RESEARCH PATHWAYS

New Approaches, New Knowledge, and New Capabilities for Our Nation

It is vital to our national interest that we meet these research needs so that we can, with increasing certainty, address the critical question: How vulnerable or resilient are the nation's natural and human resources and systems to the changes in climate projected to occur over the decades ahead?

The National Assessment has defined a new vision for climate-impacts research. This vision has at its core a focus on integrated regional analysis and a close partnership of natural and social scientists with local, regional,and national stakeholders. Integrated analysis refers to considering the full range of stresses that affect a resource or system,including climate change and variability, land use change,air and water pollution,and many other human and natural impacts. For example,in studying water quality in a particular place,the direct and indirect effects of urban development, agricultural runoff, industrial pollution,and climate change-induced increases in heavy precipitation events all would need to be considered,along with many other factors. Integrated analysis also refers to integrating across all the relevant spatial scales for an issue,and these may extend from local to regional to national and even to global,depending on the issue. In the example of the local water quality study, this would mean integrating the effects of large-scale weather patterns on precipitation,as well as pollution inputs on both large and small scales, some of which originate far from the study area. Such integration across both multiple stresses and multiple scales is needed to provide the type of comprehensive analysis that decision-makers seek.

Guided by this vision,the first National Assessment has identified a range of regional and sector vulnerabilities to climate variability and change that call for the attention of the American people and their leaders. In identifying vulnerabilities,the authors of the Assessment took great care to evaluate the likelihood of various climate-related outcomes. The likelihood of a number of outcomes was considered to be high. However, the likelihood of some of the other important potential outcomes was more difficult to judge due to lack of appropriate methods,uncertainties in knowledge,or shortcomings in research infrastructure such as computer power.

As our nation considers its strategies for dealing with climate-related vulnerabilities, scientists must work to reduce uncertainties underlying the vulnerability estimates. To assure that efforts to reduce uncertainties are efficient and to the point,the authors of the Assessment have identified a short list of priority research steps that are outlined below. These steps are organized into three categories:New Approaches,New Knowledge,and New Capabilities. It is vital to our national interest that we meet these research needs so that we can,with increasing certainty, address the critical question:How vulnerable or resilient are the nation's natural and human resources and systems to the changes in climate projected to occur over the decades ahead? With the new vision of regional analysis and scientist-stakeholder partnerships developed in the National Assessment, we have a powerful approach to effectively address this complex question.

Expanding New Approaches

This first National Assessment experimented with new approaches for linking the emerging findings and capabilities of the scientific community with the real-time needs of stakeholders who manage resources, grow food,plan communities,sustain commerce,and ensure public welfare. Teams were established in various regions across the country to look at how climate variability and change would affect particular locations. Other teams were established on particular topics that focused on how climate variability and change would affect issues of national significance. These types of efforts need to be sustained and expanded. In doing so we can build on a number of existing federal programs.

Recommendation 1: Develop a More Integrated Approach to Examining Impacts and Vulnerabilities to Multiple Stresses

The key requirement is to develop a truly integrated and widely accessible approach at regional and national scales appropriate for the examination of regional and national problems associated with biologic, hydrologic,and socioeconomic systems. A number of the regional and sector studies supporting the National Assessment have made important progress in such efforts but substantial additional efforts are required.

Expand the national capability to develop integrated, regional approaches of assessing impacts and vulnerabilities.

