STRATEGIC PLAN FOR THE CLIMATE CHANGE SCIENCE PROGRAM

By the agencies and staff of the
US Climate Change Science Program

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Foreword

In February 2002 President George W. Bush announced the formation of a new management structure, the Climate Change Science Program (CCSP), to coordinate and direct the US research efforts in the areas of climate and global change. These research efforts include the US Global Change Research Program (USGCRP) authorized by the Global Change Research Act of 1990, and the Climate Change Research Initiative (CCRI) launched by the President in June 2001 to reduce significant uncertainties in climate science, improve global climate observing systems, and develop resources to support policymaking and resource management.

The President's Climate Change Research Initiative was launched to provide a distinct focus to the 13-year old Global Change Research Program. The CCRI focus is defined by a group of uncertainties about the global climate system that have been identified by policymakers and analyzed by the National Research Council in a 2001 report requested by the Administration.

The Climate Change Science Program aims to balance the near-term (2- to 4-year) focus of the CCRI with the breadth of the USGCRP, pursuing accelerated development of answers to the scientific aspects of key climate policy issues while continuing to seek advances in the knowledge of the physical, biological and chemical processes that influence the Earth system.

This *discussion draft* strategic plan has been prepared by the thirteen federal agencies participating in the CCSP, with input from a large number of scientific steering groups and coordination by the CCSP staff under the leadership of Dr. Richard H. Moss, to provide a vehicle to facilitate comments and suggestions by the scientific and stakeholder communities interested in climate and global change issues.

We welcome comments on this draft plan by all interested persons. Comments may be provided during the US Climate Change Science Program Planning Workshop for Scientists and Stakeholders being held in Washington, DC on December 3 – 5, 2002, and during a subsequent public comment period extending to January 13, 2003. Information about the Workshop and the written comment opportunities is available on the web site www.climatescience.gov. A specially formed committee of the National Research Council is also reviewing this draft plan, and will provide its analysis of the plan, the workshop and the written comments received after the workshop. A final version of the strategic plan, setting a path for the next few years of research under the CCSP, will be published by April 2003. We appreciate your assistance with this important process.

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CHAPTER 1

INTRODUCTION

CLIMATE AND GLOBAL CHANGE: IMPROVING CONNECTIONS BETWEEN SCIENCE AND SOCIETY

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Scientists recognized the existence of a natural "greenhouse effect" and the possibility of human-induced changes in the Earth's climate and environment as early as the 19^{th} century and, over time, this possibility has become widely accepted. In the last decades of the 20^{th} century, public debate about the contribution of human activities to observed climate change and potential future changes in climate, and about courses of action to manage risks to humans and the environment, has been active and frequently contentious. These debates cover a range of both science and policy issues, including the extent to which global temperatures have in fact changed; whether most of the observed overall change in temperature of the last 50 years is attributable to human activities (principally the burning of fossil fuels and changes in land cover); how much climate might change in the future; and whether proposed response strategies, such as reductions in emissions or efforts to enhance natural carbon sequestration processes, would produce economic or other effects more detrimental than the effects of climate change itself.

Science-based information is required to inform public debate on the wide range of climate and global change issues necessary for effective public policy and stewardship of natural resources, including:

- How much have climate and other aspects of the Earth system changed since the industrial revolution, and how do recent rates and levels of change compare to those that resulted from the Earth's significant climate variability in more distant historical periods?

- What are the relative roles of natural and human-induced forces in bringing about change, and how might human-induced and natural forces interact in the future?
- How has the climate system responded to both natural and human-induced forces, and how might it respond to potential future forcing?
- What is the sensitivity of natural and managed ecosystems to climate and other global changes, and how will sensitive systems be affected by climate variability and changes in the future?
- What are the projected costs and effects of different potential response strategies to manage the risks of long-term climate change?

Developing the needed information will require addressing a wide-ranging set of fundamental science questions, significantly improving observations and data management, and implementing highly credible and transparent mechanisms for conveying research results in ways that are useful for decisionmakers and the public.

1. The Issues for Science and Society

Environmental systems on Earth are changing constantly. The climate system is highly variable, with conditions varying significantly over the span of seasons, years, decades, and longer timescales. Fluctuations in the amount of energy emitted by the Sun, slight deviations in the Earth's orbit, volcanic injections of gases and particles into the atmosphere, and natural variations in ocean temperatures and currents, all cause variability and changes in climate conditions.

Against the backdrop of these natural forces, humans have become agents of environmental change, at least on timescales of decades to centuries, even as living standards for billions of people have improved tremendously. Emissions of greenhouse gases and pollutants and extensive changes in the land surface (both tied to widespread development of modern living standards) have potential consequences for global and regional climate. They also influence air quality, the Earth's protective shield of stratospheric ozone, the distribution and abundance of water resources and many plant and animal species, and the ability of ecosystems to provide life-supporting goods and services.

The challenge is that discerning whether human activities are causing observed climatic changes and impacts requires detecting a small, decade-by-decade trend against the backdrop of wide temperature changes that occur on shorter timescales (seasons to years). A sound base of observations, as well as a solid understanding of how the Earth's environmental systems respond to different natural and human forces, is essential to detecting and attributing climate change to any specific cause. Currently, measurements taken at the Earth's surface, in various layers of the atmosphere, in boreholes, in the oceans, and in other environmental systems such as the cryosphere (frozen regions) indicate that the climate is warming. Further, in *Climate Change Science: An Analysis of Key Questions* (NRC, 2001a), the National Research

Council (NRC), the operational arm of the National Academy of Sciences (NAS), concluded that "the changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability." The NRC report elaborates on this point:

> "Because of the large and still uncertain level of natural variability inherent in the climate record and the uncertainties in the time histories of the various forcing agents (and particularly aerosols), a causal linkage between the buildup of greenhouse gases in the atmosphere and the observed climate changes during the 20th century cannot be unequivocally established. The fact that the magnitude of the observed warming is large in comparison to natural variability as simulated in climate models is suggestive of such a linkage, but it does not constitute proof of one because the model simulations could be deficient in natural variability on the decadal to century time scale. The warming that has been estimated to have occurred in response to the buildup of greenhouse gases in the atmosphere is somewhat greater than the observed warming. At least some of this excess warming has been offset by the cooling effect of sulfate aerosols, and in any case one should not necessarily expect an exact correspondence because of the presence of natural variability."

Apparently contradicting the evidence of warming are inconsistencies in the observational record, particularly related to the differences between temperature trends measured at the surface and measurements taken from satellite observations of the lower- to mid-troposphere, which show no significant warming trends in the last two decades of the 20th century. Reconciling these differences and improving observational capabilities remains an important challenge with significant potential implications for decisionmaking.

But the issues extend beyond those of "detection and attribution" to projecting how climate and other related environmental conditions could change in the future. Confidence in such projections is tied to knowledge of basic climate processes and natural variability, the ability of climate models to represent accurately these processes, and the ability of models to represent interactions of natural processes and any human-induced changes in the climate system.

Improving the capability to project future climate conditions would be of significant economic and social value. Consider, for example, the benefits of improved forecasts of the onset of the El Niño-Southern Oscillation (ENSO). ENSO is a large-scale climate oscillation in the equatorial Pacific Ocean that changes phase every few years. Its effects reverberate through the global climate system to affect precipitation and temperature in many regions of the world. Armed with a basic understanding of the processes involved, scientists intensified systematic observations and improved their models, and by the late 1990s could successfully forecast some conditions months in advance. While much additional work is required to improve ENSO forecasts, some climatic features can now be accurately predicted, with significant societal benefits. In the United States, decisionmakers are able to better estimate energy requirements, prepare for storms, manage water resources, anticipate where damage recovery efforts will be required, and foresee other potential impacts. In countries in South America, Africa, and other regions of the world, resource planners and managers are applying model results to develop agricultural plans, anticipate potential food surpluses and shortages, and prepare for other impacts. Such planning has already reduced suffering and saved crops that would have otherwise been lost to drought and other ENSO effects.

Improving the ability to project long-term trends in climate and related conditions is important to understanding the effects of different types and amounts of natural and human forcing, such as that due to different levels of greenhouse gas and aerosol emissions. Therefore, anticipating how possible future forcing could affect the climate requires development of complex computer models that incorporate the many features of the climate system and their interactions. Such models have been under construction for decades, and require ongoing observations and research into basic processes to fuel their continued improvement. Already, large-scale features of climate can be simulated, but many significant uncertainties remain to be addressed. Current models project significantly different increases in the global average surface temperature, from approximately 1^{o}C during the 21st century to more than 5^{o}C during the same period. This range of uncertainty incorporates both different estimates of climate sensitivity (the increase in temperature that results from a doubling of atmospheric concentrations of carbon dioxide (CO_2)) and a wide range in projections of future greenhouse gas emissions. Reducing uncertainty in climate models will involve improving understanding of the role of clouds in different parts of the atmosphere; improving characterization of the circulation and interaction of energy in the atmosphere and oceans; improving understanding of the Earth's natural carbon cycle; developing more detailed representations of features of and feedbacks from the land surface; incorporating additional types of forcing agents (e.g., "black carbon"); and making progress on other fundamental challenges. Improved projections of climate changes on decadal or longer timescales are also important for many areas of planning and resource management where decisions made today have implications for decades to come. However, at this point, modeled projections of the future regional impacts of global climate change are often contradictory and are not sufficiently reliable tools for planning.

Even if the scientific community were to develop a "perfect" model of the global climate, it would not be possible to predict the level and rate of future changes in climate resulting from human activities. This is because these activities are not predetermined, but rather depend on human choices, which will, in turn, affect future climate conditions. The activities in question—energy-related emissions of greenhouse gases; changing the surface of the land through clearing, conversion, and growth of different land covers; and the release of chemicals (both natural and human-made) that alter the productivity of the land and the oceans—all depend on a more basic set of human driving forces. These include population growth, living standards, characteristics of technology, and institutions (e.g., market conditions). While we cannot *predict* these conditions, we can use a different set of models to *project* the climatic and environmental consequences of different combinations of basic human driving forces. These models are useful for performing "If…, then…" scenario experiments that make it possible to begin to explore the potential implications of different technological and institutional conditions for future emissions, climate, and living standards.

Improving our ability to project potential future variations and changes in climate and environmental conditions, subject to assumptions about natural and human forcing, could enable governments, businesses, and communities to reduce damages and seize opportunities to benefit from changing conditions by adapting infrastructure, activities, and plans. But realizing this potential will require sustained research and improved understanding of the interactions among climate, natural and managed environmental systems, and human activities. Scientific research needs to address a range of issues, including:

- How might changes in climate, chemistry (e.g., the CO_2 “fertilization effect” (increased plant growth due to higher atmospheric CO_2 levels)), nitrogen deposition, and disturbance (e.g., fire, pest infestations) affect the water use efficiency, biomass allocation, and composition of natural and managed ecosystems over long periods of time?
- What is currently happening to ice sheets, sea ice, and permafrost, and what are the climatic, economic, trade, and strategic implications of future changes?
- How could climate change and sea level rise affect sediment flows, tides, waves, and biological functions of coastal areas?
- How readily can adaptation take place in different natural and socio-economic systems?

Research on such questions as these, and on development of adaptation options that are useful regardless of the origins of observed changes, will help clarify the importance of variations and potential changes in climate for the environment and society, and potentially broaden opportunities for management of risks and realization of benefits.

The complexity of the Earth’s environmental systems, the unique conditions that they provide for life, and the state of these systems, including potential impacts on society, make climate and global change among the most important issues for our generation, and perhaps for generations to come. Given what is at stake, the Nation and the international community need the best possible science to inform public debate and decisionmaking in government and the private sector.

2. The Research Program

In February 2002, President George W. Bush announced the formation of a new management structure, the Climate Change Science Program (CCSP), to coordinate and provide direction to US research efforts in the areas of climate and global change. These efforts include the US Global Change Research Program (USGCRP), which began as a Presidential initiative in 1989 and was codified by Congress in the Global Change Research Act of 1990 (P.L. 101-606), and the Climate Change Research Initiative (CCRI), which was announced by the President in June 2001 to reduce significant uncertainties in climate science, improve global climate observing systems, and develop resources to support policy- and decisionmaking. Departments and agencies of the US Government that participate in the CCSP include the Departments of

Agriculture, Commerce (the National Oceanic and Atmospheric Administration and the National Institute of Science and Technology), Defense, Energy, Health and Human Services, Interior (US Geological Survey), State, and Transportation; the US Environmental Protection Agency; the National Aeronautics and Space Administration; the National Science Foundation; and the Smithsonian Institution. The Office of Science and Technology Policy, the Council on Environmental Quality, and the Office of Management and Budget provide oversight on behalf of the Executive Office of the President.

The CCRI provides a distinct focus to the overall research program. This focus is defined by a set of uncertainties about the global climate system that have been identified by policymakers and analyzed by the NRC (NRC, 2001a). Areas addressed in the NRC report include climate observations, aerosols, North American carbon sources and sinks, climate feedbacks and modeling, scenarios of human-induced forcing, and development of methodologies for risk management. The CCRI is described more completely in Part I of this draft strategic plan.

The CCRI accelerates key areas of research that have been under development over the past thirteen years in the USGCRP. Over this period, the United States has made a large scientific investment—totaling almost $20 billion—in the areas of climate change and global change research. With these resources, research programs supported by the agencies that participate in the USGCRP, in collaboration with several other national and international science programs, have mounted extensive space-based, surface, and *in situ* (at fixed sites) systems for global observations and monitoring of climate and ecosystem variables; have documented and characterized several important aspects of the sources, sinks, abundances, and lifetimes of greenhouse gases; have begun to address the complex issues surrounding various aerosol species that may significantly influence climate; have advanced our understanding of global water and carbon cycles (but with major remaining uncertainties); and have developed several approaches to computer modeling of global climate. The program has been a comprehensive, interagency collaboration that has facilitated scientific discovery. Program results have revealed and addressed many of the complex interactions of climate and other environmental systems, and have started to lay the foundation for understanding the relationships between natural variability and human activities that may contribute to change. US researchers have developed fundamental insights into how the climate and Earth system functions: insights that are incorporated into advanced models throughout the world. The USGCRP is described more completely in Part II of this draft strategic plan.

CCSP's management will balance the CCRI's near-term focus on climate change with the USGCRP's breadth, creating a program that both accelerates development of answers to scientific aspects of key climate policy issues and supports advances in knowledge of the physical, biological, and chemical processes that influence the Earth system. This breadth is required to continue improving our understanding of the complex interrelationships among a broad set of systems that regulate climate and the global environment, as described in NRC's seminal report, *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1999a). The *Pathways* report lays out a framework of research questions that has significantly influenced the development of this strategic plan. Other reports issued by several boards, committees, and panels of the NRC have advised the USGCRP on specific aspects of climate and global change research and have influenced specific components of its research strategy. Indeed, the program has benefited from extensive interaction with the NRC, which is responsible for evaluating the USGCRP periodically for scientific merit.

Research carried out under the auspices of the CCSP addresses a diverse set of topics including:

- Improving the understanding of the driving forces of climate and global change, including natural forces such as solar variability and human forces such as changes in land cover and emissions of greenhouse gases and aerosols;
- The atmosphere and its role in integrating climate forcing factors, including the roles of emissions of different atmospheric constituents;
- The climate system, which is regulated by complex interactions among its atmospheric, oceanic, and land surface components; which oscillates on time scales from seasons to decades; and which has experienced rapid and significant levels of change in the past (based on evidence from paleoclimate research);
- Changes in clouds in different parts of the atmosphere and their potential either to dampen or accelerate climate change, and alterations in other aspects of the "water cycle" of evaporation, precipitation, and storage that affect water resources;
- The "carbon cycle," which transfers carbon among different reservoirs in the atmosphere, on land, and in the oceans, and affects the amount of CO_2 emitted from human activities that remains in the atmosphere;
- Natural and managed ecosystems, which can dampen or accelerate forcing of climate change through their regulation of fluxes (flows) of carbon and nitrogen between soils and the atmosphere, and which constitute the Earth's basic life support system and are sensitive to changes in climate, atmospheric, and other conditions;
- The potential impacts of global change on human activities and health, and analysis of different courses of action that are available to manage risks and realize benefits; and
- The potential role of developing and recently-developed technologies in reducing net greenhouse gas emissions in the short and long term, including considerations of costs, effectiveness, and both intended and unintended consequences (in association with the Climate Change Technology Program, which has responsibility for research and development of engineered technologies for reducing and sequestering (storing) greenhouse gas emissions).

The challenge: By investigating a targeted yet comprehensive set of questions, the CCSP seeks to focus attention on key climate change issues that are important for public debate and decisionmaking, while maintaining sufficient breadth to facilitate the discovery of the unexpected. Establishing a careful balance between focus and breadth is essential if scientists are to develop knowledge of the interactions between natural variability and potential human impacts on the Earth system. This is an important management issue for the program and is a prerequisite for making as effective and productive use as possible of the significant resources allocated to this purpose. Establishing this balance, and a rational sequencing of research priorities and potentials, will require input from both decisionmakers and the science community.

3. Guiding Principles for CCSP

To fulfill its mission as the publicly sponsored research program addressing climate change issues for the United States, the CCSP must continuously adhere to three guiding principles that underpin the objectivity, integrity, and usefulness of its research and reporting:

- **The scientific analyses conducted by the CCSP are policy relevant but not policy driven.** CCSP scientific analyses (including measurements, models, projections, and interpretations) are directed toward continually improving our understanding of climate, ecosystems, land use, technological changes, and their interactions. In developing projections of possible future conditions, the CCSP addresses questions in the form of "If…, then…" analyses. Policy and resource management decisions are the responsibility of government officials who must integrate many other considerations with available scientific information.
- **CCSP analyses should specifically evaluate and report uncertainty.** All of science, and all decisionmaking, involves uncertainty. Uncertainty need not be a basis for inaction; however, scientific uncertainty should be carefully described in CCSP reports as an aid to the public and decisionmakers.
- **CCSP analyses, measurements, projections and interpretations should meet two goals: scientific credibility and lucid public communication.** Scientific communications by the CCSP must maintain a high standard of methods, reporting, uncertainty analysis, and peer review. CCSP public reports must be carefully developed to provide objective and useful summaries of findings.

4. The Research Strategy

This draft strategic plan for the CCSP, incorporating both the USGCRP and the CCRI, is built around a carefully constructed set of questions and objectives for each of the major areas of the program. Primary research questions that focus on broad science issues are supported by more detailed questions and objectives that can be addressed in specific research initiatives and projects. For each major question addressed, the strategy includes a very brief description of the state of knowledge, subsidiary questions, descriptions of products and deliverables, information on activities and infrastructure needed to make progress, and the benefits or "payoffs" from research. For each major program area, linkages to important national and international research activities are also described.

The strategy for each major area of the program is described more fully in an accompanying set of white papers, which address these issues in greater depth.

Both the summary and the white papers should be considered as drafts subject to substantial revision through public comment and independent review by the NAS.

Following this introduction, Part I of the plan describes the components of the CCRI. These are organized into three broad programmatic areas:

- Research focused on key climate change uncertainties;
- Climate quality observations, monitoring, and data management; and
- Resources for decision support.

Part II of the plan describes major research questions about how the components of Earth's environmental system function, how the system may change in response to human and natural forcing, and what the implications of these changes may be for a variety of human activities and natural environments and resources. The specific topics addressed include:

- Atmospheric composition;
- Climate variability and change;
- The global water cycle;
- The global carbon cycle;
- Ecosystems;
- Land use and land cover change;
- Human contributions and responses to environmental change; and
- Grand challenges in modeling, observations, and information systems.

Part III of the plan describes communication, cooperation, and management issues that cut across all areas of the program, including:

- Reporting and outreach;
- International research and cooperation; and
- Program management and review.

References:

NRC, 1999a. Committee on Global Change Research, National Research Council, *Global Environmental Change: Research Pathways for the Next Decade* (Washington, DC: National Academy Press).

NRC, 2001a. National Research Council, Committee on the Science of Climate Change, *Climate Change Science: An Analysis of Some Key Questions* (Washington, DC: National Academy Press).

PART I

THE CLIMATE CHANGE RESEARCH INITIATIVE

OVERVIEW OF THE CLIMATE CHANGE RESEARCH INITIATIVE

In May 2001, the Administration requested the National Academy of Sciences (NAS) to review the *Third Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC, 2001) and recommend research priorities to reduce uncertainties in climate science. The resulting report, *Climate Change Science: An Analysis Of Some Key Questions* (NRC, 2001a), includes the following (summarized) recommendations:

- Reduce the range of uncertainty in climate change projections by pursuing major advances in the understanding and modeling of:
    - The factors that determine atmospheric concentrations of greenhouse gases and aerosols; and
    - The so-called "feedbacks" that determine the sensitivity of the climate system to a prescribed increase in greenhouse gases.
- Ensure the existence of a long-term monitoring system that provides a more definitive observational foundation to evaluate decadal- to century-scale changes, including observations of key state variables and more comprehensive regional measurements of climate and greenhouse gases.
- Enhance the research enterprise that seeks to improve our understanding of the interactions between the environment and society, including support of:
    - Interdisciplinary research that couples physical, chemical, biological and human systems;
    - An improved capability to integrate emerging scientific knowledge, and its significant uncertainty, into improved decision support systems; and
    - Research at the regional and sectoral level that promotes analysis of the response of human and natural systems to multiple stresses.

Following this request to the NAS, on June 11, 2001, President Bush announced the establishment of the US Climate Change Research Initiative (CCRI) to study areas of uncertainty and identify priority research areas where investments could make a difference. The President directed the Secretary of Commerce to set priorities for additional investments in climate change research, review such investments, and to improve coordination among federal agencies. He committed resources to build climate observation systems and proposed joint ventures with international partners to develop state-of-the-art climate models to improve our limited understanding of the causes and impacts of climate change.

The CCRI was developed in collaboration with the US agencies involved in climate and global change research, taking into account the NRC recommendations, and is meant to enhance the ongoing research activities of the US Global Change Research Program (USGCRP). The proposed CCRI research initiatives emerged from a common understanding of key research needs, including those priority areas already identified by the USGCRP.

The resulting CCRI represents a focusing of resources and enhanced interagency coordination of ongoing and planned research into those elements of the USGCRP that can best support improved public discussion and decisionmaking in the near term. In particular, the goal of the CCRI is to measurably improve the integration of scientific knowledge, including measures of uncertainty, into effective decision support systems and resources. Whereas the USGCRP represents an important long-term investment, the CCRI programs will produce deliverables useful to policymakers in a short time frame (2-4 years). To meet these goals, the CCRI aims to:

- Supplement ongoing USGCRP elements where additional effort would rapidly lead to critical decision support information;
- Enhance and integrate observation, monitoring, and data management systems to support climate process and trend analyses; and
- Provide structured information that can inform policy and decisionmaking, including the use of best available models to address important uncertainties about climate change and development of the range of plausible scenarios for drivers of climate change.

To be included in the CCRI, a program must both produce significant decision or policy-relevant deliverables within a short timeframe; and contribute substantively to one or more of the following activities:

- Address key and emerging climate change science areas that offer the prospect of significant improvement in understanding of climate change phenomena, and where accelerated development of decision support information is possible.
- Optimize observations, monitoring, and data management systems of "climate quality data" ("Climate quality data" are required for historical perspective, trend analysis, process evaluation, and model development and calibration. These data have particular characteristics including high quality, homogeneity, and continuity; and the availability of full documentation with respect to their technical characteristics).
- Develop decision support resources including scenarios and comparisons; quantification of the sensitivity and uncertainty of the climate system to natural and anthropogenic (human-caused) forcings through the implementation and application of models; and structured information for national, regional, and local discussions about possible global change causes, impacts, benefits, and mitigation and adaptation strategies.

References:

IPCC, 2001. Intergovernmental Panel on Climate Change, *Climate Change 2001*. Third Assessment Report of the IPCC. (Cambridge, United Kingdom, and New York: Cambridge University Press). Includes:

- IPCC, 2001a. *The Scientific Basis*, a contribution of Working Group I.
- IPCC, 2001b. *Impacts, Adaptation, and Vulnerability*, a contribution of Working Group II.

- IPCC, 2001c. *Mitigation*, a contribution of Working Group III.
- IPCC, 2001d. *Synthesis Report*. A Contribution of Working Groups I, II, and III

NRC, 2001a. National Research Council, Committee on the Science of Climate Change, *Climate Change Science: An Analysis of Some Key Questions* (Washington, DC: National Academy Press).

CHAPTER 2

RESEARCH FOCUSED ON KEY CLIMATE CHANGE UNCERTAINTIES

This chapter's contents…

The Climate Change Research Initiative (CCRI) will address key and emerging climate change science areas that offer the prospect of significant improvement in understanding of climate change phenomena, and where accelerated development of decision support information is possible. The purpose of CCRI accelerated science activities is to enhance the ongoing US Global Change Research Program (USGCRP) elements described in Part II where focused effort would rapidly lead to critical decision support information. At the request of the President, the National Research Council (NRC) identified "the areas in the science of climate change where there are the greatest certainties and uncertainties," (NRC, 2001a). This section outlines three key areas where the CCRI will address the specific uncertainties identified by the NRC, including: atmospheric concentrations of aerosols (see also Chapter 5); North American carbon sources and sinks (see also Chapter 9); and climate feedbacks and climate system sensitivities (see also Chapters 5, 6, and 7).

