and have the relevant information but lack resources to implement adaptation options. Furthermore, even with improvement in the knowledge and communication of available and emerging adaptation strategies, the feasibility and effectiveness of adaptation will depend on the adaptive capacity of the ecological system or social entity (Baron et al. 2008).

Thus, increasing adaptive capacity will require information and tools that aid in (1) understanding the combined effects on ecosystems of climate changes and non-climate stressors, and consequent implications for achieving specific management goals; (2) applying existing management options or developing new adaptation approaches that reduce the risk of negative outcomes; and (3) understanding the opportunities and barriers that affect successful implementation of management strategies to address climate change impacts (Baron et al. 2008).

Reducing the Frequency and Severity of Wildfires in the West

In the western United States, invasive annual grasses (e.g., cheatgrass) are increasing rapidly throughout the region. These fire-tolerant species increase fire frequency, eliminating native plants, wildlife and livestock forage, and habitat. USGS is providing science in support of decision making, including (1) mapping annual plant invasions (ground, aerial, satellite); (2) developing native plant restoration protocols; and (3) mapping historic fires to understand causes.[23] BLM, which is responsible for managing much of the federal land affected by these issues, is developing adaptation plans to restore native plant communities, ensure the necessary presence of pollinators, reduce the frequency and severity of wildfire, and "pre-adapt" these lands for climate change—planting communities in anticipation of local changes due to a changing climate. Specifically, BLM and its partners are conducting a natural habitat restoration effort for millions of acres in the Great Basin of Nevada, Oregon, Idaho, California, and Utah, and they are working with commercial seed producers to grow native seed for restoration.[24]

Public Health

Addressing Heat-Related Health Threats

Critical U.S. government information to support action to reduce the health impacts of excessive heat days would be routinely used during heat waves in many U.S. cities. This information has applicability under projected increases in the number of such events, due to climate change. For example, NOAA's National Weather Service provides temperature and heat index information for the determination of "heat warnings."

During heat waves in Philadelphia, a heat alert is issued and news organizations are provided with tips on how vulnerable people can protect themselves. The health department and thousands of block captains check on elderly residents, and public cooling places extend their hours. The city also operates a "heatline" with nurses ready to assist callers with heat-related health problems. In addition, the Cool Homes program offers assistance to elderly, low-income residents to install roof insulation and cool surfaces to save energy and lower indoor temperatures. Philadelphia's system is estimated to have saved 117 lives in its first three years of operation (Karl et al. 2009).

As another example, EPA and other federal agencies responsible for addressing excessive heat events (EHEs) developed a guidebook that provides interest-

[23] See http://www.usgs.gov/hazards/wildfires/.

[24] See http://www.blm.gov/id/st/en/prog/gbri.html.

ed public health officials with information on the risks of and impacts from EHEs, including guidance on EHE forecasting and identification (U.S. EPA/OAP 2006a). The guidebook also provides a menu of notification and response actions to consider when developing or enhancing a local EHE program based in part upon a review of various EHE response programs.

Developing Integrated Health Assessment Frameworks

EPA is also undertaking important work assessing the relationships between climate change and human health. This assessment work goes beyond basic epidemiological research to develop integrated health assessment frameworks that consider the effects of multiple stresses, their interactions, and human adaptive responses. Along with health sector assessments, conducted in conjunction with the USGCRP national assessment process, there are research and assessment activities focused on the consequences of global change on weather-related morbidity and vector- and water-borne diseases. In addition, the results from the USGCRP air quality assessments will be used to evaluate health consequences.[25]

Working Internationally to Fight Malaria

Internationally, NOAA, EPA, and NSF have collaborated to fund efforts, in partnership with developing country colleagues, to identify relationships between malaria and climate and to develop an early-warning system for malaria.[26] Clear relationships were identified and significant capacity was built, including through stakeholder input, to develop early-warning systems.

Coasts

Adapting to Rising Sea Levels Along the East Coast

In an example from the USGCRP assessment of coastal vulnerability to sea level rise (Titus et al. 2009), adaption options for coastal wetland ecosystems were outlined. Wetlands are rich ecosystems that provide protection from coastal storms as well as a number of other resources and services (Karl et al. 2009). To adapt to rising sea level without damaging vulnerable ecosystems through the implementation of "hard armoring" of the shorelines (e.g., sea walls), a system of "rolling easements" for property and ecosystems to migrate inland as the sea rises could be implemented. For example, in Massachusetts and Rhode Island, hard armoring of the shoreline is prohibited in some areas to allow the migration of ecosystems. Maryland has recently enacted a Living Shoreline Protection Act,[27] which requires its Department of the Environment to create maps delineating the areas where hard structures will be allowed or prohibited (Karl et al. 2009).

Preparing for Sea Level Rise

In recognition of significant potential impacts from climate change, the Coastal Zone Management Act of 1972 states: "Because global warming may result in a substantial sea-level rise with serious adverse effects in the coastal zone, coastal states must anticipate and plan for such an occurrence" (16 U.S.C. [U.S. Code] § 1451).[28] Property owners and federal, state, and local governments are already starting to take measures to prepare for the consequences of rising sea level. Most coastal states are working with the U.S. Army Corps of Engineers to place sand on their beaches to offset shore erosion. Property owners are elevating existing structures in many low-lying areas, to provide resilience to episodic storms as well as long-term change. Shoreline erosion along estuaries has led many property owners to defend their back yards by erecting shore protection structures, such as bulkheads, which eliminate the intertidal wetlands and beaches that would otherwise be found between the water and the dry land.