The regional teams supporting the National Assessment have produced new and innovative partnerships among a wide variety of scientists and stakeholders. In the process,they have catalyzed new modes of research and have demonstrated the potential of an integrated approach to assessing the consequences of climate variability and change. If the nation is to have improved projections of the impacts of and vulnerabilities to multiple stresses, we must accelerate the process of integrating research capabilities across the spectrum of natural and social sciences with the needs of public and private decision-makers. The importance of multiple stresses on specific environments and the importance of linkages between physical,biological, chemical,and human systems, require enhanced capabilities for regional analysis. The key elements of this strategy must be to (a) integrate observations at a regional level;(b) develop a comprehensive system designed to make the enormous amounts of data and information more accessible and useful to the public;(c) enable field and experimental studies that focus on solving regional problems;and (d) develop a foundation for building tractable,high-resolution coupled models that can address the outcomes associated with multiple stresses unique to each area of the country. Regional assessments add impetus for developing a comprehensive integrated approach,and this integration will engender substantial new capabilities to address the relationships between climate and air quality, energy demand, water quality and quantity, species distribution,ecosystem character, ultraviolet radiation, and human health indices in specific regions.

An integrated research approach would address such questions as:

How will the combination of high concentrations of ground-level ozone, high heat stress, and other factors affect human and plant health, especially in sensitive areas, such as the Great Smoky Mountains National Park, and metropolitan Houston?

Perform integrated national investigations of additional sectors and issues.

Assessment of US impacts, including potential benefits, will increasingly require an examination of changes and response strategies around the world, and the manner in which these are translated to the global marketplace and environment.

The choice of major sectors in this Assessment (water, forests,human health,coastal regions,and agriculture) reflected the fact that they were likely to be informative and important. Some of the themes were represented by a strong foundation of methods and models (e.g., agriculture) while others represented capabilities at very early stages of development (human health). These themes yielded a number of future research needs (e.g.,the need to better understand human health relationships to extreme temperatures,other extreme weather events,and air quality, and to better characterize the relationships between climate and disease vectors and then between vector distribution and disease). In addition,a large number of important sectors and themes were not addressed,including climate impacts on transportation,energy, urban areas,and wildlife. These will require future investment in supporting research and assessment.

Consider international linkages in assessing national impacts.

In some cases,the vulnerability and resiliency of the US to climate impacts are highly dependent on the nature of the changes in other countries. For example,in the case of agriculture,the nature of the impacts strongly depends on international markets,and therefore the production and distribution of major crops around the world. These markets will reflect the extent of temperature and precipitation changes in other nations and the ability of these nations to cope with climate change and variability. Assessment of US impacts,including potential benefits,will increasingly require an examination of changes and response strategies around the world,and the manner in which these are translated to the global marketplace and environment.

Recommendation 2: Develop New Ways to Assess the Significance of Global Change to People

New methods for examining the potential impacts of climate change,adaptation options,and the vulnerability of communities,institutions,and sectors are essential to improving the assessment process. Research on these issues would result in a far greater ability to anticipate possible surprises,incorporate socioeconomic data in our analyses,and provide information that is useful for public and private decision-makers. The key research requirements involve improving methods to:

Understand and assign value to large and non-market impacts
(e.g., on communities, resources, and ecosystems).

Changes that occur in natural and managed ecosystems,natural resources,and the other sectors are important because people assign them value,either in market or non-market terms. It is crucial to develop new ways to assign values to possible future changes in resources and ecosystems,especially in the cases of very large impacts and of processes and services that do not produce marketable goods. A focus on large impacts and non-market systems should provide insights that would enable decision-makers to understand the potential consequences of environmental change,as well as the potential consequences of particular adaptation or mitigation decisions.

Represent, analyze, and report uncertainties.

Describing scientific uncertainty is a task that faces every assessment of impacts or vulnerability. Findings in this Assessment,and their associated uncertainties,are based on the considered judgment of the NAST and on the peer-reviewed literature. The assessment process should extend the capabilities of decision-makers to understand potential uncertainties. For this reason,a range of additional methods for representing,analyzing,and reporting uncertainties should become a research focus.

Assess potential thresholds and breakpoints.

Some ecosystems and human institutions do not respond to rapid changes or stresses in continuous ways;if the stress exceeds certain thresholds,the system changes very rapidly, and sometimes in irreversible ways. It is very important to understand these types of responses because they raise particularly difficult challenges for adaptation. Using climate scenarios to help determine the conditions under which such changes might occur is therefore extremely important to pursue,because it can provide information of direct utility to decision-makers.