1. What aerosols are contributing factors to climate change and what is their relative contribution to climate change?

Aerosols play a unique role in the Earth's radiation (energy) budget, and scientists believe they play a large part in global and regional climate changes. However, because aerosols have a relatively short atmospheric residence time, have a spatially and temporally heterogeneous (non-uniform) distribution, and include a complex mixture of substances from numerous sources (e.g., black carbon, sulfate), there are substantial uncertainties in quantifying their role.

The Climate Change Science Program (CCSP) plan in Chapter 5 and the National Aerosol-Climate Interactions Program plan (NACIP, 2002) emphasize the importance of characterizing the distribution of all major aerosol species and their spatial and temporal variability, the separate contributions of aerosols from various anthropogenic activities and natural sources, and the processes by which the separate sources are linked to the global distribution of aerosols and their radiative characteristics.

Enhanced aerosol-climate research is needed to deliver focused information within 2-4 years that would be helpful in quantifying the role of aerosols in regional and global climate change in decision-relevant terms. The following research emphases will allow more meaningful assessments and projections, with a focus on decision-relevant products by 2006.

RESEARCH NEEDS

- Strongly intensity efforts to determine the composition of organic aerosols and develop simpler instruments for measurement of carbon-associated aerosols by class.
- Establish realistic aerosol and precursor source-strength estimates for specific aerosol compositions for the industrial era.
- Enhance field and laboratory studies of the processes that influence aerosol distributions and characteristics, including those involved in indirect (e.g., cloud) effects.
- Develop aerosol chemistry/transport models and carry out simulations for aerosol source-strength scenarios.
- Compare simulations of past aerosol compositions to records such as ice, bog, and lake core data.
- Focus on comparing the geographic and height dependence of simulated aerosol distributions and radiative characteristics against field and composition-specific (e.g., polarimetric) satellite data, with an emphasis on regions that can best test the reliability of current model simulations (e.g., using the extensive North American emission data base).
- Emphasize comprehensive climate-response simulations including the direct and indirect effects of aerosols, with an emphasis on placing bounds on the indirect effects and on the degree to which simulations of past conditions match observations.

PRODUCTS AND PAYOFFS

- Improved global aerosol climatology, including regional distribution by major aerosol type (e.g., black carbon) and radiative properties, which will provide updated and more reliable input to climate models.
- Empirically validated assessment of the capabilities of current models to link emissions of aerosols and their precursors to aerosol distributions and the warming/cooling properties of aerosols, which will help quantify the uncertainties in simulating the response of radiative forcing to potential emission changes.
- Improved assessment and attribution of observed climate changes, with better quantitative links between climate change and strong regional forcing, such as aerosols and tropospheric ozone.

- Improved overall assessment of the climate effects of aerosols and clouds, compared to the benchmark of the Intergovernmental Panel on Climate Change (IPCC) *Third Assessment Report* (IPCC, 2001).
- Vital quantitative support for the suite of CCRI "If…, then…" climate scenarios and options that are planned as decision support tools, including better estimates of the uncertainties associated with the scenarios.
- Information on potential options for obtaining changes in climate forcing via changes in the aerosol forcing, which, similar to those for tropospheric ozone, might be achieved more rapidly than by changing carbon dioxide (CO_2) forcing because aerosols have a shorter residence time in the atmosphere.
- Quantitative information on how changes in aerosol-related emissions associated with air quality decisions have and/or will impact the radiative forcing of climate change, thereby allowing multiple issues to be more effectively addressed.

2. What are the magnitudes and distributions of North American carbon sources and sinks, and what are the processes controlling their dynamics?

Intensive research to quantify and explain the processes controlling North America's carbon sources and sinks is a near-term priority. Accelerated research within the overall framework of the North American Carbon Program (NACP) will address fundamental questions relating to the buildup of CO_2 and methane (CH_4) in the atmosphere, and the fraction of fossil-fuel carbon being taken up by North America's ecosystems and coastal oceans.

Investments over the past decade have resulted in an unprecedented opportunity to study the carbon cycle over a scale not previously attempted—that of continents and ocean basins. Observational capabilities such as the US forest and soil inventories, flux and tall tower networks, Atlantic and Pacific ocean time series and ships of opportunity, and vegetation and ocean color remote sensing have all contributed to a better understanding of components of the carbon cycle for North America and adjacent ocean basins. Current estimates of regional distributions of carbon sources and sinks derived from atmospheric and oceanic data and models differ from forest inventory and terrestrial ecosystem model estimates. Scientific understanding has now progressed to the point where targeted investments can yield major returns within five years. The CCRI will accelerate the observational, experimental, analytical, and data management activities needed to address uncertainties, reduce errors, and produce a consistent analysis of carbon sources and sinks for North America.

RESEARCH NEEDS

The integrated NACP requires enhanced observational networks and improved monitoring techniques; studies of key controlling processes and resource management regimes that regulate carbon storage and fluxes; modeling that integrates among atmospheric, land, ocean, and human systems; and periodic reporting. Priorities for an accelerated initial phase are:

- Strengthening existing carbon measurement networks; including augmenting flux and biometric measurements at existing agriculture, rangeland, and forest sites and adding new coastal ocean carbon surveys;
- Developing and improving *in situ* carbon measurement sensors;
- Developing innovative diagnostic modeling frameworks and model-data fusion approaches to assure that data are analyzed promptly and efficiently;
- Optimizing national inventories for carbon accounting;
- Improving databases of fossil fuel use, land use and land cover, and land management; and
- Developing remote sensing technologies for measuring atmospheric CO_2, CH_4, and carbon monoxide and aboveground biomass.

An intensive regional-scale field program is needed and could begin as early as 2004. It will require *in situ* observations and process studies, intensive aircraft and remote sensing surveys, enhanced inventories, and modeling. It is also needed as a test bed for subsequent continent-wide implementation of the NACP. The NACP will leverage existing agency research activities and observational programs, but will require additional targeted investments to achieve the desired near-term results.

PRODUCTS AND PAYOFFS

- A quantitative analysis of North American carbon sources and sinks, describing land, ocean, atmosphere, and human systems, will be delivered. Uncertainties in estimates of carbon sink capacity and longevity will be reduced.
- A prototype *State of North American Carbon Report* will be produced based on a synthesis using existing data and models (2 years); a more comprehensive report, including results from an accelerated field program and integrated carbon models, will also be produced (4 years).
- Demonstration and evaluation of measurement approaches for carbon accounting.

Accelerated research within the NACP will provide near-term information for decision support, scenario analysis, and carbon management. Results of this research will also establish the scientific underpinning needed to evaluate carbon management in US croplands, forests, rangelands, soils, and coastal systems and to support analyses of greenhouse gas trends and net emissions intensity. These results will contribute to decision analysis of the impacts of various resource management policies.

3. How much of the expected climate change is the consequence of feedback processes?

WHAT IS THE CONTRIBUTION OF CLOUDS AND WATER VAPOR FEEDBACKS?

Water plays a key role in the radiative balance of the atmosphere: water vapor is the most important of the greenhouse gases, and clouds (whether liquid or ice) affect both vertical heating profiles and geographic heating patterns. In addition, results from climate models suggest there will be an overall increase in water vapor as the climate warms.

Predictions of climate change vary in large part because of differences in the way that the various feedback processes are represented in the models. The greatest differences are those associated with water vapor and cloud processes. For example, scientists do not know how the amount and distribution of clouds will change, both vertically and horizontally, as the water vapor in the atmosphere changes. More importantly, they do not know how the associated changes in radiative forcing and precipitation will affect climate. The feedback to the Earth's radiative balance and cloud structure from increased upper tropospheric water vapor is potentially quite large and could be positive or negative.

Basic understanding of the processes that control the atmospheric water vapor and clouds must be improved and incorporated into models. Better representation of the distribution of water vapor is critical given its contribution to temperature increases as an active radiative gas, as well as its role in cloud formation. Because the physical processes responsible for the horizontal and vertical transport of water vapor and cloud formation occur at scales that are not resolved by climate models, they must be parameterized (simplified for incorporation in the models). New, integrated, three-dimensional data sets of cloud properties and water vapor will be produced to reduce uncertainties due to the representation of clouds and water vapor in climate models. A combination of these data sets, new observations, and targeted process studies will be developed with a focus on model improvements.

RESEARCH NEEDS

- Combined *in situ* and remotely-sensed measurements of water vapor and radiative properties for process studies of water vapor transport into the upper atmosphere by convection, with emphasis on the tropics.
- Analysis of three-dimensional data on cloud properties and dynamics, cloud radiation, and precipitation processes using a combination of ground-based measurements and satellite remote sensing.
- Tests of cloud parameterizations for General Circulation Models (GCMs) using process-resolving models.

- Tests of cloud parameterizations against observations in the framework of operational regional or global atmospheric circulation models.
- Tests of climate model sensitivity to three-dimensional cloud representation employing cloud-resolving models.

While the studies described here will substantially improve understanding of feedbacks, other studies proposed as part of *A Plan for a New Science Initiative on the Global Water Cycle* (Hornberger et al., 2001) and the CCSP Strategic Plan (see Chapter 7) will be critical to predicting the impact of climate change on precipitation and water availability, for example, determining long-term trends in the global water cycle including the character of hydrologic events and their causes; developing the ability to bridge climate and weather modeling; and determining the relationship between the water cycle and biogeochemical/ecological processes.

PRODUCTS AND PAYOFFS

- Improved estimates of global radiative energy losses arising from water vapor variability in the upper troposphere.
- New, observationally tested cloud parameterizations for GCMs that can help to reduce uncertainties in predictions of climate change related to clouds and water vapor transport.

HOW DO FEEDBACKS IN THE POLAR REGIONS AFFECT CLIMATE CHANGE?

The polar regions, particularly the Arctic, are especially sensitive to changes in climate, and models consistently predict future warming to be much more significant in these regions than elsewhere. This sensitivity arises primarily from the positive albedo (how much radiation is reflected by the surface) feedbacks associated with melting of snow and ice that blanket most of the region, which can as much as triple the amount of absorbed solar radiation. Compounding this sensitivity is the fact that sea ice cover modulates the exchange of heat and moisture between the ocean and atmosphere. The disappearance of insulating sea ice increases the transfer of energy and water vapor from the ocean to the atmosphere, enhancing atmospheric warming. Furthermore, Arctic soils serve as significant reservoirs of CO_2 and CH_4, and warming of the region could result in increased emission of these greenhouse gases, contributing to the carbon cycle in ways that are not yet clear.

In addition to high-latitude precipitation, and freshwater discharge from melting snow and ice, sea ice cover plays a major role in the Atlantic thermohaline circulation (controlled by temperature and salinity variations) in the Arctic, and the formation of Antarctic bottom water in the Southern Hemisphere. These are two dominant factors in ocean circulation that directly influence climate throughout the world. It is unclear how future polar climate changes, in particular changes in sea ice cover, will affect these oceanic drivers of the global climate system. In the case of the Arctic, for example, it is possible that increased surface freshening (reduced salinity) associated with enhanced melting and precipitation may suppress the overturning in the North Atlantic Ocean, which may lead to major abrupt changes in climate, such as has been observed in paleoclimatic data.

Ice on land is of critical importance for climate and sea level. The Greenland and Antarctic ice sheets contain enough ice to raise sea level by more than 70 meters (230 feet). The smaller glaciers and ice caps contain the equivalent of only about 0.5 meters (1.6 feet) of sea level rise, but they are far more susceptible to near-term changes and are disappearing rapidly. While global sea level is currently estimated to be rising at a rate of nearly 2 millimeters (0.08 inches) per year, there is evidence that in the past sea level has risen by as much as 50 millimeters (2 inches) per year in some locations. Such rapid rises, consistent with recently discovered abrupt climate changes, can only be attributed to changes in the Earth's larger ice masses. Given the potential economic consequences of sea level rise, there is a pressing need to understand changes in the amount of ice stored on land, and the mechanisms that drive these changes.

Representation of polar climate in climate models is not as advanced as that of the lower latitudes. This arises in part because of the limited data available for model development, refinement, and validation, and a limited understanding of the processes at work. An enhanced observation system and the use of existing and future satellite data sets should improve the representation of these areas in climate models, which is necessary to accurately predict future climate changes and assess the potential for these changes to be abrupt.

Warming temperatures may also affect Arctic land areas. If continuous permafrost areas become discontinuous and discontinuous areas experience complete summer thawing, the hydrology of northern land areas would be substantially altered. Many of the wetlands, marshes, and perched lakes in the Arctic are underlain by permanent ice. The reduction of this ice would lead to the infiltration of the water into the soil and widespread changes in vegetation patterns. The release of greenhouse gases such as CH_4 associated with wetlands would expand in areas where melt water resulting from deeper and longer thaw periods does not have a natural drainage path to the ocean.

Warming could also lead to changes in the water cycle in polar regions. Reducing the uncertainties in current understanding of the relationships between climate change and Arctic hydrology is critical for evaluating the potential impacts of climate change on Arctic communities and their infrastructure. Further, a better understanding of these relationships may allow the development of monitoring procedures that use changes in the Arctic as a signal of the progress of global climate warming.

RESEARCH NEEDS

- Determination of basin-wide Arctic sea ice thickness, particularly in the marginal seas, for a period sufficient to determine if observed historic changes are present across the basin.
- Modeling of observed sea ice changes to determine the relative role of transport versus net loss.

- Establishing the mass balance and ice dynamic regime of the Thwaites/Pine Island drainage system of the West Antarctic Ice Sheet and assessing its stability through observationally constrained models.
- Assessment of the mass balance of the Greenland ice sheet, its variability, and its potential contributions to near-term sea level rise.
- Measurement of permafrost temperatures and thaw patterns for five years in sufficient detail to establish regional thaw patterns.

PRODUCTS AND PAYOFFS

- Reduced uncertainty in estimates of the future state of the Arctic Ocean, its impact on global climate, and its navigability for strategic and commercial purposes.
- Ability to measure sea surface salinity from space in order to detect equatorward transport of fresh water from the melting of sea ice and its impact on thermohaline circulation.
- Initial assessments of the likelihood of polar changes to contribute to abrupt climate change in the near future.
- More reliable assessment of future sea level changes and the potential for rapid sea level rise (>10 mm/yr), and reduction in the uncertainty of sea level rise estimates for the 21st century.
- Quantification of permafrost contributions to the carbon budget and climate warming.

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CHAPTER 3

CLIMATE QUALITY OBSERVATIONS, MONITORING, AND DATA MANAGEMENT

This chapter's contents…

1. How did the global climate change over the past fifty years and beyond, and what level of confidence do these data provide in attributing change to natural and human causes?
2. What is the current state of the climate, how does it compare with the past, and how can observations be improved to better initialize models for prediction?
3. How real are the differences in surface and tropospheric temperature trends?
4. How do we improve observations of biological and ecological systems to understand their response to climate variability and change?
5. How accessible is the climate record?

The US Climate Change Research Initiative (CCRI) provides resources to develop climate observation systems. It encourages partnerships with developed countries and support for developing countries in order to build a global observing system. A climate observing system must go beyond climate observations themselves to include the processing and support system that leads to reliable and useful products. To be most effective it must also provide critical data for decision support and policymakers in areas such as climate and weather forecasting, human health, energy, environmental monitoring, and natural resource management. The specific emphasis on climate observing and information systems within CCRI will be to document the past, observe the current state, and archive a high quality and consistent record that is accessible to everyone. These objectives are considered through representative research questions.

1. How did the global climate change over the past fifty years and beyond, and what level of confidence do these data provide in attributing change to natural and human causes?

Observations of current and past climates play an important role in improving the characterization of processes in the ocean, atmosphere, land surface, and polar regions, and in validation of climate models. The climate record is a time series of key variables, such as temperature, precipitation, and pressure, at monitoring sites or aggregated at regional and/or local levels. These data are essential input to climate models and therefore key to meeting the complex challenge of predicting future climate. The climate record itself provides valuable information for industrial planning in sectors such as electric utilities, transportation, construction, insurance, and many others. The need for refining, extending (both backwards and forwards), and analyzing the long-term climate record to better discriminate natural variability from human-induced global change is self-evident. Space-based and *in situ* observations, often associated with weather networks, have provided the most important data so far for the detection and attribution of causes of global change. Documentation of decadal to centennial climate changes requires records of much longer duration than available based on modern instrumentation. Therefore, we need a systematic search for, and recovery of, naturally existing proxies (substitutes) for such instrumentation—proxies that reveal the past history over hundreds and thousands of years with adequate quality and temporal resolution.

Many individuals in many countries have gathered climate system variables using many different instrument types during the past 150 years to document climate system variability. In order to document and understand change from a historical perspective, we need to develop global, comprehensive, integrated, quality-controlled databases of climate system variables based on historical or modern measurements, and to provide the user community with open and easy access to these databases. We need to integrate these records as far into the past as is practical to reduce uncertainties in the climate trend estimates of individual parameters. In addition, we can now reanalyze the past states of the climate system using the modern tools of data assimilation within the context of a numerical global circulation model. These model-based reanalyses have proven successful for the atmosphere and are now being explored for the oceans. A strategy for routine reanalysis must be established to exploit the iterative nature of improvements in this process.

Understanding the magnitude and impact of past climate variations and change is key to developing confidence about how climate may change in the future. This requires comprehensive documentation about the full spectrum of climate forcings, feedbacks, and responses, especially over the past century when human influences have been most pronounced. Although the recent Intergovernmental Panel on Climate Change (IPCC) assessment (IPCC, 2001) provides information about climate changes and variations for a variety of variables, more can be done in an organized and timely way to support climate-related policy. Much of this information is not routinely updated and integrated into a clear comprehensive assessment, nor is it combined into a convenient format for policymakers.

RESEARCH NEEDS

- Perform data archaeology and mining for specific climate related events and trends using rehabilitated historical records.
- Begin to reanalyze historical records to improve data fidelity so they are more useful for improved long-term climate records.

PRODUCTS AND PAYOFFS

- Regular ocean and atmosphere reanalyses to assess the state of the climate over the last 50 years and beyond, including a related assessment of data and observations.
- State of the climate reports describing decadal-, centennial-, and millennial-scale changes.
- A statistical characterization of climate system extremes from historical data.

2. What is the current state of the climate, how does it compare with the past, and how can observations be improved to better initialize models for prediction?

The state of the climate is determined from the global climate observing network. This network is also used to examine the current state relative to the past, often in the form of anomalies (differences) relative to a mean state, and to examine long-term trends of climate-sensitive variables, such as sea level rise, air and sea temperatures, sea ice concentration and extent, and upper ocean heat content. The future state of the climate is predicted by starting from the present state of the climate. The importance of observations for producing an accurate assessment of the present state of the climate is recognized through a core objective of the CCRI.

Climate research and monitoring require an integrated strategy of land, ocean, and atmospheric observations, including both *in situ* and remote sensing platforms, modeling, and analysis. An adequate global climate observing system should be made up of instruments on various platforms, including aircraft and satellites, ground stations, ships, buoys, floats, ocean profilers, balloons, flux towers, and samplers. The existing network is in need of repair and maintenance, and many elements must be brought up to modern standards.

One of the more pressing needs from a climate monitoring perspective is the identification and correction of time-dependent data biases in observation systems as early as possible. This is a fundamental aspect of scientific data stewardship. Too often, time-dependent biases have been discovered ten or more years after the fact, often through data archaeology or reprocessing efforts. This degrades the climate record, even if adjustments can be developed to correct the deficiencies, and often requires considerable extra effort. Achieving early detection of time-dependent biases will require new research on the most effective means of finding biases early on. In addition, a system must be put in place so that when biases are found, network operators can be notified and corrective action taken. These biases are sometimes due to sensor degradation, but just as frequently result from changes in algorithms or spatial and temporal sampling methods that at first appear innocuous. All these issues will need to be addressed.

The CCRI will enhance the existing long-term monitoring system with accelerated focused initiatives to provide a more definitive observational foundation for determining the current state of the climate. Many shortcomings of the current climate observing system relate to surface and upper air atmospheric measurements and observations of atmospheric composition, global ocean, land surface, and ice variables. For example, only half of the Global Climate Observing System (GCOS) Upper-Air Network (GUAN), established for climate purposes, has been reporting regularly in its first few years of operation, and the GCOS Surface Network (GSN) for climate has had similarly disappointing results. The ocean is poorly observed below the surface and large parts of the ocean have never been measured in some seasons (such as the Southern Hemisphere oceans in winter). Over land, the great spatial heterogeneity requires extremely detailed measurements and presents a major challenge.

A truly global observing system is only possible through international cooperation and coordination. The United States is an active and leading partner in the development and support of a global observing system that assembles key elements from a number of observing networks under the aegis of appropriate international organizations, in particular the Global Observing Systems (G3OS), which include GCOS, the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS). The full implementation of G3OS will require international coordination and commitment. Components for atmospheric, oceanic, terrestrial, and satellite observations are supported at varying levels depending on scientific priorities, availability of national contributions, and the sophistication of the relevant observing technologies.

Climate prediction systems depend on robust and broad global observations to project the present state of the climate into the future. In addition, observations are used to validate and evaluate model predictions, which leads to model improvement. Key variables, such as sea surface temperature, must be available with sufficient accuracy and resolution for prediction systems to provide maximum benefit.

RESEARCH NEEDS

- For all operational monitoring networks, develop the tools necessary to identify time-dependent biases in the data as close to real-time as possible.
- Evaluate the capacities of existing and planned networks (e.g., G3OS) to recognize changes in extremes and hazards.
- Repair the GCOS Surface Network to improve data reports.
- Improve atmospheric column observations of temperature, humidity, and winds by repairing the GCOS Upper Air Network that collects data, but fails to provide adequate and timely reports.
- Measure emissions, aerosols, and ozone in the Asia Pacific area by adding new Global Atmosphere Watch (GAW) stations. Improve global estimates of atmospheric ozone and carbon by upgrading GAW stations.
- Monitor upper-ocean temperature and salinity structure with additional ocean profiling floats and expendable bathythermographs to observe changes in heat and freshwater content.

- Improve estimates of global sea surface temperature for climate model initialization, as well as regional barometric pressure and surface current velocity for model validation, by completing the global distribution of surface drifting buoys.
- Reduce uncertainty in sea level rise estimates by obtaining absolute positions for sea level stations required for altimeter calibration and detection of long-term trends, and fixing "core network" sea level stations that do not provide data on ocean circulation.
- Monitor the state of the global tropical atmosphere and oceans with instrumented moored buoys for climate prediction and research.
- Improve model-based global air-sea flux estimates with surface flux reference moored buoy sites and Volunteer Observing Ships (which collect routine surface meteorological observations) with instrument upgrades for climate-quality observations.
- Accelerate validation of satellite-based sea ice thickness measurements by enhancing validation-oriented field measurements.

PRODUCTS AND PAYOFFS

- Reduced uncertainty related to time-dependent biases in the climate record.
- Estimates of the number of years a climate record is required at each new US Climate Reference Network station to recognize a climate trend and/or variation.
- Regular reports documenting the present state of the climate system components (i.e., atmospheric composition, climate variability and change, water cycle, carbon cycle, land cover and land use change, and ecosystems) in context with historical data to provide an essential perspective on current trends and variations.
- Integrated estimates for the general user community of the current state of important climate parameters, such as:
    - Atmospheric temperature and water vapor;
    - Sea level rise;
    - The variability of ocean heat content;
    - Surface temperatures; and
    - Sea ice thickness.

3. How real are the differences in surface and tropospheric temperature trends?

A key role for the CCRI's accelerated focus on observing systems is to reduce the significant uncertainties in our understanding of climate change. A crucial issue that remains unresolved relates to the rate of warming in the troposphere compared to the surface during the latter part of the 20th century. Climate model simulations, forced by anthropogenic changes in atmospheric composition, project significant increases in tropospheric temperature that are somewhat larger than the increases near the surface in the tropics. Several analyses of the observational data suggest that the rate of warming at the surface has been at least twice that of the troposphere, especially in the tropics and sub-tropics, since about 1980, and about the same since around 1960. The failure of the troposphere to warm at the same rate as the surface during the last few decades has called into question both our understanding of the causes of any change, in particular the impacts of enhanced greenhouse gas concentrations, and the data used to calculate temperature trends. For these reasons, the IPCC's *Third Assessment Report* (IPCC, 2001) devoted considerable discussion to assessments of both climate model simulations and observational data in order to resolve the apparent differences in the rate of warming projected inaccurately in climate models with those observed in the troposphere and at the surface. Climate models were used to help understand how the surface and tropospheric temperatures may have responded differently to a variety of natural and anthropogenic forcings. Prior to the IPCC report, a panel of the National Research Council (NRC) attempted to reconcile the differences in the observations from satellites, weather balloons, and the near-surface temperature record derived from surface weather stations and ocean ships and buoys (*Reconciling Observations of Global Temperature Change*, NRC, 2000). The IPCC (2001) concluded that it was very likely that there are significantly different trends of temperature at the surface, in the troposphere, and in the stratosphere.