Several states have adopted policies to ensure that beaches, dunes, or wetlands are able to migrate inland as sea level rises. Some states prohibit new houses in areas likely to be eroded in the next 30–60 years (e.g., North Carolina Coastal Resources Commission). Concerned about the need to protect both natural shores and private property rights, Maine, Massachusetts, Rhode Island, South Carolina, and Texas have implemented some version of "rolling easements," in which people are allowed to build, but only on the condition that they will remove the structure if and when it is threatened by an advancing shoreline (McCarthy et al. 2001; Titus et al. 2009).

Addressing Climate's Impacts on Estuaries

EPA has created the Climate Ready Estuaries program to help address climate change in coastal areas. This effort is helping the National Estuary Programs and other coastal managers develop the technical capacity to assess climate change vulnerabilities, engage and educate local stakeholders, and develop and implement adaptation strategies.[29]

Developing Assessments and Adaptation Plans

DOI through USGS is conducting a national risk assessment due to future sea level rise for the U.S. Atlantic, Pacific, and Gulf of Mexico coasts. This includes work with NPS for coastal park units. In parallel, DOI through the U.S. Fish and Wildlife Service (FWS) is working with partners to create and implement adaptation plans for specific coastal wildlife refuges. In 2008, FWS created an adaptation plan with The Nature Conservancy and Duke Energy. Solutions articulated in the plan include (1) restore wetland hydrology: restore damage caused by artificial ditches; (2) reforest and restore shoreline: protect and restore existing natural coastal and inland habitat to facilitate species migration as sea level rises; (3) restore oyster reefs: restore oyster reefs in Pamlico Sound to protect shorelines from storms and rising seas;[30] and (4) mea-

[25] See http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=203459.

[26] See http://portal.iri.columbia.edu/portal/server.pt/gateway/PTARGS_0_0_4621_223_0_43/http%3B/portal.iri.columbia.edu%3B9086/irips/projectview.jsp?id=31 and http://www.iwmi.cgiar.org/health/malaria/projects.htm#climatev.

[27] See http://mlis.state.md.us/2008rs/chapters_noln/Ch_304_hb0973E.pdf.

[28] See http://coastalmanagement.noaa.gov/czm/czm_act.html.

[29] See http://www.epa.gov/cre.

[30] See http://www.dot.gov/climate.

sure and monitor carbon sequestration: monitor the effects of management on soil carbon.

Developing Data for Informed Decision Making

Many agencies and organizations are developing data that can provide insights regarding the implications of sea level rise. Sample data include elevation models and data sets; geographic information systems; ecosystem, fish, and wetlands impact information; tidal gauge data; economic and population data; insurance information; storm surge databases; and hurricane research.

Transportation

The United States is working to provide better information to decision makers across the sector about what future climate variability and change could mean for existing and planned infrastructure and about the set of potential response strategies that might be implemented to adapt to future climate.

Incorporating Climate Change and Variability into Decision Making

DOT's Center for Climate Change and Environmental Forecasting is dedicated to fostering awareness of the potential links between transportation and global climate change, and to formulating policy options to deal with the challenges posed by climate change and variability.[18] DOT research projects are investigating the potential impacts of climate variability and change on transportation infrastructure and its operation, and provide guidance as to how transportation planners and decision makers may incorporate this information into transportation planning decisions to ensure a reliable and robust future transportation network.

"Climate Proofing" Roads

An example of adaption measures undertaken in response to climate threats to transportation includes an effort to "climate proof" a road on the island of Kosrae in the U.S.-affiliated Federated States of Micronesia. In response to projections of increased heavy downpours and sea level rise, authorities placed the road higher and introduced improved drainage systems. The additional costs to incorporating these measures were projected to be offset by the reduced repair and maintenance costs after 15 years (Karl et al. 2009).

Energy

Prospects for adaptation to climate change effects by energy providers, energy users, and society at large are speculative, in part because of the lack of research to date, although the potentials are considerable and several examples exist of early adaptation planning. It is possible that the greatest challenges would be in connection with possible increases in the intensity of extreme weather events and possible significant changes in regional water supply regimes. But adaptation prospects depend considerably on the availability of information about possible climate change effects to inform decisions about adaptive management, along with technological change in the longer term.

One example of addressing energy vulnerabilities along the Gulf Coast in association with the oil and gas industry can be found in Port Fourchon, Louisiana. The port supports 75 percent of deepwater oil and gas production in the Gulf of Mexico, and its role is increasing. The oil imported (1 million barrels/day) and produced (300,000 barrels/day) through Port Fourchon is linked to 50 percent of the refining capacity of the nation. Only one road, Highway 1, connects Port Fourchon with the nation, and it transports machinery, supplies, and workers to the port. Responding to concerns about storm surge and flooding, related in part to climate change and rising sea levels, Louisiana is upgrading Highway 1 and raising it to about the 500-year flood level, as well as building higher bridges over Bayou LaFourche and the Boudreaux Canal (Karl et al. 2009; Savonis et al. 2008).