The recommended research could help identify key thresholds beyond which certain ecosystems would no longer perform services people rely upon. For example, at what point would a particular lake no longer provide habitat for certain types of fish due to changes in climate, hydrology, and excess nutrient input from fertilizer runoff?

Develop and apply internally consistent socioeconomic futures for use in assessing impacts.

In order to consider adaptation responses and ultimate vulnerabilities to climate change and other environmental stresses,assessments need to consider alternative possible socioeconomic and climatic futures using scenarios,probability distributions,or other methods. This Assessment began this process,but new methods to develop and apply such futures will improve the quality of the evaluation of the potential for adaptation in sector, regional and national analyses.

Developing New Knowledge

Determining how climate change will affect us necessarily builds on a wide array of scientific knowledge,not just of how the atmosphere works,but of how land ecosystems,the oceans,society, and many other aspects of the Earth system interact. Building this base of knowledge was the reason for establishing the US Global Change Research Program,and for the many programs and projects that it supports. Findings of this research have been essential to the overall undertaking of the Assessment. However, in the course of this Assessment,a number of areas have been identified where specific types of new knowledge are needed to assist society in preparing for the changing conditions of the 21st century. Improving projections of the responses of ecosystems,societal and economic systems,and climate, would improve scientists' ability to answer questions that are important to decision-makers.

RESEARCH PATHWAYS

Recommendation 3: Improve Projections of How Ecosystems Will Respond

The recommended ecosystem research could address such questions as:

How will climate change combine with increased demand for agricultural production and increased urbanization to affect the rate of species endangerment in the US?

Will climate change and the increase in atmospheric CO_2 stimulate carbon sequestration in US forest ecosystems? If so, how much carbon will be sequestered and which forests will be the most effective carbon sinks?

The nature of the response of complex natural and managed ecosystems to multiple stresses is one of the most important challenges to providing more certain projections of the impacts of climate variability and future climate change. Scientific studies are needed to extend our knowledge of many types of interrelationships between climate and ecosystems. These complex,interdependent interactions determine how organisms will respond to climate and other stresses and determine the potential vulnerability and/or resilience of these systems. Areas requiring intensified research to address this challenge include:

Terrestrial and aquatic natural ecosystem responses to multiple stresses, including the consequences for productivity, biodiversity, and other ecosystem processes and services.

Information is lacking on local, watershed,and continental scales to evaluate the responses of terrestrial and aquatic ecosystems to combinations of environmental stresses. Experimentally and observationally based investigations are needed of combinations of important environmental changes (such as changes in:CO_2 concentration; climate variability, temperature,land use, air and water quality, and species composition) as they affect important ecological processes (including productivity and nutrient cycling),attributes (such as species diversity, the responses and interactions of important individual plant and animal species,and the interactions among plant and animal communities),and services (such as regulating runoff). Results from such field experiments are needed as inputs for more sophisticated generations of ecosystem models to provide the information needed to project the responses of ecosystems to combinations of stresses, rather than separately treating individual stresses.

Managed ecosystem responses to multiple stresses, including their consequences for water quality and runoff, soil fertility, agricultural and forest productivity, and pest, weed, crop, and pathogen interactions through the development of integrated observations, process studies, and models.

Effective management of agricultural lands, forested ecosystems,and watersheds is closely coupled to the influences of pests,pathogens, climate,and other environmental variables. These interactions have not been addressed adequately in an experimental fashion. Research is needed on the interactions of these factors as they affect crop and forest productivity, soil fertility, water quality and quantity, the spread of pathogens and weeds,etc. Results from such experiments would provide insight into potential vulnerabilities from the combinations of environmental stresses,and input to better management responses to changes in those stresses.