Several new analyses have been completed since the IPCC and NRC reports were published. The differential surface and tropospheric warming remains a complex issue from an observational standpoint. Several independent estimates of tropospheric temperature trends since 1958, based on radiosondes, have yielded quite different results ranging from little or no warming to 0.2ºC per decade. New and updated analyses of the satellite record indicate warming in the troposphere of more than 0.1ºC per decade in one data set, but only a statistically insignificant trend in another, both over the period 1979 to 2001.

Model simulations have been run to interpret the observational data. Coupled climate models with combined anthropogenic and natural forcings have been unable to simulate the large differences in trends reported by several of the observational analyses. The inability to reliably simulate the observed differential warming is due to a combination of model error and missing or inaccurately specified external forcings, e.g., the effects of increased greenhouse gases and stratospheric ozone depletion in the upper troposphere. An alternate explanation assumes that observational errors are not trivially small. The truth could lie somewhere in the middle.

RESEARCH NEEDS

To help resolve this issue that is central to detecting and attributing climate change, and ensure that future monitoring systems deliver data free of time-dependent biases, a focused effort will be made to ensure improved retrospective and prospective atmospheric temperature measurements. This includes:

- Improvements for data and observations
    - More comprehensive information regarding the type of radiosondes used by various countries and how they have changed over the decades.
    - More effort to obtain observations and data from overlapping measurements for the various observing systems (e.g., radiosondes, surface observations, and satellites) when instruments change or there are changes in spatial and temporal sampling.

  - Algorithm adjustments are required for the operational microwave satellite record to ensure continuity between records from adjacent satellites. Attention to calibration issues (including overlap of satellite records) needs to be increased.
  - A closer analysis of the height of the tropopause, which has been measured on radiosondes and more recently on Global Positioning System occultation data, will be useful for understanding both troposphere and stratospheric changes.
  - Updates, adjustments, and the newer versions of data sets for both the satellite-derived and the *in situ* temperature measurements are required to narrow unexplained differences in the data sets.
  - A cost effective means to implement the GCOS climate monitoring principles for satellites and *in situ* systems.

- New modeling simulations
  - Simulation of the spatial and temporal sampling of the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites used to calculate tropospheric and stratospheric temperatures in the historical record.
  - Additional ensemble simulations of the climate of the last 40-50 years from several of the key climate models with the inclusion of both natural and anthropogenic forcings are crucial to trying to explain the observed changes.
  - Analysis of data from model new reanalysis projects will be emphasized to better understand significant time-dependent biases that may have affected the observing system.

PRODUCTS AND PAYOFFS

- An improved international radiosonde network to produce better data sets of upper air temperature and humidity, with special emphasis on the tropics and subtropics where data are most difficult to harmonize with the surface.
- An improved international surface monitoring network using the principles set forth by the NRC (see Chapter 12) for improved data sets for surface temperature, precipitation, and barometric pressure.
- Data to support reduction of climate model uncertainties regarding surface and tropospheric temperature response to a variety of natural and anthropogenic forcings.
- Satellite missions adhering to the GCOS climate monitoring principles for reduced discontinuities in the satellite record.
- Evaluation of biases in the observational records to produce a more consistent climate record.

4. How do we improve observations of biological and ecological systems to understand their response to climate variability and change?

Changes in an environmental variable—most often warming, but also changes in precipitation and air quality—have often been related to observed changes in biological and ecological systems. Several examples were mentioned in the Working Group II section of the IPCC's *Third Assessment Report* (IPCC, 2001), including thawing of permafrost, lengthening of the period of leaf display in mid- and high-latitude ecosystems, poleward shifts of plant and animal species ranges, movement of plant and animal species up elevational gradients, earlier spring flowering of trees, earlier spring emergence of insects, earlier egg-laying in birds, and shifts in a forest-woodland ecotone (the boundary between the forest and the woodland). These changes in ecosystems and organisms are consistent with warming and changes in precipitation, but the possibility remains that the observed biological and ecological changes were caused (in part) by other factors such as biological invasions or human land management. Because of this, the attribution of the causes of biological and ecological changes to climatic change or variability is extremely difficult. Moreover, because many ecosystem-environment interactions play out over long periods—ultimately involving evolutionary changes and adaptations within ecosystems—long periods of study are needed in many cases to draw firm conclusions about relationships between environmental change, effects of that change on biological and ecological systems, and the significance of any observed biological or ecological changes for the functioning of ecosystems.

New research is needed to provide a significantly more complete picture of how biological and ecological systems may have responded to recent climatic change and variability, including possible biological or ecological responses to extreme events. New observational systems will also be needed to appropriately monitor potential future changes in the environment and accompanying biological or ecological changes (if any). A key challenge will be to provide organization, guidance, and synthesis for the emerging field of observed effects of climate change on biological and ecological systems.

The CCRI will initiate studies of early effects and indicator systems across diverse ecosystems and geographic regions. A substantial amount of existing climate and effects data, a variety of monitoring efforts, and comparisons to scenario-based effects studies can be marshaled in this effort. The CCRI will facilitate linked analyses of climatic trends and observed biological and ecological effects by supporting identification of appropriate past and ongoing monitoring efforts, design of new needed monitoring systems, and synthesis of results across ecosystems and regions. Research efforts will target those ecosystems that are subjected to (or may be subject to in the future) the most rapid or extensive environmental changes and/or are most sensitive to possible environmental changes.

RESEARCH NEEDS

Long-term, spatially explicit, and quantitative observations of ecosystem state variables and concomitant environmental variables are needed. Initial activities will focus on:

- Identifying ecosystems that are either sensitive or resilient to environmental change;
- Interfaces between ecosystems (ecotones), which are governed by and presumably most sensitive to environmental factors;
- Ecosystems experiencing the most rapid environmental changes today, or that may experience the most rapid changes in the near future, such as ecosystems located at high latitudes and high elevations. Coastal ecosystems should also be a priority because of ongoing sea level rise and intensive human uses;
- Concurrent trends in other factors, such as population and land use change; and
- Validation of the results of impacts studies done with the climate change scenarios over the near term or for small amounts of warming using observed climate and impact data.

PRODUCTS AND PAYOFFS

- A comprehensive report describing ecosystems that will potentially be affected by environmental change, especially climatic changes, as well as those that are resilient to change, and a detailed map of the geographic extent of those ecosystems.
- Observational design criteria related to risk assessment and identification of causes of changes in distribution of pests and pathogens (e.g., climatic change interacting with weather).
- Global, synoptic observational data products from satellite remote sensing documenting changes in biomass, albedo, leaf area and duration, and terrestrial and marine ecosystem composition for use in Geographic Information System (GIS)-based decision support systems.
- Design criteria for remote and *in situ* observations of biological and ecological systems that will help determine whether any observed ecological changes are attributable to global change.
- Links to biological and ecological datasets from monitoring programs, including those from remote sensing platforms.
- Annual reports on observed ecosystem changes attributable (or attributed) to global change.
- Requirements for a system for observing interactions of climate and ecosystems.
- Climate data at appropriate temporal and spatial scales for impact studies.
- Links to datasets documenting trends in other variables, such as population and land use change, relevant to observed climate impacts.

The payoff from the initial products will be information needed to establish effective networks of observing systems directed at identifying, quantifying, and explaining resilience as well as changes in ecosystems resulting from global changes. The information will be used to design appropriate observing systems, which will in turn be needed to implement effective observational systems that may be able to provide key information to decisionmakers and scientists about effects of global change on ecosystems. It will begin to lay the foundation for future analyses of how ecosystem responses in turn cause feedbacks to the climate system.

5. How accessible is the climate record?

The key priority for scientists and decisionmakers is access to the climate record. Scientists studying Earth system variability and change must have an accurate, uninterrupted series of key geophysical climate data records. These data records stretch from paleoclimatic proxy data to measurements from today's observation systems. To provide maximum accessibility, scientific quality assurance, and ease of utility of these key products spanning multiple decades, multiple projects, and multiple government agencies now and in the future is key to the success of understanding and providing the science-based information that is the mandate of the Climate Change Science Program (CCSP).

The provision of data and information in forms needed for cross-disciplinary analysis and projection remains a challenge. Some science questions by their very nature pose needs for the concerted gathering of "bundles" of data, information, and services. Throughout this document, which discusses key and emerging science questions, are specific needs for data sets related to large regional problems, large-impact processes, field campaigns, and analyses that combine *in situ* data, remotely sensed data, process studies, and model output. Integrated data set needs are most effectively answered by community-aggregated data, information, tools, and services dedicated to removing usage barriers, such as temporal and spatial differences.

It is now well known that for climate change research, life-cycle data management—including long-term stewardship—must be considered and planned throughout the entire design, implementation, and life cycle of any observing system. Long-term stewardship includes the long-term preservation of the scientific integrity of the data, monitoring and improving data quality, significantly enhancing access to the data, and extracting further knowledge from the data.

A continuous and complete data record for the observational instrument series or network of stations, including history and metadata (information about the data set), provides the details necessary to support a high degree of confidence in the data employed by the scientific research community in forecast and prediction modeling. In turn, this provides decisionmakers with a high degree of confidence when making environmental and economic policy decisions. In addition, data collected as part of process studies is of great value for improving the fidelity of climate models. Consequently, data providers must assemble, document, and subject these data to high quality standards. Such data should be assembled, processed, integrated, and made openly accessible to the research community. Adequate support for safeguarding by federal depository centers will ensure long-term access.

As we move to implement the CCRI, achieving integrated (land, atmosphere, and ocean) data access will require multidisciplinary analysis of data and information to an extent never before attempted. This includes the analysis of interlinked environmental changes that occur on multiple temporal and spatial scales, which is very challenging both technically and intellectually. For example, many types of satellite and *in situ* observations at multiple scales need to be integrated with models, and the results presented in understandable ways to all levels of the research community, decisionmakers, and the public. In addition, very large volumes of data from a wide variety of sources, and results from many different investigations, need to be readily accessible to scientists and other stakeholders in usable forms.

The success of every element in this plan requires accessible, high-quality, interoperable, and thus easily usable, data in order to reduce the uncertainties in our models, and to be able to understand and characterize the processes and feedbacks when addressing the key questions about atmospheric composition, the carbon and water cycles, land use and land cover, ecosystems, and climate variability and change. The data and information must be presented in a way that facilitates its use in scenario development, studies of human contributions and responses to environmental change, and decision support tools. The accessibility of quality data will be a focus of CCRI, and its success will rely on partnerships with existing national and international efforts currently focusing on these issues (i.e., G3OS, Ocean.US, the International Geosphere-Biosphere Programme (IGBP), and the World Climate Research Programme (WCRP)).

RESEARCH NEEDS

- Establish a framework for providers' data, quality control, metadata documentation standards, and formatting policies that will make possible the combined use of targeted data products important to high-priority areas of research. This will also encourage provision of common tools and services in the public and private sectors.
- Provide defined key elements for data management planning. A data management plan should be required as part of any new observational or monitoring activity. This plan needs to address the data life cycle, with special focus on data access and archiving.
- Develop a cross-agency mechanism to coordinate implementation of the climate observing system, identify where efficiencies could be gained, and support leveraged activities.
- Access and document the information architectures, systems, and data products produced and managed to provide an overall architecture diagram or catalog of information systems and services. This will enable effective management of, and facilitate access to, the distributed climate-related data and information gathered by federal and non-federal activities. This will lead to a harmonized evolution of existing distributed systems and services for utilization of data and information in analyses and models.

PRODUCTS AND PAYOFFS

- Coordinated climate observing instrument series and monitoring networks, administered by different agencies, maximizing the use and utility of the data.
- Mechanisms to encourage and permit regional, project, and commercial observational networks to make their data available for analysis and model validation and to receive feedback on data quality and utility of their data.
- Data from future monitoring and observing networks will be more readily added to the climate record, and digested into the information available for decisionmakers.
- Coordinated implementation of the climate observing system both at the national and international level.
- Provision of information portals where decisionmakers can locate the data, information, models, analysis tools, and other services that are identified as potentially important to their needs by the CCSP research community.

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CHAPTER 4

DECISION SUPPORT RESOURCES

This chapter's contents…

1. Evaluations and syntheses for policy analysis and operational resource management
2. Analytical techniques for serving decision need
3. Applied climate modeling
4. Resources for risk analysis and decisionmaking under uncertainty

The Climate Change Research Initiative (CCRI) will synthesize the results of the research conducted by the Climate Change Science Program (CCSP) to present critical information to decisionmakers and resource managers both within and outside of the US Government. Decisionmakers, as defined here, engage in the development of national policy such as setting national goals for greenhouse gas emissions and negotiating with other countries over international agreements. Along with resource managers in different regions and sectors, decisionmakers also are engaged in policy, planning, and operational decisionmaking issues related to the management and allocation of natural resources and the associated physical infrastructure. The science and decision support activities sponsored by the CCSP are designed to provide critical information about a number of the decisions and natural resource issues affected by climate variability and change. One major key element of the CCRI is the ongoing engagement of scientists, decisionmakers, resource managers, and other stakeholders in identifying issues and questions, and providing data and products that include characterizations of uncertainties and the level of confidence associated with this information.

One of the principal motivations behind the CCRI is enhancing the CCSP commitment to synthesizing scientific results and producing decision support resources responsive to national and regional needs. Decision support resources include a wide variety of mechanisms for creating and supporting a dialogue between scientists and decisionmakers to identify issues and questions of concern, and for framing the research agenda needed to answer the questions. They also include a variety of analytical techniques, including historical data analysis, scenarios, and applied climate modeling, that serve decisionmakers, and product development that arises from the strong interaction between the science and decisionmaking needs.

One component of the CCRI will focus on national-level challenges associated closely with the mitigation issues (improving understanding of the costs and benefits of particular strategies for reducing emissions) associated with long-term global climate change. In a parallel effort, the CCRI will accelerate the development of a structure and process for integrating science with decision processes to assist the development of regional and sectoral adaptation responses (actions to reduce vulnerability, seize opportunities, and enhance resilience) to variability and long-term changes in climate. These two efforts complement and reinforce each other with lessons learned about how the process of synthesizing and analyzing scientific information can inform policy and operational decisions. Although the actual process of making policy and resource management decisions should remain entirely separate from the research function, the establishment of a new class of working relationships will ensure that the sponsored research is well informed by an understanding of what information is timely and useful for decisionmakers, resource managers, and other stakeholders. Research will provide a continually stronger foundation to help decisionmakers evaluate the suite of alternative policy options and operational strategies.

This section of the Strategic Plan describes activities intended to initiate innovation in decision support resources that are particularly relevant to the driving forces and effects of climate change at a national and regional level, recognizing the need for continued progress in basic climate science questions. Because climate is not the only variable component in the decisionmaking process, and societal challenges rarely reveal themselves as neat, single-issue topics, this initial focus is nested within a commitment to integrate across temporal scales, spatial scales, and multiple effects (both positive and negative).

The following sections lay the groundwork for building decision support into the CCSP: the incorporation of science-based decision support research including scenario development; applied climate modeling; and the development and application of improved methods for dealing with scientific uncertainty in the decision process.

1. Evaluations and syntheses for policy analysis and operational resource management

For the last decade, the primary focus of the development of climate change science information at the national level has been in response to the debate on energy policy. At issue was whether human-induced climate change could be so significant as to require immediate and steep reductions in fossil fuel emissions. The main constraint on any such reductions has been the desire to maintain modern living standards by preserving the ability to serve the energy needs of a growing economy with diverse economic sectors in the context of evolving societal values. Issues central to the debate have included distinguishing between natural climate variability and human-induced climate change; the adequacy of observations to determine climate variability and change; the reliability of climate modeling; and the prediction of the immediate costs and possible benefits of mitigation options.

The CCRI will initiate a process to identify policy decisions that should influence the focus of climate change research programs. It will be important to consider likely future policy decisions, because there can be lag time in the delivery of research results. This process will include meetings with current and past decisionmakers. The resulting articulation of potential policy questions will serve as a foundation for the subsequent decision support activities. One goal is to expand the range of decisions from an emphasis primarily on energy policy to a broader agenda that includes greenhouse gases and pollution other than carbon dioxide (CO_2), emissions that result from land use (particularly deforestation and the cultivation of certain crops), and the management of other resources and decisions at a regional level. Examples of other broad policy arenas that require science-based climate information are agriculture, water resources, air quality, forestry, wildfire management, public health, and foreign aid.

The importance of climate change and variability lies in its impacts on natural resources, the economy, human health, and ecosystem sustainability. Some regions, sectors, and assets will be more vulnerable and some more resilient to climate variability and change, and taking steps to seize opportunities or identify particularly vulnerable assets and enhance their resilience will help ensure economic productivity and the well being of citizens and the environment. Decisionmakers who operate in the resource management arena are confronted with an array of influences that impact their decisions, and these must be considered in work done under the CCRI. Climate variability and change, demographic change, land use, laws, and public values are only a few of the inputs into their decision processes. In addition, they are required to make decisions on a range of time scales from a day-to-day operational perspective to a longer-term planning perspective.

The climate science issues that have emerged over the last decade that have been raised by these decisionmakers include concerns about contradictions in, and the coarse spatial scale of, information on climate change from global climate models, and the lack of availability of useful and effective climate observations and products for use in their decision processes. Regional- and local-scale analyses of potential climate impacts are limited by the fact that currently available model projections are not reliable at the smaller scales that are required for these analyses. However, regional- and sectoral- scale climate diagnostics and analyses, in cases where they prove to be accurate, can be and have been used effectively in regional decisionmaking contexts, creating an important demand for the provision of useful observational products and data.

One goal of the decision-support efforts of the CCRI is to identify national-level decisions and to use that list to develop decision support activities as well as to help prioritize climate change research. A second goal is to articulate and expand upon our understanding of the role of climate in human affairs such that science-based information can be synthesized, analyzed, and incorporated meaningfully into policy analysis and operational resource management.

Research projects that contribute to decision support will be supported under CCSP. These research projects benefit from the results of the US Global Change Research Program (USGCRP) research efforts discussed in Chapters 5-11. Links will also be made to the reporting and outreach activities

(Chapter 13) and to international research cooperation (Chapter 14). The CCRI will provide a means for synthesizing, analyzing, and evaluating scientific results that will provide supporting information for policymaking and operational resource management processes.

IDENTIFICATION OF DECISION ISSUES AT THE NATIONAL LEVEL

The type of issues requiring decisions at the national level for which information about long-term global climate change is relevant has evolved considerably in recent years. The CCRI will attempt to establish mechanisms to foster a new class of working relationships to ensure that relevant issues are identified, articulated, and communicated to the research community. This task is understood to be a particularly challenging one, where decisions for which science-based information will be useful will be a subset of a broader range of decisions. Accomplishing a productive and effective relationship among researchers, federal research managers, and policy specialists will require new working arrangements. The CCRI will devote attention to the type of institutional changes necessary to forge effective interaction between research processes and policy development.

For policy development related to mitigation, it will be difficult to generate a true representation of salient decisions. Over the last several years there has been an interest in issues as diverse as estimating the costs and impacts of concentration paths over time; costs and benefits of various stabilized atmospheric concentrations; priorities for technology R&D; evaluating regulatory instruments; analyzing uncertainties; analyzing the role of the United States with respect to the rest of the world; analyzing which gases to control and how to trade off certain greenhouse gases versus others; the connection of greenhouse gas emissions to other pollutants, such as aerosols; assessing impacts from possible climate change at a local level; high-consequence but low-probability events; and others.

Stakeholder interaction will be essential to the task of identifying decision issues at the national level, but managing this interaction will be a different type of experience than it has been at the regional level, where researchers have spent the last several years learning how to interact with resource managers and local planners. Certain sectors, such as energy, technology development, or international disaster management, are obvious candidates for exploring how to build improved stakeholder relationships. Many of the decision alternatives in these particular areas will be amenable to the "If…, then…" paradigm that uses the scenarios described in the next section.

DECISION SUPPORT RESOURCES FOR REGIONAL RESOURCE MANAGEMENT

The general approach for accelerating and enhancing decision support for regional resource management will be based on the following framework:

- Identification of regions, sectors, and decisionmakers that would most benefit from improved global change information.
- Development of indicators for assessing vulnerability and/or opportunities.
- Research to improve knowledge of global and regional changes.

- Development of data, information, analytic resources, and models to facilitate risk assessment given remaining uncertainties.
- Investigation of how to disseminate information and assist users in evaluating options.
- Promotion of sustained interactions between the scientific community and stakeholders to judiciously apply such knowledge to inform decisionmaking.

Resource managers are challenged every day by the need to make decisions despite the existence of scientific uncertainties and the inability of scientists to begin to make absolute predictions about future outcomes. Through the USGCRP, a sustained relationship between investigators and decisionmakers has been nurtured to create the basis for developing a shared understanding of the general potential for and nature of risk and benefit, and extracting from scientific findings the information to begin to support decisionmaking within a context of managing risk. Through regional and sector-specific research, investigators will continue to work closely with decisionmakers and resource managers to identify the level of certainty required for different decision contexts, and mechanisms for best communicating the uncertainties, which may include acknowledging that it may not be possible to provide meaningful information at the required level of certainty.

A major value of the regional resource management component is in deriving insights from “lessons learned” about how science can be integrated effectively into the operational decisionmaking process and, to the extent possible, into policy analysis and development. This activity involves the analysis of information from multiple disciplines—including the social and economic areas—to address the specific questions being asked by resource managers and other stakeholders. It also includes an analysis of adaptation options to improve society’s ability to respond effectively to risks and opportunities as they emerge. Based on the regional and sector-specific research that has been conducted over the last decade, preliminary target areas for accelerated research that will be considered include air quality; water availability and quality; forest and wildfire management; drought; and public health.

PRODUCTS AND PAYOFFS

- Further development of formal mechanisms to establish and perpetuate working relationships between the research and decisionmaker communities to ensure that research and assessments will address the specific issues of concern to the decisionmakers. The decisionmaker/researcher interaction will be evaluated and documented and used to identify needed improvements in decision support resources.
- Selection of a set of potential policy questions that require information support from the climate change community through a stakeholder/scientist interactive dialogue. These issues and the resulting policy-relevant science questions will influence the development of scenarios (6 months).
- Establishment of a consultative process between agency managers, investigators, and key partners in one or more of the target areas to identify the key resource management problems, resulting research questions, needed observational data, and appropriate methods of communicating and using scientific uncertainty in the decisionmaking context.

- Analysis of historical records in the target areas to gain a better understanding of past and current climate, as well as future climate, in order to provide services and design infrastructure to more effectively adapt to future changes.

2. Analytical techniques for serving decision need

LINKING RESEARCH TO DECISIONMAKING

"Decision support" refers to the provision of timely and useful information that addresses specific questions being asked by a decisionmaker. It could be a question that is pertinent to any of a full range of issues related to climate change, including adaptation, the management of resources in the face of scientific uncertainty, mitigation, or technology development. For example, a national-scale question addressing emissions might be framed as, "What are the economic consequences—costs and benefits—associated with the adoption of an emissions goal framed in terms of percentage reductions against a specified base year emissions level?" Alternatively, it might be framed on the regional or local scale to address adaptation questions, such as: "How could water resources be managed if winter snow melt shifts to an earlier time of year?"

Techniques that serve to articulate research findings in ways that resonate with decisionmakers and that incorporate parameters important from their perspective are a key part of the CCRI commitment to build and sustain productive, appropriate interaction between research and action. A variety of resources and approaches are being used to explore the possible range of consequences of climate change, including historical records; integrated assessment models; synthesis, analysis, and presentation of scientific conclusions for incorporation into existing decisionmaking frameworks; communication and outreach processes to policymakers; and sensitivity and "If…, then…" analyses. Although all of these contain sometimes profound uncertainties, their use can provide existing information for decisionmakers, resource managers, and other stakeholders.

METHODS FOR ANALYZING CLIMATE IMPACTS

A variety of methods are available for illustrating and analyzing how fluctuations in climate influence social, economic, and ecological systems, including:

- **Historic records.** Data and records from the past provide an essential perspective on how changes in climate affect human and natural systems. Analyzing variations such as warming; increases in precipitation; decade-long droughts; and reductions in the extent of snow cover, and their effects on human and natural systems, provides important insights into how vulnerable or resilient these systems may be in the future. The need for improved information on such variations, particularly at regional and local scales, is one of the highest priorities for users of climate information.
- **Sensitivity analyses.** "If…, then…" and sensitivity analyses will also be used to determine under what conditions and to what degree a system is sensitive to change. Sensitivity analyses help to identify the degree of climate change that would cause

significant impacts to natural and human systems, i.e., how vulnerable and adaptable these systems are. Such analyses are not predictions that such changes will, in fact, occur. Rather, they examine what the implications would be if the specified changes did occur. For example, an analyst might ask, "How much would temperature have to rise to cause a specified impact?"

- **Climate projections.** Climate model projections are another tool for understanding what future climate might be like, to the extent of their scientific credibility and our ability to develop quantitative statements about levels of confidence. Once again, these projections will not be viewed as specific predictions or forecasts of future outcomes, but rather as probabilistic alternative futures that "paint a picture" of what might happen under particular assumptions. They provide a starting point for investigating questions about an uncertain future and for visualizing alternative futures in concrete and human terms. Using scenarios helps to identify vulnerabilities and opportunities, and to explore potential response strategies. However, it is important to recognize that in some cases the state of knowledge about potential consequences of climate change may not be sufficient to support any climate impacts modeling. Regional- and local-scale analyses of potential climate impacts are limited by the fact that currently available model projections of shorter-term trends over the smaller scales that are required for these analyses are much less reliable than the model projections of continental-scale and century-long trends that are currently available. In fact, different model projections are at times contradictory, a symptom of the unreliability of regional-scale projections at this time.
- **Consultative processes and conceptual models.** Briefings, forums, workshops, and other forms of engagement between researchers and stakeholders, when managed and sustained, have the effect of eliciting information over time and through iteration that enrich the research and increase the likelihood that research will contribute to improved decisionmaking. Methods and products that are "co-produced" have the highest likelihood of application. Products such as "decision calendars" that integrate the worldview of resource managers in a given sector with the natural cycle of the climate system have served to enlighten both researchers and resource managers. At the same time, research must be independent of particular policy agendas in order to remain free of bias.
- **Integrated quantitative and qualitative information for refined decision products.** Climate information can be incorporated into existing sector-based (e.g., agriculture, reservoir management, wildfire management, etc.) and policy analysis/management models such that the potential effects on productivity or particular outcomes can be analyzed. Use of existing models sensitive to institutional realities offers the advantage of identifying moments where climate information is most relevant to planning, budget cycles, early warning systems, or profit maximization and efficient use of resources. Results that offer outcomes expressed in terms of probabilistic distributions of expected events can contribute to decision analysis and assessment of risk in particular settings.

One of the most productive areas for combined research and assessment activities is in building frameworks that integrate component models in response to a well-articulated decision need or "problem" focus. Knowing in advance the concerns of relevant decisionmakers, researchers and other professionals are beginning to refine the techniques necessary to customize model-based and statistical climate information; tailor outputs for consistency with hydrologic, ecological, or other information; and analyze outcomes within the parameters of decision need. Advances made in these types of aggregations of systems would afford new insights into understanding thresholds relevant to climate that are unique to various sectors. These activities also hold important potential for advancing analysis of multi-factor stresses, and can be applied to questions surrounding water resources, wildfire and agricultural management, and carbon sequestration strategies.

SCENARIO DEVELOPMENT

For many decision alternatives, an "If…, then…" analysis enabled by scenarios can be performed that provides information to a decisionmaker. Assuming a particular action is taken, the analysis predicts the consequences of that action. Scenarios play a key role in the decisionmaking process by providing the opportunity to explore options against a variety of alternative possible backgrounds. The term "scenario," as used here, refers to any description of the world as it might evolve or be made to evolve in response to decisions. The goal of the CCRI scenarios activity is to develop, maintain, and enhance the capability to answer "If…, then…" questions relevant to the full range of climate change decisionmaking, from the management of resources to the formation of national and international policy. The activity will seek to ensure that a balanced approach is taken that maintains objectivity and avoids focusing on "worst-case analysis" alone.

Scenarios provide a vehicle for *posing and analyzing* questions, for example, "What if the United States adopts an emissions goal?" The question as framed above, however, is insufficiently specified. It lacks detail. For example, no mechanism by which the goal might be attained is specified. Further, there is no description of areas of concern, such as the effectiveness of the limitations in environmental terms; the impact on jobs, Gross Domestic Product, the economic health of important economic sectors and regions of the country, and international trade; the implications for energy and national security; and the effects on ecosystem goods and services. Decisionmakers and stakeholders, through interactions with researchers, can provide the necessary level of specificity and may together create a better list than either could separately generate. All scenarios start with information originating outside the system in question, contain some description of the system of interest, and provide a mechanism for evaluating a variety of approaches that may be employed.

Scenario development techniques abound, and range from qualitative approaches to formal computer models. Models link statements about key external factors, such as population growth and migration; the abundance and availability of resources; market structure; energy cost and use; international trade; and technology deployment, through algorithms that attempt to capture their relationships. Some scenario development techniques may combine both qualitative and modeling approaches, similar to gaming exercises that provide computer models for role-playing. The Intergovernmental Panel on Climate Change (IPCC) has made extensive use of scenarios to drive climate models, although the model outputs have seen limited use in studying the impacts of climate change. Other qualitative and quantitative scenarios have been used extensively in controversial assessments of the potential consequences of climate change for particular sectors and regions in the United States. The development of scenarios also makes possible potentially fruitful communications with other important policy realms such as the National Climate Change Technology Initiative (NCCTI).

RESEARCH APPROACHES

Research is essential to every part of the scenario process. Scenarios will require the acquisition and synthesis of knowledge about factors that lie both within and outside of the processes in question, including economic growth; energy supply and demand; land use; agricultural practices; ecosystem characterization; and the characterization of the cryosphere, hydrosphere, ocean, and atmosphere. Models of such processes can be extremely detailed, with some requiring extensive time (weeks) on the fastest available computers. It is important to realize that the nature of the question being asked by the decisionmaker, as well as the level of scientific certainty required, influence the construction of the scenario and the type of modeling undertaken.

CCRI scenario development will go beyond past scenario activities such as those of the IPCC. Decisionmakers, resource managers, and other stakeholders will be engaged to help identify the types of scenarios that could be used to provide them with timely and useful information. The CCRI will develop logical and internally consistent scenarios with input from the full range of relevant stakeholders, which potentially include environmental non-governmental organizations (NGOs), industry representatives, natural resource managers, government agencies, and research scientists. It will undertake independent analysis to extract up-to-date information on projections for key variables (e.g., demography; technology characteristics and costs; and economic growth and characteristics) and the relationship of key driving forces to environmental change (e.g., land use and land cover) and adaptive capacity. The CCRI will coordinate its scenario development plans with the new IPCC scenario efforts. The IPCC may be interested in adopting some of the CCRI scenarios or combining CCRI and IPCC efforts.

PRODUCTS AND PAYOFFS

- A new stakeholder-oriented process for ongoing identification of questions relevant to decisionmakers, and scenarios that could be used to address these questions, will be in place. This component of the program will incorporate the most up-to-date scientific information about socio-economic, climatic, and environmental factors. Modeling, integrated analysis, and reporting of results will also be supported.
- A specific set of scenarios that can be used to address relevant policy and resource management questions—at the national, regional, and sectoral levels—will be developed in collaboration with stakeholders (2 years). The scenarios will be used as

input to integrated assessment and other region- and sector-specific impacts models, which will evaluate the consequences of the different scenarios. Reports summarizing insights relevant to the questions posed by the decisionmakers and regional/sectoral resource managers, along with an analysis of the uncertainty, will be written (2 years). Additional reports will summarize the results of more extensive efforts using integrated assessment models linked with natural resource decisionmaking models and the implications for development of risk-management options for resource management and national climate change policy (4 years). A final report on the state of the art of scenarios will be written.

- Integrated assessment models will be improved both in skill and breadth of coverage in order to realistically represent an increased number of actions and consequences important to the decision process.

3. Applied climate modeling

INTRODUCTION

Climate models have been a central part of the US climate program since the 1970's. Models are an essential tool for synthesizing observations, theory, and experimental results to investigate how the Earth system works and how it is affected by human activities. Such models can be used in both a retrospective sense, to test the accuracy of modeled changes in Earth system forcing and response by comparing model results with observations of past change, and in a prognostic sense, for calculating the response of the Earth system to projected future forcing. For the CCSP, we need to consider a subset of the broad domain of climate modeling, in particular those specific tasks that can provide near-term information products to inform management and policy decisions involving climate. This is the area of Applied Climate Modeling. It provides the means for translating the scenarios described in the preceding section into the decision support resources.

There are a number of obstacles facing the application of the best of US capability in climate science to these critical applied modeling issues. The NRC (2001b) found that when comparing US and European high-end modeling, the United States is still lagging in its ability to rapidly produce accurate high-resolution model runs. In addition, there is a need to increase confidence in model results and expand their immediate utility for decision support. These considerations prompt several priority directions for Applied Climate Modeling.

IDENTIFY, QUANTIFY AND SYSTEMATICALLY REDUCE UNCERTAINTY IN CLIMATE MODEL PROJECTIONS

Sensitivity Comparisons

Climate sensitivity is a measure of the climate's response to a unit change in radiative forcing due, for example, to changing atmospheric concentrations of greenhouse gases. It accounts for a major part of the uncertainties in climate projections. The current crop of world-class climate models exhibits an unacceptably large range in climate sensitivity. The major US models that have been used for IPCC scenario assessments—the Community Climate System Model (CCSM), operated at the National Center for Atmospheric Research, and the model developed at the Geophysical Fluid Dynamics Laboratory (GFDL)—lie close to the opposite ends of this range, making them ideal resources for investigating the processes and assumptions responsible for uncertainty in sensitivity.

All current climate models fail to adequately simulate several climate system processes and their feedbacks. One example of such a process is ocean mixing, which to a large degree controls the rate of projected global warming. Atmospheric convection, hydrologic processes, and representation of clouds, all of which strongly influence the magnitude and geographical distributions of global warming, are also poorly simulated. These deficiencies are thought to be related to the large range of climate sensitivity and contribute significantly to model uncertainties. High-priority research will focus on representations in models of the relevant physical feedback processes, using available observational data and, where required, new field observations. This work will enable focused model comparisons to understand the reasons for differences in climate sensitivities. Products will include new knowledge about important climate feedback processes and their improved representation in climate models, potentially leading to a significant reduction in known uncertainties in climate projections. Particular attention will be devoted to cloud/water vapor processes, as described in Chapter 2 (see also Chapter 6).

Characterize and Reduce Key Uncertainties

It will be important to identify the one or two largest sources of uncertainty in feedback processes currently represented in climate models, determine the causes of the uncertainty, and improve the physical representation of those processes in the models. Comparing model simulations and observations indicates that the major problems are generic, affecting all climate models. Climate Process Teams (CPT), a new approach to focused research designed to more rapidly reduce known uncertainties in climate model projections, will conduct the research. The teams of climate process researchers, observing system specialists, and modelers will work in partnership with multiple modeling centers (see also Chapter 6).

Enhance Model Credibility through a Formal Program of Model Testing

In moving towards the development of a more operational applied climate modeling capability, it is necessary that models be put through a more rigorous program of testing than has been the case to date. For weather prediction, such testing is straightforward: information on the accuracy of the forecast is immediately available, and statistics can be generated. For applied climate modeling, such immediate feedback is impossible. It is necessary, as climate modeling moves beyond the research domain, that models be formally tested against specific observational data sets. This needs to be done with sufficient care and fidelity to detect small differences in future climate trajectories. The observations must have tight tolerances for accuracy, sampling protocols, data availability, and cost, and must meet the criteria for long-term stable climate records, as described in Chapter 3. Lastly, there must be a formally reviewed assessment of models' performance, both against these specialized data sets and against each other. The testing program would have four particular components:

- **Testing against the climate record.**
  Model outputs have long been compared to the global average temperature record, with notable successes. But given the number of parameterizations in high-end climate models, it is not clear that that this comparison is sensitive enough (i.e., models might be getting the right answers for the wrong reasons). This implies a need for consistent, climate-quality analyzed fields for the climate record of the 20^{th} century with a particular focus on the last 25 years (for which satellite observations are available) so that models can be tested against such parameters as precipitation and ocean heat content. A periodically repeated reanalysis of the climate record is required, in order to incorporate new and recovered observational data and recent modeling advances. A particular need is for a full exploitation of the satellite data record. The operational satellite archives must be reprocessed to fully exploit their potential and properly test model forecasts. But the operational archives by themselves are insufficient and must be supplemented by current and planned research instruments (EOS, TRMM, CloudSat) that target key climate feedback processes. Lastly, particular attention must be given to the climate forcing data sets used to drive climate models. These data sets are themselves the source of considerable uncertainty, and their ranges of uncertainty must be identified.

  It is also critical that models be tested against the paleoclimatic record. It is not clear that the 20^{th} century will be representative of the future state of the Earth's climate. Models must be able to represent past states of the climate system as seen in the paleoclimatic record in order to project future states. Paleoclimate proxy data must be used in the routine model evaluation process.

  With regard to the climate record, one of the central areas of controversy has been the difference between the surface and tropospheric temperature records. To provide insight into the nature of this difference, a series of model runs will be carried out focusing on surface and tropospheric temperatures and the processes that may lead to their differences. This effort must be coupled with improved analysis of the observational record and improved observing systems and techniques to remove potential future biases.

- **Testing against specialized data sets.**
  In addition to testing models against the climate record in general, there are specialized data sets that may be of particular use in isolating climate feedbacks and their representation in models. There is a need for an innovative and disciplined comparison strategy to connect details of the specialized, consistent observations to the structure of the forecast model. For example, because radiative feedbacks from clouds and water vapor are the primary contributors to the uncertainty in climate model forecasts, any

strategy to improve climate forecasts must test both the integrated global response of the model as well as the individual feedback processes that ultimately determine the response. Specialized data sets are required to first test simulations of feedback processes using simple and/or individual component models (e.g., cloud processes using atmospheric single column models). Data assimilation methods can also be used to examine process representation in models, as has been done successfully in global aerosol modeling. The more demanding and definitive tests must be conducted using the fully coupled climate system model.

Both branches of this strategy—individual component processes and integrated response—require either new data sets or an improved interface with existing data sets.

More generally, there is a need for specific climate benchmark records to provide absolute values of key measurements for testing climate models. Such benchmark records would consist of a limited number of carefully selected measurements focusing specifically on climate forcing and response. A focus on accuracy, with measurements tied to laboratory standards, is a key characteristic. Current examples of benchmark measures include sea level altimetry, solar irradiance, and atmospheric CO_2 measurements. Prospective benchmark observations would include ground and space-based GPS radio wave refraction, which is a direct function of atmospheric density variations, and spectrally-resolved absolute radiances to space.

- **Sensitivity to unresolved ocean processes.**
Of particular note among the key uncertainties in climate change modeling is the role of the ocean. Because of computer resolution, none of the current coupled climate models resolve the small ocean eddies (with horizontal scales of tens of kilometers) that constitute the dominant scale of oceanic variability. These eddies are thought to play a substantial role in regulating oceanic heat transport (via boundary currents) and heat and carbon storage by regulating transport to deep water. A series of eddy-resolving global ocean sensitivity studies are required to assess how well the parameterizations in current climate models portray the ocean's sensitivity to forcing. In addition, such studies will be used to assess whether the role of marginal sea processes in determining the properties of the dominant ocean water masses and in driving the thermohaline circulation are captured well by the primary coupled climate models.

- **Ability to simulate major modes of climate variability.**
Another major area of climate model testing concerns the ability of models to simulate known modes of climate variability such as the El Niño-Southern Oscillation (ENSO), the Arctic Oscillation (AO), the Pacific Decadal Oscillation (PDO), and monsoon systems. The research base examining these is detailed in Chapter 6. While these modes of variability by their nature may not be predictable, it is nonetheless necessary that models simulate their amplitudes and frequency structure. If a model does not have a realistic ENSO cycle present, for example, it calls into question the fundamental

dynamics of the predictive system. For this reason, verification against data sets produced by the climate variability research community is a fundamental aspect of climate model testing.

PRODUCTS AND PAYOFFS

As a near-term product, a critical comparison of the model sensitivity of major US models will be undertaken by the major modeling centers (1-1.5 years), followed by publication of a reviewed interim report (3 years). Considerable progress has been made already, as the modeling and diagnostics communities are developing scientific and protocol plans for examining differences between models, as well as differences between models and observations.

CLIMATE CHANGE IN RESPONSE TO SPECIFIED EMISSIONS SCENARIOS AND NATURAL FORCINGS

One of the highest priority applications of climate modeling is the development of new, state of the art projections of the impact on global climate resulting from different scenarios of greenhouse gas emissions. As described in the previous section, well-developed scenarios are essential vehicles for asking the central "If…, then…" questions. These scenarios must consider potential economic changes, possible changes in energy sources, and suites of potential new technologies, along with possible environmental changes which may themselves act as agents of climate change. Analysis of uncertainties will be included as part of the scenario exercise.

PRODUCTS AND PAYOFFS

- **Sets of ensemble global simulations projecting possible climate change at continental and regional scales from various emissions scenarios.** Using these scenarios as input conditions, climate model runs will be generated for research, assessment, and policy applications for the United States (3 years). These ensemble model runs then form the basis for regional analyses, potentially using downscaling techniques (see Chapter 6). The CCRI will coordinate with the IPCC in determining what scenarios to run. It is important that the CCRI modeling plans take into consideration, and work in the context of, international efforts (see Chapter 14).

- **North American scenarios for short-lived species: tropospheric ozone, sulfur-based and black carbon aerosols, and methane.** As described in Chapter 5, the CCSP will furnish a set of scenarios, with uncertainties, that will link potential changes in North American pollutant precursor emissions to resulting changes in the radiative forcing of climate change (4 years). With these radiative-forcing scenarios as part of the input, simulations of potential future climate changes can include a meaningfully broader set of possibilities and hence options.

STRENGTHENING US APPLIED MODELING CAPABILITY

Several recent NRC reports have documented the need to strengthen US modeling capability. In response, a number of steps will be taken to enhance the US climate modeling capability:

- **Two Center Strategy.**
  The US contributions to the IPCC's century-long scenario runs and assessments will be primarily accomplished by the high-end models developed at two complementary high-end modeling centers. The first, the Community Climate System Model (CCSM), operated at the National Center for Atmospheric Research, is an open and accessible modeling system that integrates basic knowledge from the broad, multi-disciplinary basic research community for research and applications. The second model, developed at the Geophysical Fluid Dynamics Laboratory (GFDL), benefits from these community interactions and will focus on model product generation for research, assessments, and policy applications as its principal activity. The success of these two endeavors depends on modeling of specific aspects or sub-components of the climate system conducted by multiple US laboratories and universities.

- **Common Modeling Infrastructure**.
  To optimize modeling resources and enable meaningful collaborations among modelers, it is necessary to build common and flexible infrastructure at our major modeling centers. By adopting common coding standards and system software, researchers will be able to test ideas at any of the several major modeling centers and the centers themselves will be able to easily exchange parameterizations as well as entire modules so that each benefits from the other's work. Products will include more efficient and rapid transfer of research results into model applications.

- **Access to Computational Capability.**
  To improve the effectiveness of the US climate modeling effort, enhanced and stable computational resources should be focused on modeling activities, including climate variability and predictability on seasonal to centennial time scales; national and international climate projections and assessments of anthropogenic climate change; regional impacts of climate change; assimilation of carbon data; and national and international ozone assessments. These activities will require a substantial increase in US computational capability in the form of dedicated machine time for climate model runs.

4. Resources for risk analysis and decisionmaking under uncertainty

Decisionmaking associated with climate change and variability can be viewed as a subset of a larger class of problems that involve decisionmaking under uncertainty. Decisions are made and public policy is developed in many areas other than climate change that involve uncertainties, such as terrorism and genetic engineering. Although each of these issues is associated with its own unique set of factors, they all involve the need to understand longer-term risks for systems where there are many variables, each of which interacts with the others in complex, often nonlinear ways. Fruitful lines of inquiry include many different approaches, such as game theory, preference elicitation, and decision sequencing.

Advancement of theory, approaches, and resources to improve decisionmaking associated with climate change and variability will take a variety of forms. New paradigms will be needed to better integrate the variable spatial, temporal, and organizational scales at which interconnected natural and human systems function. New approaches are needed to conceptualize problems and to obtain and analyze relevant data from a diverse set of sources. New resources need to be created that combine improved operational capabilities with more effective user interfaces, thereby making them more readily useful to decisionmakers and other stakeholders. These resources will require integration of the latest advances in information systems technology with statistical advances, such as visualization and stochastic modeling. Also needed are the development and deployment of more effective forms of communication to facilitate broader dissemination and implementation of scientific insights and information to a broad range of end users.

PRODUCTS AND PAYOFFS

An accelerated fundamental research program will be put in place to develop applications of existing capabilities to the issues of uncertainty in the climate change decisionmaking context as well as to the robust analysis of risk and vulnerability of natural resource systems. Additional research programs will focus on the development of new resources for addressing scientific uncertainty in decisionmaking.

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PART II

THE US GLOBAL CHANGE RESEARCH PROGRAM (USGCRP)

USGCRP INTRODUCTION AND OVERVIEW

The United States Global Change Research Program (USGCRP) was created in 1989 as a high-priority national research program to address key uncertainties about changes in the Earth's global environmental system, both natural and human-induced; to monitor, understand, and predict global change; and to provide a sound scientific basis for national and international decisionmaking. Since its inception, the USGCRP has strengthened research on global environmental change and fostered insight into the processes and interactions of the Earth system, including the atmosphere, oceans, land, frozen regions, plants and animals, and human societies. The USGCRP was codified by Congress in the Global Change Research Act of 1990 (PL 101-606). The basic rationale for establishing the program was that the issues of global change are so complex and wide-ranging that they extend beyond the mission, resources, and expertise of any single agency, requiring instead the integrated efforts of several agencies.

The USGCRP is organized into a set of linked research program elements, which together support scientific research across a wide range of interconnected issues of climate and global change. Each of these research elements focuses on topics crucial to documenting and monitoring change, improving projections of change, or developing useful products to support decisionmaking. The program focuses on these elements because they are all major components of the Earth's environmental systems, they are undergoing changes due to a variety of natural and human-induced causes, and changes in one area affect processes and the state of the others such that it is not possible to understand how the Earth system or its any of its components (e.g., climate) will evolve without understanding important characteristics of the others.

The research program elements include:

Atmospheric Composition—USGCRP-supported research focuses on how the composition of the global atmosphere is altered by human activities and natural phenomena, and how such changes in atmospheric composition influence climate, ozone, ultraviolet radiation, pollutant exposure, ecosystems, and human health. Research addresses processes affecting the recovery of the stratospheric ozone layer; the properties and distribution of greenhouse gases and aerosols; long-range transport of pollutants and implications for air quality; and integrated assessments of the effects of these changes. Atmospheric composition issues involving interactions with climate variability and change—such as interactions between the climate system and the stratospheric ozone layer, or the effects of global climate change on regional air quality—are of particular interest at present.

Climate Variability and Change—USGCRP-supported research on climate variability and change is being focused on how climate elements that are particularly important to human and natural systems—especially temperature, precipitation, clouds, winds, and storminess—are affected by changes in the Earth system that result from natural processes as well as from human activities. Activities in the program are specifically oriented toward predictions of seasonal to decadal climate variations (e.g., the El Niño-Southern Oscillation (ENSO)); improved detection, attribution, and projections of longer-term changes in climate; the potential for changes in extreme events at regional to local scales; the possibility of abrupt climate change; and ways to improve the communication of this information (including characterization of uncertainty) to inform national dialogue and support public and private sector decisionmaking.

Global Water Cycle—USGCRP-supported research on the global water cycle focuses on the effects of variability and change in the water cycle and climate systems on the capacity of societies to provide adequate supplies of clean water; and how natural processes and human activities influence the distribution and quality of water within the Earth system and to what extent the resultant changes are predictable. Specific areas include: identifying trends in the intensity of the water cycle and determining the causes of these changes (including feedback effects of clouds on the global water and energy budgets as well as the global climate system); predicting precipitation and evaporation on timescales of months to years and longer; and modeling physical/biological processes (including interactions with human health) and human use of water, to facilitate efficient water resources management.

Land Use/Land Cover Change—USGCRP-supported research on changes in land use and land cover focuses on the processes that determine the temporal and spatial distribution of land cover and land use change at local, regional, and global scales; how land use and land cover can be projected over timescales of 10-50 years; how the dynamics of land use, land management, and land cover change will affect global environmental changes and regional-scale environmental and socioeconomic conditions, including economic welfare and human health; and how global environmental changes will affect land use and land cover. Research will identify and quantify the human drivers of land use and land cover change; improve monitoring, measuring, and mapping of land use and land cover and the management of data systems; and develop projections of land cover and land use change under various scenarios of climate, demographic, economic, and technological trends.

Global Carbon Cycle—USGCRP-supported research on the global carbon cycle focuses on: (1) identifying the size and variability of the dynamic reservoirs and fluxes of carbon within the Earth system and how carbon cycling might change and be changed in the future; and (2) providing the scientific underpinning for evaluating options being considered by society to manage carbon sources and sinks to achieve an appropriate balance of risk, costs, and benefits. Specific programs and projects focus on North American and oceanic carbon sources and sinks; the impact of land use change and resource management practices on carbon sources and sinks; projecting future atmospheric carbon dioxide and methane concentrations and changes in land-based and marine carbon sinks; and the global distribution of carbon sources and sinks and how they are changing.

Ecosystems—USGCRP-supported research on ecosystems focuses on: (1) how natural and human-induced changes in the environment interact to affect the structure, functioning, and services of ecosystems at a range of spatial and temporal scales, including those ecosystem processes that in turn influence regional and global environmental changes; and (2) what options society may have to ensure that desirable ecosystem goods and services will be sustained, or enhanced, in the context of still uncertain regional and global environmental changes. Among the specific focus areas are the structure and functioning of ecosystems, including cycling of nutrients, and how these nutrients interact with the carbon cycle; and key processes that link ecosystems with climate.