The importance and interactions of climate, land cover, and land use in nutrient cycling, water supply and quality, runoff, and soil fertility.

Current land use models include socioeconomic variables such as human population size,affluence,and culture. However, the influences of climate change on land use,and of land use changes on regional climate are not adequately considered.

Available analyses of ecological change tend to make one of two simplifications: either that a region is covered by its potential natural vegetation (the vegetation that would exist in the absence of human activities) or that the land-cover and land-use will remain as it is now, independent of climatic or other stresses. Both of these perspectives are limiting because they simplify the feedbacks between land use, ecological systems,and climate. New models of land-use change that integrate actual land-cover and land use information with ecological and economic processes would provide a crucial context for examining the potential consequences of human land-use decisions on a wide variety of ecosystem goods and services.

Better observations and models of ecosystem disturbance, and species dispersal and recruitment.

The ability to project changes in the ranges of important tree and plant species,and therefore changes in the make-up of forests and other ecosystems,is critically limited by information about the frequency of fires and other disturbances,the ability of seeds to disperse across current landscapes,and the factors that determine the success of plants in establishing themselves in new habitats and locations. Field observations, experimental studies,and historical analyses of past ecosystem changes are needed in order to understand both what is possible and the distances and rates of range changes that important species might actually achieve as climate changes. Such results would help fill crucial gaps in knowledge and enhance our ability to project the future ranges and distribution of important species.

To assess real impacts on people and their societies, we need to improve our understanding of how people and institutions will adapt to change and of the factors that will determine their vulnerability.

Recommendation 4: Enhance Knowledge of How Societal and Economic Systems Will Respond to a Changing Climate and Environment

A greater understanding of the vulnerability and resilience of societal and economic systems is essential to addressing key uncertainties. Human roles in and responses to climate change and other environmental stresses are among the most important features of impact assessments. To assess real impacts on people and their societies, we should improve our understanding of how people and institutions will adapt to change and of the factors that will determine their vulnerability. Gaining such knowledge will require investing in the following key areas:

Understanding the resilience of communities, institutions, regions, and sectors (e.g., human health, urban areas, transportation, and international linkages).

The ability of communities,institutions, regions,and sectors to adapt has only begun to be addressed in this Assessment. Understanding how the capacity to adapt to a changing climate might be exercised,and therefore what vulnerabilities to climate change and other environmental stresses might remain,is an important next step in the human dimensions research agenda. The results of this research would enable a more integrated evaluation of both natural and social science aspects of human responses.

RESEARCH PATHWAYS

The recommended research could help address questions such as:

What are the likely costs of adapting to increases in average temperature and heat index?

To what degree can cities take climate change into account in planning for new infrastructure, such as water distribution and routing, bridges, and peak power demands?

Improving understanding of how people and institutions have adapted to past climate variability and extreme events.

There is a wealth of information available on how people and institutions have responded to climate variability and other environmental changes in the past. New research that documents these responses, analyzes the underlying reasons for them, and explains how individual and institutional decisions were actually made will provide important insights into the feasibility of coping and adaptation options that might be available and considered in the future.

Greater information and analysis of specific potential adaptation options (e.g., costs, efficacy, time horizons, feasibility, and other impacts).

One of the critical unknowns in this Assessment's consideration of adaptation options stems from a lack of information about their potential costs,efficacy, time horizons required for implementation,other consequences,and feasibility. This type of information should be gathered as decision-makers consider specific adaptation options.

Recommendation 5: Refine our Ability to Project How Climate Will Change

This first National Assessment has revealed a number of key uncertainties in projecting climate change and variability at global,national,and regional scales. These uncertainties limit our ability to assess the responses of natural and managed ecosystems and societal and economic systems. Of greatest significance to decision-makers will be reducing uncertainties in several key areas by pursuing research that will lead to:

Improved understanding and analysis of the potential for future changes in severe weather, extreme events, and seasonal to interannual variability.