Human Contributions and Responses—USGCRP-supported research on human contributions and responses to global change is relevant to each of the other research program elements. The current focus of this research is on the potential effects of global change on human health; human forcing of the climate system, land use, and other global environmental changes; regional and sectoral assessments of vulnerability and resilience; decision support under conditions of significant complexity and uncertainty; and integrated assessment methods.

Contents of Part II Chapters—The chapters of Part II of the draft Strategic Plan provide an overview of each research program element, including research questions, an overview of the current state of knowledge, products and benefits from the research, needed scientific inputs to reach objectives, and linkages with other national and international programs.

International Linkages—Internationally, the World Climate Research Programme, the International Geosphere-Biosphere Programme, and the International Human Dimensions Programme provide the broad framework within which US research efforts are coordinated with those of other nations. Robust collaborative efforts with international partners through the Integrated Global Observing Strategy and the Global Climate, Oceans, and Terrestrial Observing Systems enhance the productivity of US investments in observations. USGCRP agencies also have developed bilateral and multilateral cooperative activities with a range of developed and developing countries: a few examples include ongoing scientific cooperation with Japan and partnerships with international organizations and national governments to apply forecasts of ENSO and other products of the program. The program benefits from and supports activities in developing countries that serve both research and capacity-building purposes through the System for Analysis, Research, and Training, the Inter-American Institute for Global Change Research, and other efforts. International linkages particular to specific areas of research are described in relevant sections of each chapter. Chapter 14 provides an overview of international activities conducted under the Climate Change Science Program by the Climate Change Research Initiative and the USGCRP.

CHAPTER 5

ATMOSPHERIC COMPOSITION

This chapter's contents…

The global and regional composition of the atmosphere—its gases and particles—is at the intersection of global and regional changes and their relation to humankind:

- **The atmosphere is shared by all.** It links the other components of the Earth system, including the oceans, land, terrestrial and marine plants and animals, and the frozen regions. Because of these linkages, the atmosphere is a *conduit of change*. For example, natural events and human activities that change atmospheric composition will change the Earth's radiative (energy) balance. Subsequent responses by the stratospheric ozone layer, the climate system, and regional chemical composition (air quality) create multiple environmental effects that influence the well being of human and natural systems.
- **Atmospheric composition changes are indicators of many potential environmental issues.** Observations of trends in atmospheric composition are among the very earliest harbingers of global changes, such as the growth rates of carbon

dioxide (CO_2) concentrations in the atmosphere. Similarly, the decline of the concentrations of ozone-depleting substances, such as the chlorofluorocarbons (CFCs), has been the first measure of the effectiveness of international agreements to end production and use of these compounds.

- **The atmosphere can be a forcing-agent "reservoir" for long-term changes.** The long removal times of some compounds, such as CO_2 (>100 years) and perfluorocarbons (>1000 years), may imply virtually irreversible global changes over decades, centuries, and millennia—for all countries and populations, not just the pollutant emitters.

An effective program of scientific inquiry relating to managed or unmanaged changes in atmospheric composition must address two major foci:

- **A focus on Earth system interactions:** How do changes in atmospheric composition alter and respond to the energy balance of the climate system? What are the interactions between the climate system and ozone layer? What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical change on regional air quality?
- **A focus on Earth system and human system linkages:** How is the composition of the global atmosphere, as it relates to climate, ozone depletion, ultraviolet radiation, and pollutant exposure, altered by human activities and natural phenomena? How do such composition changes influence human well being and ecosystem health?

The *overall research approach* is integrated application of long-term systematic observations, laboratory and field studies, and modeling, with periodic assessments of understanding and significance to decisionmaking. Specific emphasis will also be placed on *national and international partnerships*, recognizing that such partnerships are necessitated by the breadth and complexity of current issues and because the atmosphere links all nations.

In looking ahead at what the specific information needs associated with atmospheric composition will be, five broad challenges are apparent, with goals and examples of key research objectives outlined below.

Question 1: What are the climate-relevant chemical and radiative properties, and spatial and temporal distributions, of human-caused and naturally occurring aerosols?

STATE OF KNOWLEDGE

Research has demonstrated that certain atmospheric particles (aerosols) cause cooling of the climate system (e.g., sulfate), while others result in warming (e.g., black carbon or soot). When climate models incorporate this knowledge, they simulate the observed trends much better.

However, one of the largest uncertainties about the impact of aerosols on climate is the diverse warming and cooling influences of the very complex mixture of aerosol types and their spatial distributions. Further, the poorly understood impact of aerosols on the formation of both water droplets and ice crystals in clouds also results in large uncertainties in the ability to predict climate changes.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are the sources of atmospheric aerosols, and what are their magnitudes and variability?
- What are the global distributions and radiative characteristics of aerosols?
- What are the processes that control the spatial and temporal distributions and variability of aerosols and that modify their chemical and radiative properties during transport, and how well can these processes and resulting spatial distributions currently be simulated?
- How do aerosols affect a cloud's radiative properties and ability to generate precipitation?

RESEARCH NEEDS

A series of research activities are focusing on these questions. Remote-sensing instruments paired with correlative *in situ* observations will provide better data on global distributions of aerosols, their temporal variabilities, and resulting changes in radiative balance. Emission estimates and supportive direct measurements are critical for assessing the balance of human and natural influences on aerosol distributions. The exploration of critical aerosol and chemical processes will involve field experimentation, some laboratory studies, and model development and testing. Diagnostic model estimates, assessed against observations, will characterize aerosol-determined temperature change and its uncertainties. Measurements and models will form the basis for describing the interactions of various types of aerosols and their impact on the radiative effect of clouds.

PRODUCTS AND PAYOFFS

- Improved description of the global distributions of aerosols (2-4 years).
- Empirically tested assessment of the capabilities of current models to link emissions to (i) global distributions and (ii) chemical and warming/cooling properties (and their uncertainties) of atmospheric aerosols (2-4 years).
    - These capabilities will support the scenarios planned as decision support resources by providing better estimates of the uncertainties associated with those simulations.
    - Because of the relatively short atmospheric residence times of aerosols, this assessment will yield potential options for changing radiative forcing within a few decades, in contrast to the longer response times associated with CO_2.
- An improved estimate of the indirect climate effects (e.g., on clouds) of aerosols, compared to the benchmark of the Intergovernmental Panel on Climate Change (IPCC, 2001) (2-4 years).
- More accurate detection and attribution of temperature changes and more accurate analysis of climate model projections (4-6 years).

- Better understanding and description of uncertainties about the physical and chemical processes that form, transform, and remove aerosols during long-range atmospheric transport (4-6 years).
- Characterization of the impact of human activities and natural sources on global aerosol distributions (4-6 years).

Question 2: What is the current quantitative skill for simulating the atmospheric budgets of the growing suite of chemically active greenhouse gases and their implications for the Earth's energy balance?

STATE OF KNOWLEDGE

The increasing concentrations of atmospheric constituents that absorb infrared radiation, such as CO_2 (see Chapter 8), methane (CH_4), tropospheric ozone, nitrous oxide (N_2O), and the chlorofluorocarbons (CFCs) are the primary gases that are forcing agents of global climate change. The anthropogenic emission sources leading to the observed growth rates of CH_4 (the second-most influential anthropogenic greenhouse gas) and N_2O are qualitatively understood but poorly quantified (e.g., CH_4 emitted by rice agriculture). Trends in tropospheric ozone (the third-most influential anthropogenic greenhouse gas) are not well determined and are driven by a mix of emissions, including regional pollutants and CH_4. The atmospheric concentrations and sources of the CFCs are well studied because of their role in stratospheric ozone layer depletion. In addition to these gases, water vapor plays a strong role in amplifying greenhouse warming (see Chapter 6). Observations and trends of this highly variable constituent are problematic.

ILLUSTRATIVE RESEARCH QUESTIONS

Driven by the need to have a predictive understanding of the relationship between the emission sources of these gases and their global distributions and radiative forcing, several question face the research community. These include:

- What are global anthropogenic and natural (biospheric – see Chapter 10) sources of CH_4 and N_2O?
- What are the causes of the observed large variations in their growth rate?
- What are the global anthropogenic and natural sources (both biogenic and lightning-related) of nitrogen oxides?
- What are the trends in mid-tropospheric ozone, particularly in the Northern Hemisphere, and how well can the variations be attributed to causes?
- What water vapor observations will best test and improve the understanding of the water vapor feedback?

RESEARCH NEEDS

Field and laboratory studies, satellite observations, and diagnostic transport/chemical modeling are focusing on these questions. Examples of activities are:

- Global monitoring sites to continue recording the growth rate of CH_4 and its variations.
- Satellite observations to provide estimates of the global distributions of tropospheric ozone and some of its precursors (e.g., nitrogen dioxide).
- Planned satellite (Aura) measurements and focused field studies to better characterize water vapor in the climate-critical area of the tropical tropopause (the boundary between the troposphere and the stratosphere).
- Model studies to simulate past trends in tropospheric ozone to improve the understanding of its contribution to radiative forcing over the past ~50 years.
- Field studies to characterize the regional- and continental-scale changes occurring between emission areas and global tropospheric ozone distributions, thereby providing tests of and improvement in the ozone-related process representation of models.

PRODUCTS AND PAYOFFS

- Observationally-assessed and improved uncertainty ranges for future scenarios of the radiative forcing of the chemically-active greenhouse gases, which will be part of the 2006 Climate Change Research Initiative (CCRI) suite of climate change scenarios.
  - As a result, there will be a broader suite of options (i.e., in addition to CO_2) for potential choices to influence radiative forcing, particularly in coming decades (4 years).
- Better understanding of the processes that control water vapor in the upper troposphere and lower stratosphere, resulting in improved input to the planned evaluation of the knowledge of water vapor feedback in climate models (4-6 years).

Question 3: What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical change on regional air quality and atmospheric chemical inputs to ecosystems?

STATE OF KNOWLEDGE

Increased development in rapidly industrializing regions of the world has the potential to impact air quality and ecosystem health in regions far from the sources. Paleo-chemical data from ice cores and snow document past perturbations and demonstrate that even pristine areas, such as Greenland, are influenced by worldwide emissions.

ILLUSTRATIVE RESEARCH QUESTIONS

This emerging picture is shaping several policy-relevant questions, which include the following examples:

- What are the chemical exposures experienced by food-producing areas that are in proximity to large urban areas?

- How do the primary and secondary pollutants from the world's megacities contribute to global atmospheric composition?
- What are, and what contributes to, North American "background" levels of air quality—that is, what levels of pollution are beyond national control?

RESEARCH NEEDS

These questions are being addressed by measurements of key tropospheric constituents, including both global mapping by satellites and intensive local observations from surface sites or airborne platforms, supported by analyses and model simulations. The near-term goals include the following:

- Characterize the outflow from polluted regions around the world, with an initial emphasis on North American impact;
- Understand the balance between long-range transport and transformation of pollutants;
- Establish baseline observations of atmospheric composition over North America and globally;
- Quantify the inflow-outflow atmospheric composition budget of North America and project future changes; and
- Carry out the first global survey of vertically-resolved distributions of tropospheric ozone and its key precursor species.

PRODUCTS AND PAYOFFS

- Description of the changes in the impacts of global tropospheric ozone on radiative forcing over the past decade brought about by clean air regulations (2-4 years).
- A 21st century chemical baseline for the Pacific region, against which future changes can be assessed (2-4 years).
- An assessment of the vulnerability of ecosystems to urban growth, with an emphasis on food production (4-6 years).

Question 4: What are the time scale and other characteristics of the recovery of the stratospheric ozone layer in response to declining abundances of ozone-depleting gases and increasing abundances of greenhouse gases?

STATE OF KNOWLEDGE

The primary cause of the stratospheric ozone depletion observed over the last two decades is an increase in the concentrations of industrially-produced ozone-depleting chemicals. The depletion has been significant, ranging from a few percent per decade at mid-latitudes to greater than fifty percent seasonal losses at high latitudes. Notable is the annually recurring Antarctic ozone hole, as well as smaller, but still large, winter/spring ozone losses recently observed in the Arctic. Reductions in atmospheric ozone levels lead to increased fluxes of ultraviolet radiation at the surface, with harmful effects on plant and animal life, including human health. In response to these findings, the nations of the world ratified the *Montreal Protocol on Substances That Deplete the*

Ozone Layer and agreed to phase out the production of most ozone-depleting chemicals. Ground-based *in situ* and satellite measurements show that concentrations of many of these compounds are now beginning to decrease in the lower atmosphere. In the absence of other atmospheric change, as the atmospheric burden of ozone-depleting chemicals falls in response to international efforts, stratospheric ozone concentrations should begin to recover.

ILLUSTRATIVE RESEARCH QUESTIONS

- How will changes in the atmospheric composition of greenhouse gases, such as CO_2 and N_2O, and the resulting changes in the radiation and temperature balance (e.g., stratospheric cooling), alter ozone-related processes?
- How will changes in the physical climate affect the distributions of ozone (e.g., unusually cold Arctic winters and particle-enhanced ozone-loss processes)?
- What are the ozone-depleting and radiative forcing properties of new chemicals, such as the substitutes for the now-banned ozone-depleting substances?

RESEARCH NEEDS

Improving our understanding of this complex and interactive ozone layer-climate system calls for detailed investigation of the relationships between the distributions of ozone, water vapor, aerosols, temperature, and relevant trace constituents, notably chlorine and bromine compounds and nitrogen oxides. Research needs include the following:

- Continue global monitoring of the changes in ozone-depleting substances and their substitutes and assessing compliance with the Montreal Protocol.
- Test the "ozone and climate friendliness" of proposed substitutes with laboratory chemistry and atmospheric models to provide early information to industry prior to large plant investments.
- Carry out focused aircraft, balloon, and ground-based campaigns, and chemical transport modeling activities with emphases on:
    - Cross-tropopause processes to better understand the ozone-depleting role of the newly proposed, very short-lived (days to months) substances;
    - The role of particles in accelerating ozone-loss chemistry; and
    - Stratospheric transport to better understand ozone-layer responses to climate change.
- Extend interagency and international satellite observations of ozone trends, with an emphasis on detecting and attributing recovery.
- Continue monitoring of the trends in ultraviolet radiation, particularly in regions of high radiation exposure and high biological sensitivity.

PRODUCTS AND PAYOFFS

- In 2006, the international ozone research community will provide decisionmakers an updated assessment of the state of the ozone layer, including new ozone and ultraviolet radiation trends, analysis of compliance, and forecasts of recovery. This sixth in the series of "operational" products of the ozone science community is a key to accountability in this issue; namely, is the outcome expected from international actions being observed?

Question 5: What are the couplings among climate change, air pollution, and ozone layer depletion, which were once considered as separate issues?

STATE OF KNOWLEDGE

The atmosphere does not segregate atmospheric composition phenomena by scientific discipline or societal issue. For example, research has demonstrated that stratospheric ozone depletion not only causes increased exposure to ultraviolet radiation at the surface, but also exerts a cooling influence on the global climate. Conversely, climate-related changes may cool the lower stratosphere and increase the depletion of the ozone layer at high latitudes. Formation of tropospheric ozone, previously of concern primarily as a component of smog, is not only a local health risk, but also exerts a warming influence on the global climate. Emissions of sulfur dioxide from fossil-fuel combustion not only lead to the formation of regional acid rain, but also contribute to the hemispheric sulfate aerosol haze, which exerts a cooling influence on the global climate system. It is now clear that multiple issues that have been treated separately by scientists and policymakers alike are indeed coupled phenomena.

ILLUSTRATIVE RESEARCH QUESTIONS

- How do actions taken or considered with regard to one issue influence other issues, positively or negatively?
- What are the multiple stresses that climate change, ozone layer depletion, and regional air quality exert on humans and ecosystems?

RESEARCH NEEDS

- Build and evaluate diagnostic/prognostic models of the coupled climate, chemistry, transport, and ecological systems (in collaboration with other elements of the program).
- Synthesize the understanding of the impacts of multiple stresses on humans (e.g., heat and air quality) and ecosystems (e.g., soil moisture and chemical exposure).
- Build and evaluate models that couple the biogeochemical systems with the decisionmaking frameworks.
- Carry out multiple issue state-of-understanding assessments, in partnership with the spectrum of stakeholders, with the aim of characterizing integrated "If…, then…" options.

PRODUCTS AND PAYOFFS

- A policy-relevant assessment of the issues related to intercontinental transport and the climatic effects of air pollutants, in order to provide scientifically sound information to policymakers for consideration in developing integrated control strategies to benefit both regional air quality and global climate change, and to assess local attainment of air quality standards (2-4 years).

- A *State of the Atmosphere: 2006* report that describes and interprets to the Nation the annual status of atmospheric phenomena such as atmospheric composition, ozone layer depletion, temperature, rainfall, and ecosystem exposure (see Chapter 3).
- Diagnostic/prognostic models of the coupled climate, chemistry/transport, and ecological systems (in collaboration with other elements of the program).
- A process that bridges various issues and stakeholders in order to conduct multiple-issue integrated assessments.

Key Linkages

The Atmospheric Composition research focus is linked via co-planning and joint execution to several national and international planning and coordinating activities. A few examples are:

- **USGCRP/CCRI:**
  - Interaction with the US Global Change Research Program (USGCRP) Climate Variability and Change (Chapter 6) and Water Cycle (Chapter 7) components, including radiative forcing input to climate model simulations, as well as characterization of other composition–climate processes (e.g., impact of aerosols on cloud formation and precipitation).
  - Interaction with the CCRI Scenarios near-term focus (Chapter 4), providing explicit simulations of emissions, atmospheric composition, and radiative forcing changes.
  - Interactions with the USGCRP Carbon Cycle component (Chapter 9) for CH_4 changes, Ecosystems (Chapter 10) for assessing chemical impacts, and Human Contributions (Chapter 11) for health impacts.
- **Interagency Programs:** Joint planning, such as the National Aerosol–Climate Interactions Program (NACIP) is a major vehicle for carrying out USGCRP/CCRI objectives.
- **Committee on Environment and Natural Resources: Air Quality Research Subcommittee (AQRS):** Joint research on the global/continental scales of the USGCRP and on the regional/local scales of the AQRS (global influences on the "natural background" of air pollutants and linkages with the stakeholders via the AQRS).
- **International Global Atmospheric Chemistry (IGAC):** IGAC, a Core Project of the International Geosphere-Biosphere Programme, coordinates several international projects focused on the chemistry of the global troposphere and its impact on the radiative balance, such as the new Intercontinental Transport and Chemical Transformation project, which involves Asian, North American, and European researchers.

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CHAPTER 6

CLIMATE VARIABILITY AND CHANGE

This chapter's contents…

Climate variability and change profoundly influence social and natural environments throughout the world. The consequent impacts on natural resources and industry are large and far-reaching. For example, seasonal to interannual climate fluctuations determine the success of agriculture, the abundance of water resources, and the demand for energy, while long-term climate change may significantly alter landscapes, recreational activities, agricultural productivity, and the services that ecosystems supply. Recent advances in climate science are beginning to provide information for decisionmakers and resource managers to better anticipate and plan for potential impacts of climate variability and change. Further advances in climate sciences will substantially improve our national capabilities to apply science-based information to increase economic efficiency and better protect the environment.

Over the past decade, global change research has indicated that: decreases in Northern Hemisphere sea ice extent exceed what would be expected from natural variability alone; large climate changes can occur within decades or less, yet last for centuries or longer; and the observed global warming during the 20th century exceeds the natural variability of the past 1,000 years. Moreover, model simulations that incorporate a full suite of natural and anthropogenic forcings have indicated that the observed changes over the past century are likely consistent with a contribution from human activity.

Global change research has also significantly advanced our knowledge of the temporal and spatial patterns of climate variability. Substantial improvements in our ability to monitor the upper tropical Pacific Ocean now provide the world with an "early warning" system that shows the development and evolution of El Niño-Southern Oscillation (ENSO) events as they occur. This improved observational system, together with a greatly improved understanding of the mechanisms that produce ENSO, have led to skillful climate forecasts at lead times of up to a few seasons. This developing capability has given the world an unprecedented opportunity to prepare for, and reduce vulnerabilities to, this major natural climate phenomenon.

Research supported by the US Global Change Research Program (USGCRP) has played a leading role in these scientific advances, which have provided new climate information to help the public and decisionmakers better anticipate and mitigate potential effects of climate variability and change. While progress in this area has been impressive, there still remain many significant unresolved questions about key aspects of the climate system, including some that have enormous societal and environmental implications. For example, we are just now beginning to understand how climate variability and change may influence the local and regional occurrence and severity of extreme events such as hurricanes, floods, droughts, and wildfires. We have identified several major recurrent natural patterns of climate variability other than ENSO, but do not yet know to what extent they are predictable. Our predictive capabilities at local and regional scales show promise in some regions and for some phenomena, but are still quite poor in many instances. We have yet to obtain confident estimates of the likelihood of abrupt global and regional climate transitions, although such events have occurred in the past and, in some climate model simulations, have been projected to occur within this century. Perhaps most fundamentally, we do not yet have a clear understanding of how these natural climate variations may be modified in the future by human-induced changes in the climate, particularly at regional and local scales, and how emerging information about such changes can be used most effectively to evaluate the vulnerability and sustainability of both human and natural systems.

The transformation of knowledge gained from climate research into information that is useful in supporting decisions presents many challenges, as well as significant new opportunities to forge essential relationships between the climate research community and the rapidly expanding base of public and private sector users of climate information. For continued progress over the next decade, research on climate variability and change will focus on answering two overarching questions:

- **How are the climate elements* that are important to human and natural systems, especially temperature, precipitation, cloudiness, and storminess, affected by variations and changes in the Earth system that result from natural processes and human activities?**
- **How can emerging scientific findings on climate variability and change be further developed and communicated to most effectively meet the needs of policymakers and public and private sector decisionmakers, in order to enhance human well-being, strengthen the economy, and reduce risks and vulnerability of climate-sensitive activities and resources?**

* As used in this chapter, *climate elements* refers to climate variables, such as clouds, temperatures, winds, and precipitation, while *climate effects* refers to social, economic, or environmental consequences that are directly related to (but whose impacts are not uniquely controlled by) climate variability and change, such as floods, droughts, wildfires, and sea level changes.

Providing policy and decision-relevant answers to these questions will require new research infrastructure that includes:

- Establishment of a highly focused and adequately funded modeling and prediction activity (see Chapter 4);
- A high-level international commitment to a sustained, long-term observing system of a quality adequate for climate research and assessments (see Chapters 3 and 12); and
- A standing, research-based infrastructure that brings together the evaluated scientific information required by public and private sector decisionmakers and resource managers and needed to support national and international climate assessments (see Chapter 4), which is largely dependent on realizing significant gains on the preceding issues.

In addition, a coordinated research management effort will be essential to ensure a broad-based and collaborative research program spanning academic institutions, government laboratories, and other public and private sector expertise in order to provide sustained basic research into the mechanisms of climate processes and their interactions; and advanced graduate and post-doctoral training for the next generation of climate scientists.

The research effort will require improvements in paleoclimatic information as well as modern observational data systems, because in general the latter have been present for too short a time to extract robust features of climate variability on decadal time scales, or to identify climate variability on centennial to millennial time scales. For example, in the Arctic, few climate stations have records extending back beyond 50 years but those that do indicate that the Arctic warmed by about 1°–2°C between 1910 and 1945. Paleoenvironmental data collected from a network of lakes, wetlands, tree-ring sites, ice cores, and marine sources further demonstrate that both the magnitude and spatial extent of 20th century Arctic warming may be unprecedented over the past 400 years.

As described in the following section, the overarching policy-relevant questions in the areas of climate variability and change can most effectively be addressed by focusing attention on five key science questions and their associated research objectives.

Question 1. What is the sensitivity of climate change projections to feedbacks in the climate system?

STATE OF KNOWLEDGE

The range in estimates of climate sensitivity accounts for a major part of the range of projections for long-term changes in the climate. Climate sensitivity is a measure of the climate's response to changes in the Earth's radiative balance, (e.g., the change caused by a doubling of the atmospheric concentration of carbon dioxide (CO_2)). Past research has identified important climate feedback processes (e.g., cloud formation, atmospheric convection, and ocean circulation) that amplify or diminish the influence of radiative perturbations. World-class climate models exhibit a large range in the estimates of the strengths of these feedbacks, with the major US models used in recent Intergovernmental Panel on Climate Change (IPCC) assessments lying close to the opposite ends of this range. The uncertainty that this range in climate sensitivity introduces to the overall findings makes US models an ideal setting for investigating sensitivities to feedbacks. In addition, all current climate models fail to accurately simulate certain climate system processes and their associated feedbacks due to anthropogenic forcing.

Among the least well-represented processes are ocean mixing, which to a large degree controls the rate of projected global warming; and atmospheric convection, hydrological, and cloud processes, which strongly influence the magnitude and geographical distributions of global warming. These deficiencies are thought to be related to both limits in understanding the physics of the climate system and insufficient fine-scale treatment of the key processes, together contributing significantly to model uncertainties in projections of climate change. As a result, limitations in model representations of climate feedbacks and climate sensitivity create significant uncertainties in estimating the impacts of future climate change, in consideration of response strategies, and ultimately in formulation of optimal environmental and energy policies.

High priority research will focus on several sub-questions:

- What are the key feedbacks in the climate system that determine the magnitude and time histories of climate changes for a specified radiative forcing, and how and to what extent can uncertainties in these feedbacks be reduced?
- How sensitive are climate change projections to various strategies for limiting changes in radiative forcing, such as by enhancing biogeochemical sequestration or limiting changes in land use and cover?

- How can observations of the Earth's past variations in climate be used to reduce uncertainties concerning climate sensitivity and feedbacks and to provide bounds for the major elements of climate change projections for the next century?
- How may information about climate sensitivity and feedbacks be used to develop effective strategies for the design and deployment of observational systems?

RESEARCH NEEDS

This research will require the undertaking of coordinated observation, process, and modeling programs by teams of scientists with diverse interests and focused common goals. One mechanism for focusing the research will be through Climate Process Teams (CPTs). CPTs will enable the research community to work together to rapidly identify, focus attention on, characterize, and ultimately reduce uncertainties in climate model projections. For problems that are generic to all climate models, the teams of climate process researchers, observing system specialists, and modelers will work in partnership with designated modeling centers (see also Chapter 4, section on Applied Climate Modeling).

PRODUCTS AND PAYOFFS

- Refined estimates of the role of climate feedback processes in affecting climate sensitivity and improvements in their representation in climate models, leading to a narrowing of the range of climate model projections (2-4 years).
- More certain estimates of the global and regional manifestations of future changes in climate (5-15 years).
- Increased understanding and confidence in attribution of the causes of recent and historical changes in the climate (2-4 years).
- More accurate estimates of the response of the climate to different emission (e.g., CO_2 and aerosols, including black soot) and land use scenarios (2-4 years).
- More useful information for improving the effectiveness of global observing systems, including deployment of new systems and re-deployment of existing systems, as needed (2-4 years).

Question 2. To what extent can predictions of near-term climate fluctuations and projections of long-term climate change be improved, and what can be done to extend knowledge of the limits of predictability?

STATE OF KNOWLEDGE

Simulations of past climate events as documented in observed or paleoclimatic data, and for which estimates of climate forcings have been obtained, are an effective and practical means for assessing the scientific credibility of climate models. Such simulations also enable detailed investigations of naturally recurring modes of climate variability. Past research has identified a few modes, or patterns, of variability, which have a disproportionately large influence on global and regional climates. These include ENSO, the North Atlantic Oscillation (NAO), the Arctic

Oscillation (AO), the Pacific Decadal Oscillation (PDO) and the monsoon systems. As the global observation network becomes more complete and long-lived, further exploration of Southern Hemisphere modes will provide a clearer perspective of global climate variability.

Our knowledge of the mechanisms and processes that produce and maintain these natural climate modes is limited, and thus model simulations and projections inadequately represent their influences. This increases the uncertainties in climate projections and in estimates of the limits of climate predictability. In addition, while the models simulate reasonably well statistics of observed *global average* characteristics of climate variability and the *global average* structure of climate trends, important details of seasonal and *regional-scale* variability are poorly simulated. Indeed, the predictability of regional climate and of coupled climate system behavior is just beginning to be studied, although such issues are fundamental to addressing many of the "If…, then…" questions posed by decisionmakers. This research poses major science challenges because of the less-advanced states of coupled and regional climate models relative to models of the global atmosphere.

High priority research will seek answers to the following subsidiary questions:

- How can advances in observations, process understanding, and modeling of tropical ocean variability, especially related to ENSO, be exploited to further improve climate predictions on seasonal to decadal time scales?
- How long does it take for the climate to equilibrate after responding to changes in the land surface, the deep ocean, or sea ice, and how does this "memory" contribute to climate predictability on multi-year to decadal time scales?
- How are changes in oceans, ice cover, the solid earth, and terrestrial storage currently influencing sea level, and what will be their influence on sea level in the future?
- What is the potential for improved representation of modes of climate variability, such as the PDO and the AO, to extend and improve climate predictions?
- How might human-induced changes that affect the climate system, such as changes in atmospheric composition and aerosols, or changes in ground cover and land use, alter climate forcing and hence climate variability and predictability?
- How do current and projected climate changes compare with past changes and variations in the climate in terms of patterns, magnitudes, and regional manifestations? For example, is the magnitude and time scale of the observed 20^{th} century warming of the Arctic unprecedented in the last 1,000 to 10,000 years?

RESEARCH NEEDS

Essential needs include the development of, and support for, long-term, sustained climate modeling and observing systems; retrospective data including new high-resolution paleoclimate datasets; field observations and process studies, and current operational data necessary for this research; and focused research efforts (e.g., CPTs) to improve climate prediction and projection models. Instrumental sea level observations, geodetic reference frame measurements, ice sheet and glacier volume estimates, as well as advanced modeling are required to further refine sea level change projections. Other research needs include data sets from ensembles of extended model simulations, and an updated, consistent reanalysis product suitable for climate studies, ideally including all of the 20th century.

PRODUCTS AND PAYOFFS

- Improved predictions of ENSO, particularly the onset and decay phases (2-4 years).
- Provision of probabilistic estimates of regional fluctuations in the climate resulting from ENSO extremes (5-15 years).
- An assessment of potential predictability beyond ENSO, e.g., PDO, AO, monsoons (5-15 years).
- Extended, model-based data sets to assess predictability and develop new approaches to improving seasonal to interannual climate predictions (2-4 years).
- Predictions of regional patterns of different modes of climate variability (5-15 years).
- Development and extension of critical data sets, including model-based reanalyses, to improve attribution of causes of long-term climate variations (2-4 years).
- Improvements in the projections of major modes of climate variability (see Question 1) (5-15 years).
- Improved ability to critically evaluate the strengths and weaknesses of climate projections, such as those carried out for the IPCC (5-15 years).
- A new estimate of ocean thermal expansion from a merger of observation and model analyses (2-4 years).
- A new estimate of sea level rise that incorporates the most recent ice sheet and glacier change estimates (2-4 years).
- Improved representation of processes (e.g., thermal expansion, ice sheets) critical for simulating and projecting sea level changes (5-15 years).
- An online database of paleoclimatic time series and GIS-based maps of high frequency (annual to decadal resolution) Arctic climate variability over the past 2,000 years (2-4 years).
- An improved ability to separate the contributions of natural versus human-induced climate forcing to climate variations and change, resulting in more credible answers to “what if” policy-related questions (5-15 years).
- More advanced knowledge about the changes in natural variability that may result from anthropogenic forcing (5-15 years).

Research to address Questions 1 and 2 will provide essential support to the United States and international decisionmakers and resource managers and will assist climate assessment efforts by increasing understanding of critical processes required to evaluate and improve major climate models (see Chapter 4, and Chapter 11).

Question 3. What is the likelihood of climate-induced changes that are significantly more abrupt than expected, such as the collapse of the thermohaline circulation or rapid melting of the major ice sheets?

STATE OF KNOWLEDGE

Paleoclimatic data have revealed that abrupt regional-to-global climate changes have occurred often in the past, and some models suggest the possibility for abrupt changes during the 21st century. We have learned a great deal about the structure and geographic extent of past abrupt climate changes, but much remains unknown about their causes and probabilities, leading to subsidiary questions such as:

- What are the primary natural mechanisms for abrupt climate changes?
- How common are they, based on past climate records?
- How soon might future abrupt changes be expected to occur and what would be the expected global and regional manifestations of such changes?
- What is the nature and extent of abrupt climate change in the Holocene? Are these stochastic events or the result of periodic forcing?
- What are the environmental consequences of extreme warming in the Arctic and how do these changes feed back to the global climate system?

RESEARCH NEEDS

Improved paleoclimatic information will be essential for analyzing past abrupt climate change. This research will also require the development and implementation of expanded observing and monitoring systems, particularly for key regions or phenomena that may be especially vulnerable or contribute most strongly to abrupt climate change, such as the tropical oceans, the Arctic and Antarctic regions, and the thermohaline circulation of the ocean. Moreover, significant research into how to numerically model the full three-dimensional circulation of the ocean will be required in order to accurately project the time scales and impacts of abrupt changes in thermohaline circulation.

PRODUCTS AND PAYOFFS

- Quantitative estimates of the probabilities and risks of abrupt global and regional climate-induced changes, such as the collapse of the thermohaline circulation or abrupt sea level rises, as well as the potential for climate “surprises,” to support development of informed environmental policies and adaptation strategies (5-15 years).
- Improved understanding of thresholds and nonlinearities in the climate system, especially for coupled atmosphere-ocean, oceanic deepwater, hydrology, land surface, and ice processes (5-15 years).
- Improvements in paleoclimatic data related to abrupt climate changes (5-15 years).

Question 4. Whether and how are the frequencies, intensities, and locations of extreme events, such as major droughts, floods, wildfires, heat waves, and hurricanes, altered by natural climate variations and human-induced climate changes?

STATE OF KNOWLEDGE

Past research has revealed strong relationships between major modes of climate variability and extreme events; for example, between ENSO and severe flooding in otherwise dry regions, and between the AO/NAO and extreme temperature anomalies in high latitude regions. Limited progress has been made in developing methods to downscale information provided by climate models to spatial and temporal scales relevant to those of extreme weather and climate events, including droughts, floods, heat waves, wildfires, hurricanes, and storm surges. Scientific understanding is currently inadequate to answer subsidiary questions such as:

- What are the main climatic and hydrological causes of floods and droughts (see also Chapter 7)?
- How are climate extremes, intensities, frequencies, and locations likely to change over the next century in the United States, and what are the causes of these changes?
- What is the potential for high-impact climate changes, such as much drier and warmer summers over the mid-continents of North America and Eurasia, accelerated Arctic warming, and more intense coastal storm surges and coastal erosion due to rising sea levels?
- How can the emerging findings of climate science be best formulated to contribute to evaluation of societal and environmental vulnerability and opportunities?
- To what extent are extreme events predictable?

RESEARCH NEEDS

This research requires high-resolution observations in key regions and sectors to evaluate regional projections; and improved capabilities to model climate variations and change on regional and local scales through finer global model resolution, nested model approaches, and/or other downscaling techniques. This research also requires extensive hydrological data sets and more sophisticated coupled physical climate-land surface-hydrology models (see Chapter 7).

PRODUCTS AND PAYOFFS

- A rapid-response attribution product to aid in interpreting the causes of high-impact climate events, such as major droughts or unusually cold or warm seasons (2-4 years).
- An assessment of how climate extremes are likely to change over the United States in the next century, if that proves possible, including probabilistic estimates of change in the distribution, frequency, and intensity of extreme weather events that may result from natural variability and human influences on climate (5-15 years).
- Annually resolved records of North American drought over the last 800 years (2-4 years).

- A geographical information system that includes distribution and frequency data on current extreme events, and current locations of vulnerable populations and infrastructure. This system will be coupled with potential scenarios of change in both extremes and vulnerabilities to identify potential strategies for reducing disaster-related losses (5-15 years).

Question 5. How can interactions between producers and users of climate variability and change information be optimally structured to ensure essential information needed for formulating adaptive management strategies is identified and provided to decisionmakers and policymakers?

STATE OF KNOWLEDGE

Research in this area focuses on climate information needs for integrated assessment and risks management. Ongoing assessment activities have focused on particular end users, such as water managers, to determine how scientists can accelerate development of products that are more useful to decisionmakers, and thereby improve the value of climate information that can be provided to address a broad range of social, economic, and environmental issues. Outstanding questions include:

- What are the regions and sectors for which improved climate information is most important, and who are the decisionmakers for whom such information would be most useful?
- What types of new climate information would provide the greatest potential for benefits, and what specific types of climate information would be most useful in formulating adaptive management strategies?
- What are the most likely vulnerabilities and opportunities arising from climate variability and potential future climate changes, and what climate indicators would be of the most benefit in assessing climate vulnerability and resilience in sectors such as agriculture, water, and other environmental resources, and for assessing other potential societal impacts (positive and negative), including human health? With what frequency and timing do these indicators need to be provided in order to allow maximum adaptive response to climate-induced change?
- What are potential entry points and barriers to the use of climate information, and how can access to and understanding of climate information and predictions be accelerated and simplified to realize their greatest value to the scientific community, public, and decisionmakers?

RESEARCH NEEDS

The scientific underpinnings for this research are the observational, diagnostic, and modeling expertise required to develop new product lines at regional levels, link global to regional climate variability and change, and infuse advances in science and technology into new climate information products. Increasing understanding of regional climate variability under current conditions is vitally important in developing downscaling methods for future climate scenarios derived from climate change model simulations, interpreting how the regional climate changes are likely to produce societal and environmental impacts, and thereby clarifying options for adaptation or mitigation strategies.

Major research needs will be to improve capabilities to describe, interpret, and predict climate variability and change and their potential consequences at regional scales, much of which is contingent on improving understanding of the range of fundamental scientific issues associated with global climate change that are outlined in this strategy. Regional "test beds" or "enterprises" will be required to develop and evaluate the effectiveness and potential use of climate information at regional scales. Such test beds will enable more effective, sustained interactions between the climate research community and the rapidly expanding base of users of climate information, particularly on regional to local scales.

PRODUCTS AND PAYOFFS

- Climate monitoring and forecast capabilities for regional applications and risk reduction (5-15 years).
- Focused regional climate discussions and assessments, including characterization of uncertainties (2-4 years).
- Enhanced extreme event monitoring, including higher resolution drought monitoring (5-15 years).
- An assessment of the adequacy of existing operational climate monitoring networks to provide regional decision support, and to identify major data gaps in addressing critical regional and policy issues (5-15 years).
- Development of real-time quantitative hazards assessments down to regional scales (5-15 years).
- A new capability to implement focused rapid responses in anticipation of predictable climate anomalies and in response to extreme events (e.g., regional impacts of ENSO; response to major droughts) (5-15 years).
- Improved documentation of the regional impacts of climate extremes, and evaluation of implications for potential future climate change (5-15 years).
- Improved access to climate information and products for addressing regional concerns and issues (5-15 years).

Key Linkages

Owing to the complex and coupled nature of the climate system it is critically important for the Climate Variability and Change research community to work cooperatively with other Climate Change Research Initiative and USGCRP research elements and other programs. Chief among these are the Water Cycle (Chapter 7), Carbon Cycle (Chapter 9), and Atmospheric Composition (Chapter 5) elements and other national and international programs that contribute to climate observations and research.

Water is a key element in all five Climate Variability and Change questions. As noted in Chapter 7, the water cycle is an integral part of the Earth's climate system (through processes involving, for example, evaporation, clouds, precipitation, snow packs, groundwater, floods, and droughts, and through feedbacks and interactions involving them). Atmospheric Composition and the Carbon Cycle are also key elements for Questions 1, 2, and 3. Interactions with other research elements, specifically Ecosystems (Chapter 10), Land Use/Land Cover Change (Chapter 8), and Human Contributions and Responses (Chapter 11), are also required to successfully implement the Climate Variability and Change research agenda. Moreover, internationally coordinated research programs such as the World Climate Research Programme (WCRP) and its projects Climate Variability and Predictability (CLIVAR), Stratospheric Processes and their Role in Climate (SPARC), Climate and Cryosphere (CliC), the Global Energy and Water Cycle Experiment (GEWEX); as well as the International Geosphere-Biosphere Programme (e.g., PAGES paleoscience project), are critical for developing global infrastructure and research activities designed to ensure that global aspects of climate variability and change are addressed.

CHAPTER 7
WATER CYCLE

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Question 1: To what extent does the water cycle vary and change with time, and what are the internal mechanisms and external forcing factors, including human activities, responsible for variability and change?

Question 2: How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

Question 3: What are the key uncertainties in seasonal to interannual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

Question 4: How do the water cycle and its variability affect the availability and quality of water supplied for human consumption, economic activity, agriculture, and natural ecosystems; and how do its interactions and variability affect sediment and nutrient transports, and the movement of toxic chemicals and other biogeochemical substances?

Question 5: What are the consequences of global water cycle variability and change, at a range of temporal and spatial scales, for human societies and ecosystems? How can the results of global water cycle research be used to inform policy and water resource management decision processes?

Key Linkages

The global water cycle is an integral part of the Earth/climate system, manifesting itself through many processes and phenomena, such as clouds, precipitation, mountain snow packs, groundwater, droughts, and floods. The cycling of water exerts an important control on climate variability as a result of its complex feedbacks and interactions with other components of the climate system. Many of the uncertainties with respect to long-term changes in the climate system and their potential impacts, as described in Intergovernmental Panel on Climate Change (IPCC) reports, arise from our inadequate understanding of, and inability to model, water cycle processes as they feed back on the climate system. In particular, clouds, precipitation, and water vapor produce feedbacks that alter surface and atmospheric heating and cooling rates, and redistribution of the associated heat sources and sinks lead to adjustments in atmospheric circulation and precipitation patterns. The current inability to adequately represent these complex multiscale processes in climate models is a major source of uncertainty in long-term climate change projections and impacts, and seasonal to interannual climate forecasts.

The needs for adequate supplies of clean water and advance preparations for extreme hydrologic events, such as floods and droughts, pose major challenges to social and economic development and to the management of natural resources and ecosystems. Water supplies are subject to a range of stresses, such as population growth, pollution and industrial and urban development. These stresses are exacerbated by variations and changes in climate that alter the hydrologic cycle in ways that are currently unpredictable. These concerns are documented in a recent report on research needs and opportunities, *A Plan for a New Science Initiative on the Global Water Cycle* (Hornberger et al., 2001). This report identified questions and strategies for research on climate change and water cycle trends, prediction, and the linkages between water and nutrient cycles in terrestrial and freshwater ecosystems.

Advances in observing techniques, combined with increased computing power and improved numerical models, now provide new opportunities for significant scientific advances through a concerted, integrated Global Water Cycle research effort. Recently, reasonably accurate predictions of variations in the water cycle have been produced for some years in some regions. This new capability to produce credible predictions provides a basis for dialogue between the scientific community and water system and land managers. This dialogue is enabling the research community to understand decisionmakers' management processes and information needs. It will also identify opportunities for improving the adaptability of infrastructure and management practices to runoff variations, long-term changes and extremes.

To address the urgent need for better information on the water cycle, the Climate Change Science Program (CCSP) is planning its Global Water Cycle research program around two overarching questions, namely:

- **How do water cycle processes (including climate feedbacks) and human activities influence the distribution and quality of water within the Earth system, and to what extent are changes predictable? How are these processes and activities linked to the cycling of important chemicals, such as carbon, nitrogen, other nutrients, and toxic substances, and how do they affect human and ecosystem health?**
- **How will large-scale changes in climate, demographics, and land use (including changes in agricultural and land management practices), affect the capacity of societies to provide adequate supplies of clean water for human uses and ecosystems and respond to extreme hydrologic events?**

Question 1: To what extent does the water cycle vary and change with time, and what are the internal mechanisms and external forcing factors, including human activities, responsible for variability and change?

STATE OF KNOWLEDGE

Recent observations suggest that there have been notable changes in critical water variables: precipitation amounts, location, and type; surface and subsurface runoff; cloud cover, both amount and type; atmospheric water vapor; soil moisture; groundwater; etc. Although techniques for measuring many of these variables have improved, the number of observations is limited and, in some cases, new sensors are needed. Current models cannot properly simulate the global water cycle. Moreover, we cannot definitively attribute observed trends to human-induced climate changes as opposed to natural variability.

ILLUSTRATIVE RESEARCH QUESTIONS

- How have the characteristics of the water cycle changed in recent years, and are the changes due to natural variability or human induced causes?
- What are the key mechanisms and processes responsible for maintaining the global water cycle and its variability over those space and time scales relevant for climate?
- How are the rates of regional groundwater recharge, soil moisture availability, and runoff production affected by changing global precipitation patterns, vegetation distributions, and cryospheric processes (processes occurring in frozen regions)?
- How have changes in land use and water management infrastructure and practices affected trends in regional and global water cycles?

RESEARCH NEEDS

New observing capabilities, both satellite and *in situ*, will be critical to detecting patterns and quantifying fluxes, especially instruments for global measurement of terrestrial water cycle variables such as soil moisture. Existing *in situ* networks need to be maintained and enhanced, and data sets developed to ensure consistency between historical and new observations. Network enhancements and open data exchange are needed to address water quantity issues in critical areas such as high mountain areas and river deltas. Also needed are new data assimilation techniques that combine different kinds of data, and data with varying spatial and temporal characteristics, to produce consistent data products for research and process studies of key water cycle variables, such as clouds, precipitation, and soil moisture. Complementary research is planned under the Land Use/Land Cover Change program (Chapter 8).

PRODUCTS AND PAYOFFS

- Documentation of trends in key variables through data analysis and comparison with model-simulated trends to evaluate uncertainty in climate predictions for policy developers (2-5 years).

- Integrated long-term global and regional data sets of critical water cycle variables from satellite and *in situ* observations for monitoring climate trends and early detection of climate change (5-15 years).
- Improved regional water cycle process parameterizations based on process studies conducted over regional test beds to improve the reliability of climate change projections (5-15 years).

Question 2: How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

STATE OF KNOWLEDGE

As global temperatures warm, the atmosphere will hold more moisture. Given the same carbon dioxide (CO_2) increase, climate models produce different rates of warming and drastically different patterns of circulation, precipitation, and soil moisture depending on their parameterizations (simplified representations) of basic water cycle processes. This large discrepancy in model predictions indicates that the representation of key water cycle processes is rudimentary at best. A better understanding of these changes and the consequences of sub-grid processes (processes occurring at smaller scales than the model grid size) are needed to improve the reliability of climate projections. In particular, while some progress has been made in cloud parameterizations, the representation of clouds and cloud processes remains the greatest uncertainty in climate models. Further, cloud processes are inextricably linked to other critical water cycle processes.

ILLUSTRATIVE RESEARCH QUESTIONS

- What is the sign and magnitude of the net water vapor-cloud-radiation-climate feedback effect and how does it vary with latitude and season?
- How do changes in water vapor and water vapor gradients, from the stratosphere to the surface, affect climate variables such as radiation fluxes, surface radiation budgets, cloud formation and distribution, and precipitation patterns, globally and regionally?
- How do aerosols, their chemical composition, and distribution affect cloud formation and precipitation processes and patterns?
- How do freshwater fluxes to and from the ocean that affect the global ocean circulation and climate vary, and how may they be changing?
- How do changes in global and regional water cycles feed back on biogeochemical processes (e.g., vegetative growth and carbon sequestration), in cold regions where climate change is expected to have a substantial impact on permafrost melting, seasonal snow packs, and freeze/thaw cycles?
- How do changes in global and regional water cycles feed back on tropical and higher-latitude regions in the form of altered frequencies of droughts, floods, and storms, including hurricanes?

RESEARCH NEEDS

Model development will be accelerated by interdisciplinary field studies over regional test beds that provide much needed understanding of scaling effects. New parameterizations of water cycle/climate feedbacks (e.g., cloud-aerosol and land-atmosphere) and sub-grid scale processes (e.g., clouds, precipitation, evaporation, etc.) will have to be developed and validated, and the sensitivity of global models to these new parameterizations will have to be evaluated. Complementary research is planned under the Atmospheric Composition (Chapter 5) and Climate Variability and Change (Chapter 6) programs, and components of these programs, accelerated through the Climate Change Research Initiative (CCRI), are described in Chapter 2.

PRODUCTS AND PAYOFFS

- New parameterizations for water vapor, clouds, and precipitation processes for use in climate models, using new cloud-resolving models created in part as a result of field process studies (see Chapter 2) (2-5 years).
- Enhanced data sets for feedback studies including water cycle variables, aerosols, vegetation, and other related feedback variables generated from a combination of satellite and ground-based data to evaluate the role of human influences in climate change (5-15 years).
- New models capable of simulating the feedbacks between the water cycle and the climate system (including biogeochemical cycles) will support the development of carbon management strategies and resource management tools (5-15 years).

Question 3: What are the key uncertainties in seasonal to interannual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

STATE OF KNOWLEDGE

Current global and regional models demonstrate limited skill in predicting precipitation, soil moisture, and runoff on time scales beyond a few days. One of the most critical deficiencies in climate change projections involves precipitation and soil moisture—essential parameters for assessments of the impacts of climate change and variability. While the large scale conditioning of the atmosphere by El Niño-Southern Oscillation (ENSO) events has been documented, memory effects of land conditions on the atmosphere are not fully quantified, and cloud and precipitation feedbacks and the interactions of the lower boundary layer (lower 500 meters of the atmosphere) with land and ocean surface conditions are not well understood. In addition, data sets are needed for the calibration of global coupled climate models and the development of regional downscaling and statistical forecasting techniques.

ILLUSTRATIVE RESEARCH QUESTIONS

- For different model resolutions, how can key water cycle processes be better simulated in current climate models, in order to enhance the capability of producing more accurate seasonal to interannual predictions of water cycle variables?
- How can the representation of water cycle processes in climate change models be improved to reduce uncertainties in climate change projections for hydrologic variables?
- What are the critical hydrological and atmospheric factors that are present in major flood and drought events that can be isolated, quantified, and incorporated into water cycle prediction methodologies?
- To what extent will the seasonality, intensity, and variability of high latitude freshwater fluxes (evapotranspiration, runoff) and stores (soil moisture, permafrost) change as a result of climate warming?
- How can we best characterize the uncertainty in the prediction of water cycle variables and effectively communicate this uncertainty to water resource managers?