Many of the results in this Assessment demonstrate that changes in climate variability across a wide range of spatial and time scales have very important impacts on ecosystems,natural resources,and human systems. Long-term climate variations are strongly affected by how the oceans store and transport heat from warm regions near the equator to cold regions at high latitudes. For example,the El Niño-Southern Oscillation (ENSO) influences extreme weather and climate events by affecting the paths,frequency, and severity of winter and tropical storms. While model projections of ENSO and other sources of variability have advanced greatly over the past few years, much additional work is needed on how human-caused climate change might affect these patterns of variability. Much greater understanding is also needed about how climate change will influence the frequency, intensity, and likely locations of severe weather and climate events such as droughts,hurricanes, tornadoes,severe thunderstorms,and meteorological events that produce severe flooding.

Improved understanding of the spatial and temporal character of hydrologic processes, including precipitation, soil moisture, and runoff.

Some of the most important differences among climate model simulations involve projections of precipitation,soil moisture,and runoff, and these are of the greatest significance for ecosystems, agriculture,and water quality and quantity. Despite their importance,there is incomplete understanding of the physical processes that govern the water cycle and the extent to which these processes will be modified by climate change. The differences are sufficiently large in some regions of the country that we cannot even project whether there will be an increase or a decrease in soil moisture and runoff in these regions. A critical element of climate research must be an improved ability to simulate all aspects of the water cycle. Results of this research would substantially improve the estimates of potential vulnerabilities to climate change and other stresses.

Increased information on the nature of past climate, including its spatial and temporal character.

Model-generated scenarios of climate change and variability are only one way to examine potential futures. Another important method is to reconstruct the regional record of past changes in climate and their consequences in order to improve our understanding of how the natural world has operated in the past. These records illustrate the nature of past variability, provide an opportunity to assess climate model sensitivity, and offer insights into the response of ecological systems to past climate change. Results of this research would raise our confidence in the application of climatic information to evaluate impacts and vulnerability.

Every three to seven years, the US is affected by a cycle of El Niño and La Niña events that leads to major changes in the frequency of hurricanes and in the paths of other weather systems that are responsible for extremes of precipitation and temperature across the US. The recommended research will enable future assessments to project how climate change will alter the frequency and severity of these extreme weather events.

Adding New Capabilities

The nation needs a stronger capability for providing climate information that serves the national requirements for assessing vulnerabilities and impacts. A stronger national capability could deliver climate projections,including increased access to reliable model outputs and observational information,improved understanding of limitations,and greater availability of the specialized products required by increasingly sophisticated assessment science. Climate modeling and analysis are the foundation for developing climate scenarios that describe alternative futures for analysis of potential impacts of climate change,adaptation options,and vulnerability. Several steps can be taken in the near-term to enhance our capabilities to provide and use scenarios.

Recommendation 6: Extend Capabilities for Providing Climate Information

Addressing the broad spectrum of future societal needs will require continued improvements in observations,analysis,and the ability to forecast a wide variety of environmental variables. The elements required to develop comprehensive capability include:

RESEARCH PATHWAYS

A commitment to sustained high-quality observations is necessary for detecting changes in important aspects of our environment. New and improved data sets are required to address questions such as: how is our environment is being altered by climate change? And how much confidence can we place in future projections, given our ability to understand past changes and variations?

A national modeling and analysis capability designed to provide long-term simulations, analysis of limitations and uncertainties, and specialized products for impact studies.

The nation's climate modeling expertise is widely recognized throughout the world and this expertise is dedicated to developing state-of-the-science model capability. Ensembles of long-term simulations, extending from the start of the robust historical record to at least the next 100 years, would provide important information to the nation. Further, the regional and sector teams in this Assessment have been requesting a host of specialized climate products that more directly tie future climate projections to specific decisions or vulnerabilities. The assessment process requires greater access to and a greater understanding of the limitations inherent in future projections in order to weigh the advantages and risks of alternative courses of action. Substantially higher model resolution is required to link climate with the scales of human decisions. The demand for these climate services exceeds the capabilities of the research functions of the nation's climate modeling centers.

Dedicated computer capability for developing ensemble climate scenarios, high-resolution models, and multiple emission scenarios for impact studies.

There is a need for ensemble climate simulations based on multiple-emission scenarios devoted to studies of climate impacts,vulnerabilities,and responses. The investment that is needed is to enhance the capacity of the climate modeling community to generate and analyze model runs that are dedicated for use by impact analysts. Similarly, future assessments need to investigate a range of plausible emissions and atmospheric concentrations of carbon dioxide and other greenhouse gases. The results of enhancing the capability to generate dedicated scenarios of emissions and climate would be a dramatic improvement in the range of outcomes that future assessments of vulnerability could analyze.

Reliable long-term observations and data archives.

One of the most often encountered limitations to the conduct of this Assessment, and one of the most often expressed needs of participants in the regional and sector assessment process,has been the lack of databases that truly reflect changes and variations in the environment,as opposed to those that unduly reflect uncertainties in observing methods. A commitment by the nation to provide integrated databases and information on multiple environmental conditions and trends,and indicators/measures of climate and related environmental changes,is essential to support and implement the research agenda. The US has tremendous potential to create more efficient and comprehensive measurement,archive,and data access systems that would provide greater scientific benefit to society by building upon existing weather and hydrologic stations and remote sensing capability, and integrating current efforts of local,state,and federal agencies. Improved data and information archives will substantially enhance future assessments.

Addressing the Full Agenda

While the proposed research activities are all important individually, it will not be possible to substantially reduce our uncertainties and gaps in knowledge without consideration of their interconnections and interdependencies. The National Assessment Synthesis Team is convinced that the nation will benefit from multi-year investments in this focused program of research. Benefits will include major enhancement in our knowledge of the impacts of and vulnerabilities to global change on scales appropriate to the national interest and in our capacity to assess their importance.

We must accept the challenge to learn more and to conduct future assessments of multi-dimensional changes in climate, other environmental processes, and socioeconomic conditions. Meeting this challenge will require the new approaches, new knowledge, and new capabilities outlined above that can help reduce uncertainties while taking advantage of the great amount that we already know. Many of the building blocks of scientific knowledge, analytical capability, and commitment to the required integration are now in place. Through its regional, sector, and integrated approach, this Assessment has taken an important first step toward that future.

We must accept the challenge to learn more and to conduct future assessments of multi-dimensional changes in climate, other environmental processes, and socioeconomic conditions. Meeting this challenge will require the new approaches, new knowledge, and new capabilities outlined above that can help reduce uncertainties while taking advantage of the great amount that we already know.

Areas with High Potential for Providing Needed Information in the Near-Term

Expand the national capability to develop integrated, regional approaches of assessing the impacts of multiple stresses, perhaps beginning with several case studies.

Develop capability to perform large-scale (over an acre) whole-ecosystem experiments that vary both CO_2 and climate.

Incorporate representations of actual land cover and land use into models of ecosystem responses.

Identify potential adaptation options and develop information about their costs, efficacy, side effects, practicality, and implementation.

Develop better ways to assign values to possible future changes in resources and ecosystems, especially for large changes and for processes and service that do not produce marketable goods.

Improve climate projections by providing dedicated computer capability for conducting ensemble climate simulations for multiple emission scenarios.

Focus additional attention on research and analysis of the potential for future changes in severe weather, extreme events, and seasonal to interannual variability.

Improve long-term data sets of the regional patterns and timing of past changes in climate across the US, and make these data-sets more accessable.

Develop a set of baseline indicators and measures of environmental conditions that can be used to track the effects of changes in climate.

Develop additional methods for representing, analyzing, and reporting scientific uncertainties related to global change.