RESEARCH NEEDS

Advances in prediction capabilities will depend on improvements in model structure and initialization, data assimilation, and parameter representations. Predictability studies will be required to determine the regions, seasons, lead times, and processes most likely to provide additional predictive skill. Better understanding and improved model representations of less-well-understood processes, such as the seasonal and longer-term interactions of mountains, vegetative cover, soils, oceans, and the cryosphere with the atmosphere are needed. In addition, model evaluation studies with enhanced data sets are needed to improve models and to characterize and reduce uncertainties. Complementary research is planned under the Climate Variability and Change (Chapter 6) and Carbon Cycle (Chapter 9) programs.

PRODUCTS AND PAYOFFS

- New drought monitoring and early warning tools based on improved measurements of precipitation, soil moisture, and runoff, and data assimilation techniques to inform the implementation of drought mitigation plans (2-5 years).
- Metrics (measures) for quantifying the uncertainty in predictions of water cycle variables, and progress in improving the accuracy of predictions and for making forecasts more useful in water resources management (2-5 years).
- Downscaling techniques, such as improved regional climate models, that bridge the disparate spatial and temporal scales between global model outputs and atmospheric, land surface, and river basin processes for improved evaluation of potential water resource impacts arising from climate change (5-15 years).

Question 4: How do the water cycle and its variability affect the availability and quality of water supplied for human consumption, economic activity, agriculture, and natural ecosystems; and how do its interactions and variability affect sediment and nutrient transports, and the movement of toxic chemicals and other biogeochemical substances?

STATE OF KNOWLEDGE

Our ability to quantify the role of flowing water as the primary agent for sediment transport that reshapes the Earth's surface, and for nutrient transport that feeds riparian habitats and degrades water bodies, is rudimentary. Currently, we do not have the monitoring framework needed to generate a database to support research on these processes. The priority challenges are to quantify water flow and the various transport rates, biochemical transformations, and constituent concentrations and feedbacks whereby the water cycle alters media and ecosystems. Furthermore, the consequences of variations in water availability and quality for agriculture, energy production and distribution, and urban and industrial uses need to be integrated into a common modeling framework.

ILLUSTRATIVE RESEARCH QUESTIONS

- How does the water cycle interact through physical, chemical, biophysical, and microbiological processes with other Earth system components at the watershed scale?
- How do changes in climate, land cover, and non-point waste discharges alter water availability, water quality, and the transport of sediments, nutrients, and other chemicals, and how do these changes affect human and ecosystem health?
- How do surface and subsurface processes change the quality of water available for human and environmental uses?

RESEARCH NEEDS

Overall, there is a basic need to develop an integrated research vision (complete with hypotheses) for addressing multiple-process (hydrological, physical, chemical, and ecological) interactions between water and other Earth systems. Techniques that scale up processes active at watershed and sub-watershed scales to the larger scales widely used in climate studies must be developed and tested. In addition, it is necessary to refine geophysical methods and the use of tracers, including isotopes, to determine subsurface paths, flow rates, and residence time, and to track pollution plumes. Complementary research is planned under the Land Use/Land Cover Change (Chapter 8), Carbon Cycle (Chapter 9), Ecosystems (Chapter 10), and Human Contributions and Responses to Environmental Change (Chapter 11) programs.

PRODUCTS AND PAYOFFS

- Reliable, commensurate data sets at the watershed scale that scientists from various disciplines will use to examine critical water-Earth interactions for improved integrated watershed management (2-5 years).
- Models that partition precipitation among surface and subsurface pathways, route flows, and quantify physical and chemical interactions for evaluating climate and pollution impacts (5-15 years).
- Development and application of more cost effective methods for monitoring subsurface waters for inventorying current and future water availability (5-15 years).

Question 5: What are the consequences of global water cycle variability and change, at a range of temporal and spatial scales, for human societies and ecosystems? How can the results of global water cycle research be used to inform policy and water resource management decision processes?

STATE OF KNOWLEDGE

Variability and changes in the water cycle have been shown to lead to profound impacts on human societies and ecosystems (including on human health), but many of the linkages between change and outcome are not yet understood in the detail needed for appropriate policy and management responses. Water management takes place within a set of constraints that include, among other things, stringent flood control standards, federal and state environmental regulations, hydropower production schedules, and increasing irrigation, urban, industrial, and recreational demands for water. There is evidence that the results of recent research on the water cycle can contribute to the decisionmaking capacities of policymakers and water managers who must operate within these constraints. However, advances in water cycle research have found little use in water management and decisionmaking. Factors such as regulatory inflexibility, institutional structures, and time pressures make it difficult to change established management and decision systems. In addition, there is a mismatch between research products and operational information needs. Efforts to eliminate the barriers between research and research users have been initiated and indicate that early collaboration and side-by-side demonstrations may be effective tools for speeding innovation.

ILLUSTRATIVE RESEARCH QUESTIONS

- How can water cycle research products, such as the hydroclimatological projections (predictions of future states of hydrologic components (e.g., runoff) of the climate system) and forecasts from global and regional climate models, remote sensing data streams, and snow pack information, be deployed to improve policy decisions and water resource management?
- What is the best means for transferring climate/water cycle variability and long-term change information into operational reservoir management and hydropower production, and the planning and design of water resources infrastructure?

- What are the gaps in current understanding of water cycle functions critical to US riparian (relating to rivers) and estuary environments and what research activities are needed to close those gaps?
- What are the implications of water cycle research for managing conflicting demands on transboundary waters?
- What are the current patterns of water consumption and how are they likely to change as a result of potential changes in temperature, land cover and land use, demographics, and water policies?
- What kinds of changes in institutional arrangements and management practices will be needed to respond to changes in water resource availability over a range of temporal and spatial scales?

RESEARCH NEEDS

In order to make rapid progress in projecting the consequences of variability and change it will be necessary to integrate data from a broad range of sources and disciplines. Basic needs to achieve this goal include frameworks for integration, such as improved mechanisms for integrating remote sensing, GIS capabilities, and existing databases in decision support tools for water managers. In order to determine patterns and trends, it will also be necessary to inventory existing data sources and regional and sectoral studies, especially for data for which regional, national, and global repositories are rare or non-existent, such as for water demand, diversion, use, and consumption. In order for scientific information to have an impact, it will have to rely on refined and extended research on the role, entry points, and types of water cycle knowledge required for water management and policy decisionmaking processes. Complementary research is planned under the Climate Variability and Change (Chapter 6), Land Use/Land Cover Change (Chapter 8), and Human Contributions and Responses to Environmental Change (Chapter 11) programs.

PRODUCTS AND PAYOFFS

- Technology transfer and enhanced capability to produce operational streamflow forecasts over a range of spatial and temporal scales (days, weeks, months, and seasons), for more effective water management decisions (2-5 years).
- Decision support tools integrating historic climate variability, water cycle predictions, and socio-economic analyses to produce planning and management tools that include these major decision factors (2-15 years).
- Observing system simulation and forecast demonstrations using advanced watershed and river system management models and decision support systems, to facilitate acceptance and utilization of these advanced technologies for improved hydropower production and river system management (5-15 years).
- Integrated models of total water consumption for incorporation into decision support tools that identify water-scarce regions and efficient water use strategies (5-15 years).

Key Linkages

A strong Global Water Cycle research program is essential for, and will derive critical inputs from, the following CCSP elements: Climate Variability and Change, Carbon Cycle, Land Use/Land Cover Change, Ecosystems, Atmospheric Composition, and Human Contributions and Responses to Environmental Change. In particular, the modes of water cycle variability arising from ocean sea surface temperatures will be addressed by the Climate Variability and Change element. Furthermore, to carry out this ambitious Global Water Cycle program, support will be required in the areas of Climate Quality Observations (Chapter 3) and in Decision Support Resources (Chapter 4). In addition, there will be a need to work closely with the Decision Support Resources activity to ensure that Water Cycle research is more effectively used in policy development and decisionmaking. Finally, sustained progress toward answering the questions addressed by the Global Water Cycle research program will depend on development of the modeling, observations, and information systems described in Chapter 12.

There are strong international linkages between the Global Water Cycle program and the World Climate Research Programme's (WCRP) Global Energy and Water Cycle Experiment (GEWEX). Other connections to international programs occur in the observational area with Integrated Global Observing Strategy (IGOS) Partners in terms of its emerging Water Cycle theme as well as the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS). In addition, the water cycle program will collaborate with a number of international programs concerned with water cycle research, water resources, and climate. These include the WCRP, International Geosphere-Biosphere Programme (IGBP), International Human Dimensions Programme (IHDP), and Diversitas Joint Water Project; the World Meteorological Organization's Hydrology and Water Resources Programme; and United Nations Educational, Scientific and Cultural Organization's International Hydrology Program and Hydrology for Environment, Life and Policy (HELP), as well as the Dialogue on Water and the 3rd World Water Forum. Also, the Global Water Cycle program will contribute to work through bilateral treaties, particularly with countries like Japan, that have placed a priority on water cycle research.

References:

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CHAPTER 8

LAND USE/LAND COVER CHANGE

This chapter's contents…

Question 1: What are the primary drivers of land use and land cover change?

Question 2: What tools or methods are needed to allow for better characterization of historic and current land use and land cover characteristics and dynamics?

Question 3: What advances are required to allow for the projection of land use and land cover patterns and characteristics 10-50 years into the future?

Question 4: How can projections be made of potential land cover and land use change over the next 10-50 years for use in models of impacts on the environment, social and economic systems, and human health?

Question 5: What are the combined effects of climate and land use and land cover change and what are the potential feedbacks?

Key Linkages

Land use and land cover change is perhaps the most prominent form of global environmental change since it occurs at spatial and temporal scales immediately relevant to our daily existence. The changes in land use and land cover, especially when coupled with climate change and variability, are likely to affect natural resources and ecosystems in complex ways. The National Research Council recently identified Land Use Dynamics as one of the grand challenges for environmental research (NRC, 2001d).

Determining the effects of land use and land cover change depends on an understanding of past land use practices, current land use and cover patterns, and projections of future land use and cover, as affected by human institutions, population size and distribution, economic development, technology, and other characteristics. The combination of climate and land use change may have profound effects on the habitability of the planet in more significant ways than either acting alone. While land use change is often a driver of environmental and climatic changes, a changing climate can in turn affect land use and land cover. Climate variability alters land use practices differently in different parts of the world, highlighting differences in societal vulnerability and resilience. The feedback between land use and climate change is poorly understood and will require the development of new models linking the geophysics of climate with the socioeconomic drivers of land use. Providing a scientific understanding of the process of land use change, the impacts of different land use decisions, and how they will be complicated by a changing climate and increasing climate variability is a priority area for research.

This research element provides the scientific underpinning for land use decisionmaking and projections of future land use, and has substantial benefits beyond climate change assessment and mitigation by supporting a wide array of issues important to public users of this information. To meet multiple objectives, the land use and land cover change research element will address two overarching questions:

- **What processes determine the temporal and spatial distributions of land cover and land use change at local, regional, and global scales, and how can land use and land cover be projected over time scales of 10-50 years?**
- **How may the dynamics of land use, management, and cover change affect the global environment and national environmental and socioeconomic conditions, including economic welfare and human health?**

To address these overarching questions and to make the science useful for decisionmaking will require a focused research agenda that includes ongoing mapping, measurement, and monitoring of land use and land cover change from local to global scales; identification of the driving forces or agents of change; the capabilities to model and project future changes in land use and land cover; and assessment of the implications of land use change. In addition, research collaboration with other program elements will be necessary to gain detailed understanding of the direct impacts of land use and land cover change on climate, as well as the combined effects of land use and climate change on ecosystems and water and carbon cycles. Answers to the overarching questions will require research focused on the five specific questions posed below.

Question 1: What are the primary drivers of land use and land cover change?

STATE OF KNOWLEDGE

The ability to forecast land use and land cover change and, ultimately, to predict the consequences of change, will depend on our ability to document and understand the past drivers of land use and land cover change. Historical land use and cover change has occurred primarily in response to population growth, technological advances, economic opportunity, and public policy. Patterns of human settlement are shaped by both the interaction of environmental (e.g., climate, geology, topography, and vegetation) and social (e.g., cultural customs and ethnicity) forces around the world. An improved understanding of historical land use and land cover patterns provides a means to evaluate variations in past causal factors and responses as well as a method for evaluating the trends of human activities present in the current baseline. The systematic evaluation of these historical and contemporary factors will improve the ability to develop projections of future land use and management decisions. This type of analysis will require the integration of various disciplines from the physical and social sciences.

ILLUSTRATIVE RESEARCH QUESTIONS

- How does the historical development and spread of land uses reveal the various events and trends that shaped its expansion at different points in the past?
- Why and how have land use and land management systems (e.g., agriculture) spread historically?
- How have the driving forces of change affected the rates and patterns of historical and contemporary change at different (i.e., local, regional, and global) scales?
- How, and to what extent, do extreme events (e.g., natural hazards, public health emergencies, and war) affect land use and land cover change?
- How will environmental, institutional, political, technological, demographic, and economic processes determine the temporal and spatial distribution of land use and land cover over the next 50 years?

RESEARCH NEEDS

Improvements are needed in process models of land use and land cover change dynamics in space and time, combining field-level case studies for analysis of processes, statistical studies for large regions, and empirical analyses using remote sensing change detection. This process-level understanding of land use and cover dynamics will aid the analysis of land use and land cover change across scales. Work will also be required to understand how, for example, one agent or cause of land use change influences another. This comprehensive understanding of land use and cover change processes also needs to consider interactions between socioeconomic factors and biophysical factors, including synergies between land use dynamics and climate change and variability.

PRODUCTS AND PAYOFFS

- Summary of the regional driving forces of US land use and land cover change (< 2 years).
- Contemporary (last 30 years) rates of US land cover change (2-4 years).
- Long-term (300 years) national land use and land cover history (2-4 years).
- Long-term (300 years) global land use and land cover history (>4 years).
- Analysis of the impact of major disturbances on land use and land cover (>4 years).

Question 2: What tools or methods are needed to allow for better characterization of historic and current land use and land cover characteristics and dynamics?

STATE OF KNOWLEDGE

A significant component of this research element involves improvements in data collection systems and data products. Research on current land use and land cover will provide new information to enable the production of regular updates on the distribution of land cover at scales relevant for global-scale analyses and resource management decisions. The information will also provide the data needed to parameterize climate and other environmental factors in models. Remote sensing provides quick and comparatively inexpensive information about land cover changes over large areas. Ground-based networks in the United States also offer a wealth of historical data (often with data records extending back 50-100 years), and can provide detailed information on site conditions, including species composition, soil type, habitat quality, tillage and crop rotation history, wildlife population statistics, and land use classification. Integrating ground-based and remote sensing data collection systems provides an opportunity to vastly improve the speed and overall quality of land use and land cover data for use in applied research.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are the current patterns and attributes of land use and land cover at national to global scales that affect the carbon cycle, atmospheric processes, and ecosystem form and function?
- What are the national and global rates, patterns, and characteristics of contemporary land use and land cover change?
- Where are the current hot spots of rapid land use and land cover change at the national and global levels?
- What improvements need to be made to current observing systems and what programs need to be put in place to provide the necessary long-term data and information to support the study of land use and land cover change at the global, regional, and national scale?
- What are the methodological advances needed to improve land use and land cover change analyses, including strategies for integrating ground-based data, socioeconomic statistics (e.g., census information), and remotely sensed measurements?

RESEARCH NEEDS

Evolving public and private land management questions call for new types of data and information and improved scientific bases for decisionmaking. They also require long-term continuity in data collection, and the acquisition of data at the global scale. With the current suite of satellite sensing systems and archived data sets available to the research community, studies at the large spatial scales needed to depict land cover and management changes can begin. While considerable progress has been made in mapping land cover characteristics, the ability to accurately map the wide range of landscape attributes, including land use and biomass, will require a considerable research effort. In addition, improvements in remotely-sensed data quality and in algorithms for detection of local changes and their characteristics are needed. Data integration will be a particularly important research strategy so that *in situ*, remotely sensed, and other forms of data can be merged and used to derive the needed land use and land cover information. As scientific demands and needs for land use and land cover information change, parallel innovation in the resulting data products will be essential.

PRODUCTS AND PAYOFFS

- National land cover database that includes attributes of land cover and vegetation canopy characteristics (<2 years).
- Global moderate resolution land cover database with attributes required for environmental parameterization (<2 years).
- Map of global land use and land cover change hot spots (<2 years).
- Quantification of rates of US land use and land cover change (<2 years).
- Improvements in land use and land cover change detection procedures that enable accurate and real time detection of local to global change (2-4 years).
- Continued acquisition of calibrated coarse, moderate, and high-resolution remotely-sensed data (2-4 years).
- Global high-resolution land cover database with attributes required for national to global scale applications (>4 years).
- Operational global monitoring of land use and land cover conditions (>4 years).

Question 3: What advances are required to allow for the projection of land use and land cover patterns and characteristics 10-50 years into the future?

STATE OF KNOWLEDGE

In order to understand the historical and contemporary linkages between land use and land cover change and its resulting effects on biogeochemical cycles, climate, ecosystem health, and other systems, it will be necessary to make significant advances in documenting the rates and causes of land use and land cover change. Our current understanding of historic land use and land cover change is weak due to the anecdotal nature of past research in this area. Future understanding of land use and land cover changes will be greatly improved due to new systematic methods and study designs for land use change research. In order to understand the forces of change that operate at different scales, it will be necessary to conduct studies that explicitly reveal the regional variations in change characteristics. With this, the historical and contemporary data needed to develop models that project land use and land cover for specific intervals into the future will be produced.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are the research challenges associated with developing a new generation of land use models resulting from multiple and potentially interacting agents and causes and that address environmental and socioeconomic impacts?
- Given specific climate, demographic, and socioeconomic projections, what is the current level of skill in projecting characteristics of land use and land cover change 5, 10, 20, 40, and 50 years into the future?

RESEARCH NEEDS

A new suite of models that combine physical, socioeconomic, and climate data to model projected changes at scales relevant to resource management are needed. This calls for a better understanding of the drivers of land use change and credible predictions of land cover and land use at decadal time scales. Integration among the Carbon Cycle (Chapter 9), Ecosystems (Chapter 10), and Human Contributions and Responses (Chapter 11) research elements will be needed to develop and test models needed to generate scenarios of land use and land cover change and projections of change that take into account the various influences of ecosystem functioning, carbon, water, and energy cycling as well as human managed systems. Model validation will be a particularly challenging element of this research area. Simulation of past conditions will be a necessary strategy for testing the performance of models, placing more significance on the need to understand land use and land cover change in both an historical and contemporary context.

PRODUCTS AND PAYOFFS

- Urban growth models (<2 years).
- Identification of the regional components of a US land use and land cover change model (<2 years).
- National land use and land cover change projection model.
- Identification of the regional components of a global land use and land cover change model (2-4 years).
- Global-scale land use and land cover change projection model (>4 years).

Question 4: How can projections be made of potential land cover and land use change over the next 10-50 years for use in models of impacts on the environment, social and economic systems, and human health?

STATE OF KNOWLEDGE

There is clear evidence that changing land use and land cover has significant impacts on local environmental conditions and economic and social welfare. Some of the impacts are local while others have global ramifications. For example, estimates of trace gas emissions and removals by sinks depend strongly on land cover and land use practices, while the deposition of atmospheric constituents affects the potential rate and magnitude of terrestrial sinks. The water cycle depends heavily on vegetation, surface characteristics, and water resources development by humans (e.g., dam construction, irrigation, channeling, and drainage of wetlands), which in turn affect forecasts of water availability and quality. The other Climate Change Science Program (CCSP) research elements provide complementary information about the environmental and biophysical forces that influence potential land uses (e.g., atmospheric chemistry and processes, climate variability and change, water resources, nutrient flows, and ecological processes) and the anthropogenic pressures that will give rise to various land uses and processes (e.g., the Human Contributions and Responses element, Chapter 11). The land use/land cover change element will develop projections of changes in land cover and use that are critical to developing accurate forecasts in the other areas of the program. The following research questions address the effects of changes in land use and land cover on other research elements (i.e., Ecosystems, Water Cycle, and Carbon Cycle). Research will require multidisciplinary cooperation to develop land use and land cover projections that address the necessary spatial and temporal scales, and include the necessary physical, biological, and social factors of interest, to ensure that projections of land use and land cover can be incorporated into models of impacts.

ILLUSTRATIVE RESEARCH QUESTIONS

- How will acute land use change stress or enhance the productivity of our natural resource base and the industries that depend on it, including agriculture and forestry?
- How will changes in urban and rural land use and land cover influence the spatial and temporal distribution of wildlife and what are the resulting economic, social, and ecological impacts?
- How will the form and use of public lands change given different climate change scenarios, and how will those changes affect the management of the vital economic and ecological resources of those lands?

RESEARCH NEEDS

In order to understand the impacts of land use and land cover change, there must be ongoing close cooperation with other CCSP research elements that will improve understanding of the interrelationships and dynamic feedbacks between land use/land cover change and carbon, ecosystems, atmospheric chemistry, water resources, and climate variability. The challenge will be to use contemporary impacts of land use and land cover change to calibrate impacts on ecosystem goods and services; biogeochemical, water, and energy cycles; and climate processes. These investigations must be undertaken on multiple scales so that the full dimensions of the perturbations of environmental processes can be determined.

PRODUCTS AND PAYOFFS

- Report on the impacts of urbanization on other land uses (<2 years).
- Maps and evaluations of the relationship between US urban areas and wildfire hazards (<2 years).
- Report evaluating the impacts of land use and land cover change in the coastal zones of the United States on coastal resources (2-4 years).
- Reports on the relationship between land use and land cover change and human health (with the Human Contributions and Responses research element) (2-4 years).

Question 5: What are the combined effects of climate and land use and land cover change and what are the potential feedbacks?

STATE OF KNOWLEDGE

Land use and land cover change is linked in complex and interactive ways to other global environmental changes, human actions (both as causes of change and responses to impacts), and environmental feedbacks at multiple spatial and temporal scales. The outflow of soil nutrients, for example, has immediate impacts on land productivity, vegetation, and soil erosion rates; medium-term impacts on landscape fragmentation, land productivity, and downstream aquatic ecosystems; and possible long-term impacts on climate. Land use and land cover change, climate change, and other environmental changes all interact to affect natural resources. The research associated with this question will require collaboration with the Climate Variability and Change (Chapter 6), Ecosystems (Chapter 10), Water Cycle (Chapter 7), and Carbon Cycle (Chapter 9) research elements.

ILLUSTRATIVE RESEARCH QUESTIONS

- How will the combined effects of land use and climate change affect agriculture, aquatic ecosystems, rangeland, and forest extent and productivity, and what are the implications for land management and economics?
- How does the combined stress of climate and land use change affect our ability to mitigate and manage greenhouse gases?
- What is the impact of future changes in land use and land cover on water supply and quality, considering climate-induced changes in the patterns and characteristics of water resources (research will be undertaken with the Water Cycle team)?
- Using focused case studies, how can landholders, land managers, and decisionmakers formulate land use and land management decisions and practices at various scales in light of climate change?

RESEARCH NEEDS

Development of coupled climate-land use/cover models, that incorporate socioeconomic factors, should be accelerated. Simulation of climate-land use/cover feedbacks will require advancement of current understanding of multiple stress processes at local to global scales. Validation of the interacting climate-land use effects for specific regions of the globe will be particularly challenging. International cooperation will be needed to optimize the currently existing and emerging observational networks.

PRODUCTS AND PAYOFFS

- Climate models incorporating land use and cover data (<2 years).
- Identification of the regions in the United States where the combination of land use effects and climate change may be most pronounced (<2 years).

- Report on how urban expansion of impermeable surfaces and associated "heat islands" affect regional weather and climate, primarily with respect to temperature and precipitation patterns (<2 years).
- Evaluation of how the type and distribution of land cover affects regional weather and climate patterns (2-4 years).
- Global-scale, fully interactive climate-land use/cover model (>4 years).
- Report on trends in land cover or land use that are attributable to changes in climate (e.g., changes in forest type, changes in specific agricultural crops, or changes in the presence or absence of agriculture) (>4 years).
- National model with a coupled climate-land use system (>4 years).

Key Linkages

The implementation of the Land Use and Land Cover Change research element will require an interdisciplinary approach involving scientists from physical, natural, and social science communities. Crucial to these activities will be the transfer of accrued knowledge to policy and decisionmaking communities. Success will depend on close linkages with other CCSP research elements. In particular, collaboration with the Water Cycle (Chapter 7), Carbon Cycle (Chapter 9), Ecosystems (Chapter 10), and Climate Variability (Chapter 6) research elements will be needed to understand the larger effects of land use and land cover changes over time.

Regional observational and monitoring networks and associated case studies are key to understanding phenomena at fine scales, and provide a test bed for models and a mechanism for comparative analysis. In the next 10 years the establishment of international land use and land cover science programs will augment ongoing efforts such as the International Geosphere-Biosphere Programme to help bridge the gap between climate change researchers, land managers, and decisionmakers. For example, Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) is a new program for coordinating global land observations, implemented through regional networks of data providers and users to address a combination of global change and natural resource management questions, and engaging local scientists with local and regional expertise and knowledge.

Another example is the United Nations (UN) Land Cover Network - an emerging cooperative activity of the UN Food and Agriculture Organization (FAO) and the UN Environment Programme (UNEP) to develop monitoring and measurement of land cover change in support of their global environmental outlooks and assessments (e.g., the Millennium Ecosystem Assessment). In addition to these activities, development agencies are attempting to address questions concerning the societal impacts of global change through new programs such as the US Agency for International Development's (USAID) Geographic Information and Sustainable Development program. Such programs can help in strengthening the scientific underpinning for the decisionmaking process.

There are a number of programs that have identified land use and land cover change as part of their individual agency research agendas (e.g., the National Aeronautics and Space Administration, the US Geological Survey, the National Science Foundation, the US Environmental Protection Agency, and the US Department of Agriculture) and have played an active role in developing this research element. It will be important as the program proceeds to engage multiple agencies and organizations working in this and related fields (e.g., the National Institutes of Health, the Department of Transportation, the Bureau of Land Management, and USAID). In the next decade of global change research it will be particularly important to include stakeholders (e.g., the Council of Governors, non-governmental organizations, and state and local land managers) in guiding this research element.

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CHAPTER 9

CARBON CYCLE

This chapter's contents…

Carbon is important as the basis for the food and fiber that sustain and shelter human populations, as the primary energy source that fuels economies, and as a major contributor to the planetary greenhouse effect and potential climate change. Atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4) have been increasing for about two centuries as a result of human activities. Future atmospheric concentrations of these greenhouse gases will depend on trends and variability in natural and human-caused emissions, and the capacity of terrestrial and marine sinks to absorb and retain carbon.

Elevated atmospheric CO_2 concentrations, additions of nutrients, and changes in land management practices can significantly enhance (and sometimes reduce) ecological carbon sinks. Engineering approaches for carbon sequestration provide additional options to reduce atmospheric greenhouse gas concentrations or reduce their rate of increase. However, uncertainties remain about how much additional carbon storage could be achieved, the efficacy and longevity of carbon sequestration approaches, whether they will lead to unintended environmental consequences, and just how vulnerable or resilient the global carbon cycle is to such manipulations. Successful carbon management strategies will require solid scientific information about the basic processes of the carbon cycle and an understanding of its long-term interactions with other components of the Earth system such as climate and the water and nitrogen cycles. Breakthrough advances in techniques to observe and model the atmospheric, terrestrial, and oceanic components of the carbon cycle have readied the scientific community for a concerted research effort to identify, characterize, quantify, and predict the major regional carbon sources and sinks—with North America as a near-term priority.

The overall goal for the US Carbon Cycle Science Program research is to provide critical scientific information on the fate of carbon in the environment and how cycling of carbon might change in the future, including the role of and implications for societal actions. In this decade, research on the carbon cycle will focus on two overarching questions:

- **How large and variable are the dynamic reservoirs and fluxes of carbon within the Earth system, and how might carbon cycling change and be managed in future years, decades, and centuries?**
- **What are our options for managing carbon sources and sinks to achieve an appropriate balance of risk, cost, and benefit to society?**

National and international decisionmakers have called for better information on the global carbon cycle in order to reduce uncertainties concerning the potential for climate change and to evaluate carbon sequestration options for climate change mitigation. A well-coordinated, interagency, and multidisciplinary research strategy, bringing together a broad range of needed infrastructure, resources, and expertise, will be essential in providing this information. Specific research questions that will be addressed in support of the two overarching questions are covered in the following sections.

Question 1: What are the magnitudes and distributions of North American carbon sources and sinks and what are the processes controlling their dynamics?

STATE OF KNOWLEDGE

There is growing evidence of a current Northern Hemisphere terrestrial sink averaging 1.8 billion metric tons of carbon per year. Recent work suggests that this sink may be a result of land use change, including recovery of forest cleared for agriculture in the last century, and land management practices, such as fire suppression. Other studies suggest that elevated CO_2, nitrogen deposition, and changes in regional rainfall patterns also play a role. Atmospheric studies indicate that the terrestrial sink varies significantly from year to year. Current estimates of regional distributions of carbon sources and sinks derived from atmospheric and oceanic data differ from forest inventory and terrestrial ecosystem model estimates. The Carbon Cycle

Science Program has created a structure for coordinating observational, experimental, analytical, and data management activities needed to address the discrepancies, to reduce the errors, and produce a consistent result for North America in a North American Carbon Program (NACP). Assuming corresponding international research projects in Europe and Asia, this research will contribute to improving estimates of quantities, locations, and uncertainties of the Northern Hemisphere carbon sink.

ILLUSTRATIVE RESEARCH QUESTIONS

- How large and variable are North American carbon sources and sinks?
- What are the most important mechanisms, both natural and human caused, that control North American carbon sources and sinks, and how will they change in the future?
- How much do North America and adjacent ocean basins contribute to the Northern Hemisphere carbon sink?

RESEARCH NEEDS

Continued and enhanced NACP research will require multidisciplinary investigation of atmospheric concentrations, vertical profiles, and transport of CO_2 and CH_4; micrometeorological estimates of net CO_2 and CH_4 fluxes with accompanying biometric measurements at ecosystem and landscape scales; biomass and soil inventories of carbon in forests, crop and range lands, and unmanaged ecosystems; coastal zone carbon processes; and carbon modeling to integrate and assimilate diverse sources of data. A field program, with intensive campaigns and remote sensing of productivity and land cover, will be conducted initially at a central location in the United States, and subsequently expanded to include the entire continent. Research on ecosystem and ocean margin processes that control carbon exchange, including experimental work, will be needed to explain changes in sources and sinks and to parameterize models. Improved ecosystem, inverse, and data assimilation modeling approaches will be needed to analyze carbon source and sink dynamics.

PRODUCTS AND PAYOFFS

- Prototype *State of North American Carbon Report* (2 years).
- Quantitative measures of atmospheric CO_2 and CH_4 concentrations in undersampled locations (2-4 years).
- Carbon cycle models: customized for North America (2-4 years); with improved physical controls and characterization of respiration (2 years); and the first carbon data assimilation models (2-4 years).
- Quantitative estimates of carbon fluxes from managed and unmanaged ecosystems in North America, with regional specificity and uncertainties quantified (> 4 years).
- Landscape-scale estimates of carbon stocks in agricultural, forest and range systems and unmanaged ecosystems from spatially resolved carbon inventory and remote sensing data (> 4 years).
- Identification of the processes controlling carbon sources and sinks through manipulative experiments, studies of disturbance, and integration of decision sciences and risk management studies (> 4 years).

- Comprehensive *State of North American Carbon Report* (> 4 years).

New data and models will provide enhanced capability for estimating the future capacity of carbon sinks, which will guide full carbon accounting on regional and continental scales. These results are a prerequisite for planning, implementing, and monitoring carbon sequestration practices in North America. Decisionmakers will receive a series of increasingly comprehensive and accurate reports about the status and trends of carbon emissions and sequestration in North America for use in policy formulation and resource management.

Question 2: What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and which processes control their dynamics?

STATE OF KNOWLEDGE

The ocean plays a significant role in the global carbon cycle. Globally, the ocean's net uptake of carbon is estimated to be approximately 2 billion metric tons of carbon per year. However, uncertainties remain in this estimate due to regional variations in ocean uptake, seasonal to interannual variation in nutrient supply, and inadequate representation of coastal margins in models. The discovery that iron is a limiting nutrient for major regions of the world's ocean has profound implications for understanding controls on ocean carbon uptake, as well as for evaluating carbon management options. Estimates of regional ocean sinks can now be used in combination with atmospheric data to constrain estimates of terrestrial carbon sinks. Near-term focus will be on the North Atlantic, North Pacific, and Southern Oceans to provide independent constraints on estimates of the Northern Hemisphere carbon sink.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are the locations and magnitudes of global ocean carbon sources and sinks?
- What biogeochemical, ecological, and physical processes control the uptake and release of carbon in the ocean, and how may these processes change in the future due to elevated atmospheric CO_2 and climate change?

RESEARCH NEEDS

The Carbon Cycle Science Program will need to continue and enhance ocean observations (*in situ* and remotely-sensed) to track the fate of carbon in the ocean, characterize fluxes of CO_2 from the land and atmosphere to the ocean over large space and time scales, and to achieve process-level understanding of the physical and biological controls on those fluxes now and in the future. The program will generate data required to support the development and implementation of models linking climate, ocean circulation, and ocean carbon biogeochemistry to assess more accurately the relationship of carbon sources and sinks to global and climatic change. Focused process studies in the North Atlantic, North Pacific, and along the margins of those basins, including inputs from rivers, are needed in the next several years to permit quantification of the Northern Hemisphere carbon sink and to develop needed understanding of the mechanisms and magnitudes of carbon exchange between land, sea, and air. In 5-10 years, an intensive Southern Ocean carbon program will be needed to resolve uncertainties in the size, dynamics, and global significance of the Southern Ocean as a carbon sink as well as the processes controlling this sink.

PRODUCTS AND PAYOFFS

- Greater understanding of the role of nutrients (including iron inputs), phytoplankton functional groups, and primary productivity on deep-sea carbon storage (2-4 years).
- Models of ocean carbon cycling based on linkages between carbon and nitrogen in coastal environments (2-4 years).
- Quantification of global air-sea fluxes of CO_2, delivery of carbon from the land to the ocean, and the spatial distribution of carbon in the ocean on seasonal to interannual time scales using remote measurements and *in situ* measurements from newly-developed autonomous CO_2 sensors (> 4 years).
- Models of ocean carbon sequestration that incorporate biogeochemistry, ocean circulation, and the potential impact on ecosystems (> 4 years).

This research will quantify the capacity of the oceans to absorb fossil fuel CO_2 and remove carbon from the Earth's dynamic reservoirs through export to the deep sea. Uncertainties in the size of the global oceanic carbon sink will be reduced. Information will be provided on the effects of deliberate carbon management approaches for the ocean.

Question 3: What are the magnitudes and distributions of global terrestrial, oceanic, and atmospheric carbon sources and sinks and how are they changing over time?

STATE OF KNOWLEDGE

A major advance in the past decade has been the ability, enabled by new techniques for atmospheric measurement, to distinguish the roles of the ocean and land in the uptake and storage of atmospheric carbon. Inverse modeling approaches are beginning to allow continental-scale resolution of sources and sinks, but with significant uncertainties. Key processes dominating uptake and release of carbon can vary in different regions of the world, and can change in response to changes in natural and human forcings. New remote sensing observations have engendered a new appreciation for the significant spatial and temporal variability of primary productivity in Earth's ecosystems. There is a growing realization that the carbon cycle must be studied as an integrated Earth system carbon cycle.

ILLUSTRATIVE RESEARCH QUESTIONS

- What is the current state of the global carbon cycle?
- What natural processes and human activities control carbon emissions and uptake around the world?

- How will changes in climate, atmospheric CO_2 concentration, and human activity influence carbon sources and sinks both regionally and globally?

RESEARCH NEEDS

Sustained investments will be needed in the collection, reporting, analysis, and integration of relevant global carbon monitoring and inventory data; in our understanding of carbon cycling processes; and in the development of coupled, interactive carbon-climate and, ultimately, Earth system models. New *in situ* and space-based observational capabilities will be needed. Process studies must focus on characterizing key controls as they vary around the world and on explaining changes in the growth rates of atmospheric CO_2 and CH_4. Improving models will require development of innovative new assimilation and modeling techniques and rigorous testing, evaluation, and periodic intercomparison. The carbon cycle science program will collaborate with all CCSP research elements to assemble, merge, and analyze carbon, biogeochemical, physical, and socioeconomic information for comprehensive reporting on the state of the global carbon cycle. An ongoing dialogue with stakeholders will be essential to ensure that the carbon cycle information provided will be useful. Continued international cooperation will be necessary to achieve results and ensure widespread utility.

PRODUCTS AND PAYOFFS

- US component of international carbon observing system, including carbon storage, fluxes, and complementary environmental data (ongoing; enhancements within 2 years).
- Identification and quantification of the processes controlling soil carbon storage and global CO_2 exchange among the land, ocean, and atmosphere (2-4 years).
- First prototype *State of the Global Carbon Cycle Report* (4 years).
- Global maps of carbon storage derived from model-based analysis of actual land cover (1 kilometer resolution: 2 years; 30 meter resolution: > 4 years).
- Estimates of carbon flux strength in remaining regions of the world with significant uncertainties (i.e., regions not addressed in questions 1 and 2 above) (Amazon forest: 2-4 years; Northern Eurasia: 4 years; Pan-tropics: > 4 years; balanced global carbon budget: > 4 years).
- Global, synoptic data products from satellite remote sensing documenting changes in primary productivity, biomass, vegetation structure, land cover, and atmospheric column CO_2 (all but CO_2 ongoing; CO_2 > 4 years).
- Evaluation of the potential for dramatic changes in carbon storage and fluxes due to changes in climate, atmospheric composition, and ecosystem disturbance, and characterization of potential feedbacks to the climate system (> 4 years).
- Full *State of the Global Carbon Cycle Report* (> 4 years).

Policymakers and resource managers will be provided with consistent, integrated, and quantitative information on global carbon sources and sinks that can be used in national and worldwide carbon accounting and for evaluating carbon management activities. Improved global carbon models and understanding of key process controls on carbon uptake and emissions, including regional variations, will be made available to improve applied climate models and inform scenario development for decision support.

Question 4: What are the effects of past, present, and future land use change and resource management practices on carbon sources and sinks?

STATE OF KNOWLEDGE

Historic and current land use changes and resource management practices impact the overall carbon cycle. For example, there has been widespread reforestation since 1900 in the eastern United States following the movement of agricultural production toward the Midwest. Forest growth and conversion of forests to long-lived wood products increase the carbon stored in the forest products pool. Better land management practices (e.g., reduced soil tillage in cropping systems), increased agricultural productivity, and conversion from cropland to grassland can increase carbon storage in soil. However, changes in land use and management, such as clearing forests and grasslands and intensive tillage and harvest practices, release CO_2 to the atmosphere. Research in this area will require collaboration with the Land Use and Land Cover Change research element to document global patterns of land use and land cover and to understand changes in them, along with land management practices, as powerful drivers of terrestrial carbon sinks and sources. This information highlights an urgent need for improved understanding of the processes of land use change and the impacts of environmental and resource management decisions.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are the roles of past and current land use and management in terrestrial carbon sources and sinks at local to continental scales?
- How do resource management practices and likely future changes in management affect carbon that is stored in terrestrial ecosystems and durable products?
- How do social, political, and economic forces influence human decisions regarding land use and resource management, and how might changes in these forces affect the carbon cycle?

RESEARCH NEEDS

Maintenance and enhancement of the data collection and synthesis capabilities of national networks of long-term experimental sites in forests, rangelands, wetlands, agricultural lands, and other ecosystems is needed to provide an essential foundation of ecosystem monitoring data. US Carbon Cycle research will collaborate closely with operational resource management and inventory programs to ensure the availability of these needed long-term observations of ecological processes, environmental changes and impacts, and treatment effects. Continued monitoring of carbon storage and fluxes (in soil, litter, vegetation, forest products, and woody debris) and their response to various land use changes and resource management practices will be required to accurately quantify the role of land cover and use change in the global carbon cycle. Continued satellite land cover data products and new remote sensing estimates of aboveground biomass are needed. Process studies linked with observations and long-term manipulative experiments will be required to identify cause-and-effect relationships. Models are needed to link ecosystem, management, policy, and socioeconomic factors to better project future changes in both carbon storage and flux and land use and development.

PRODUCTS AND PAYOFFS

- Database of agricultural management effects on carbon emissions and sequestration in the United States (2 years).
- Syntheses of effects of land cover and land use change on carbon sources and sinks in Amazonia (2-4 years), Northern Eurasia (4 years), and the Pan-tropics (> 4 years).
- Evaluation of the impacts of disturbance (e.g., fire, logging, and land conversion) on the fate of carbon in selected ecosystems (2 years) and additional major ecosystems (> 4 years).
- Quantification of the effects of different land use changes and management practices on biomass and soil carbon storage and release (> 4 years).
- Analysis of the effects of historical and contemporary land use on carbon storage and release across environmental gradients (> 4 years).
- Linked ecosystem, resource management, and human dimensions models that enable scientific evaluation of a wide range of policy scenarios and assessment of effects on carbon sequestration, market prices, land allocation decisions, and consumer and producer welfare (> 4 years).

Quantifying past and current effects of land use change and resource management on the carbon cycle will enable policymakers and resource managers to predict how current activities will affect the carbon cycle at multiple scales and to develop alternative policies and practices to mitigate the continued buildup of atmospheric carbon (e.g., carbon sequestration through agricultural management practices).

Question 5: What will be the future atmospheric carbon dioxide and methane concentrations, and how will terrestrial and marine carbon sources and sinks change in the future?

STATE OF KNOWLEDGE

Accurate projections of future atmospheric CO_2 and CH_4 levels are critically needed to calculate radiative forcings in models that project changes in climate and their impact on the sustainability of natural resources and human populations. Changes in the size or intensity of terrestrial and marine carbon sinks directly affect the amount of carbon emissions that remain in the atmosphere, and, thus, must be projected as well. There are several different types of carbon models available, but most lack complete integration of all components, interactive coupling, and/or full validation. While no one of these models is ideal, as a group they are becoming quite useful for exploring global change scenarios and bounding potential future CO_2

conditions and responses of ecosystems. Current models are less useful for projecting future CH_4 conditions. Modeling of future carbon conditions will require collaboration with the Human Contributions and Responses and Atmospheric Composition (for CH_4) research elements and rely on scenarios requested by decisionmakers and provided by the Scenario Development element.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are important land use-climate-carbon cycle interactions and feedbacks, and which have the potential to lead to anomalous responses?
- How will carbon sinks and sources respond to future increases in CO_2, changes in climate, and inherent natural variability?
- How can we best represent carbon cycle processes in models to produce realistic projections of atmospheric concentrations?
- How will the distribution, strength, and dynamics of global carbon sources and sinks change in the in the next few decades and in the next few centuries?

RESEARCH NEEDS

Research under this topic area will focus on incorporating improved process understanding into carbon cycle models, developing new generations of terrestrial and ocean carbon exchange models, and developing Earth system models with a dynamic coupling between carbon cycle processes and the climate system. In particular, improved models must address managed as well as natural ecosystems and incorporate the effects of multiple, interacting factors and human influences. Advances in the future will be made through a combination of observations, manipulative experiments, and synthesis via models enabled by increases in computational capabilities. Collaboration with the Ecosystems research element will be essential.

PRODUCTS AND PAYOFFS

- Advanced carbon models that include the long-term effects of actual land use history (2-4 years).
- Advanced carbon models that are able to simulate interannual variability at ecosystem and landscape scales (2-4 years).
- Synthesis of whole ecosystem response to increasing CO_2 based on experimental manipulation of CO_2 (2-4 years).
- Analysis of global CH_4 dynamics, with the potential for reduced uncertainties, based on a new synthesis of observational data and improved modeling (2-4 years).
- Advanced carbon cycle models that incorporate improved parameterizations based on data from manipulative experiments and soil carbon transformation studies (> 4 years).
- Synthesis of whole ecosystem response to combined warming and increasing CO_2 (> 4 years).
- Improved projections of climate change forcings and quantification of dynamic feedbacks among the carbon cycle, human actions, and the climate system, with better estimates of uncertainty and errors, from prognostic carbon cycle models (> 4 years).

New understanding of the controls on carbon cycle processes will be provided to improve parameterizations and/or mechanistic portrayals in climate models. Projections of future atmospheric concentrations of CO_2 and CH_4 will be made available for use in applied climate models. Both will aid in improving model projections of future climate change and its effects on the Earth system.

Question 6: How will the Earth system, and its different components, respond to various options being considered by society for managing carbon in the environment, and what scientific information is needed for evaluating these options?

STATE OF KNOWLEDGE

Questions about the effectiveness of carbon sequestration, the longevity of storage, the practicality of reducing emissions, technological options, resultant impacts on natural and human systems, and the overall economic viability of carbon management approaches create an imperative for better scientific information to inform decisionmaking to manage carbon. Presently, there is limited scientific information to support carbon management strategies, and little is known about the long-term efficacy of new management practices for enhancing carbon sequestration or reducing emissions or how they will affect components of the Earth system. This element links to the National Climate Change Technology Initiative (NCCTI), which focuses on engineered technologies, carbon offsets, and economic systems.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are potential magnitudes, mechanisms, and longevity of carbon sequestration by terrestrial and marine systems?
- How will elevated CO_2, climatic variability and change, and other environmental factors and changes (such as air, water, and land pollution; changing landscapes and natural disturbance; and intrinsic human productivity) affect carbon cycle management approaches?
- What scientific and socioeconomic criteria should be used to evaluate the sensitivity of the carbon cycle and the vulnerability and sustainability of carbon management approaches?

RESEARCH NEEDS

Research to analyze the effects on terrestrial and marine systems and to scientifically assess the short- and long-term efficacy of carbon management practices is needed. Field studies, manipulative experiments, and model investigations will be needed to evaluate the effectiveness of designed management approaches to manipulate carbon in the ocean, land, and atmosphere, and to assess their impacts on natural and human systems. New monitoring techniques and strategies to measure the efficacy of carbon management activities will also be needed. Experiments and process studies will also be needed to evaluate the likelihood of unintended environmental consequences resulting from enhanced carbon sequestration. Research on the scientific underpinning for carbon management draws upon products from carbon cycle research questions 1-5, and will coordinate with the Ecosystems research element and the NCCTI as well as public and private programs responsible for developing and/or implementing carbon management. Two types of models are required: those that incorporate understanding of basic processes into evaluation of natural and enhanced mechanisms of carbon sequestration, and those that assess the economics of carbon management options in the agricultural and forestry sectors. Research is also needed to support assessments of carbon management and sequestration potentials, decisionmaking processes that involve multiple land management scenarios, and the role of sequestration mechanisms for calculating net carbon emissions intensity.

PRODUCTS AND PAYOFFS

- Monitoring techniques and strategies to improve quantitative measurement of the efficacy of carbon management activities (2-4 years).
- Evaluation of the biophysical potential of US ecosystems to sequester carbon (selected regions: 2 years; US: 4 years) and assessment of carbon sequestration management practices in crops and grazing systems (warm and cool season grasses: 2 years; irrigated systems and grazing systems and other crops: 4 years).
- Identification of the effects of enhanced nutrient availability on carbon uptake in the ocean and of elevated CO_2 on terrestrial plant physiology and carbon allocation (> 4 years).
- Analysis of options for science-based carbon management decisions and deployment by landowners (> 4 years).
- Scientific criteria and model tests of carbon management sustainability that take into account system interactions and feedbacks (> 4 years).

This research will provide the scientific foundation to inform decisions and strategies for managing carbon stocks and enhancing carbon sinks in terrestrial and oceanic systems. Firm quantitative estimates of key carbon cycle properties (e.g., rate, magnitude, and longevity) will provide fundamental information for projecting carbon sequestration capacity, for calculating net emissions, and for full carbon accounting.

Key Linkages

US carbon cycle science will be conducted in cooperation with all the other Climate Change Research Initiative (CCRI) and US Global Change Research Program (USGCRP) research elements as well as other research, operational, infrastructure, and technology development programs. Cooperation with programs that provide national computational infrastructure and data management systems will be essential. Collaboration with the Land Use/Land Cover Change research element (Chapter 9) for Carbon Cycle question 4 will be especially critical. The enhanced observational networks needed to address Carbon Cycle questions 1-3 will need to be planned in close coordination with the Climate Quality Observations, Monitoring, and

Data Management element (Chapter 3). Addressing Carbon Cycle question 6 will require scientific studies conducted in close cooperation with the NCCTI and public and private projects that develop and implement management approaches to sequester carbon or reduce emissions. Linkages to Ecosystems (Chapter 10), Water Cycle (Chapter 7), Applied Climate Modeling (Chapter 4), Atmospheric Composition (Chapter 5), Human Contributions and Responses (Chapter 11), Climate Variability and Change (Chapter 6), and Scenario Development (Chapter 4) research elements will also be important.

International cooperation will be necessary to coordinate global observational networks, integrate scientific results from around the world, and ensure widespread utility of the *State of the Carbon Cycle Report* and model projections. Partnerships are anticipated with Integrated Global Observing Strategy (IGOS) Partners and the global observing systems. Interactions with and contributions to the Global Carbon Project of the International Geosphere-Biosphere Programme, the International Human Dimensions Programme, and the World Climate Research Programme will be important. US carbon cycle research will contribute to bilateral activities being developed by the administration.

CHAPTER 10

ECOSYSTEMS

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Question 1: What are the most important linkages and feedbacks between ecosystems and global change (especially climate), and what are their quantitative relationships?

Question 2: What are the potential consequences of global change for ecosystems and the delivery of their goods and services?

Question 3: What are the options for sustaining and improving ecosystem goods and services valued by societies, given projected global changes?

Key Linkages

Ecosystems sustain life on Earth by providing a wide variety of goods and services, including food, fiber, shelter, energy, clean air and water, and recycling of elements. From a human perspective, ecosystems provide renewable resources, together with cultural, spiritual, and recreational benefits. During the next 10 years, research on ecosystems will focus on two overarching questions:

- **How do natural and human-induced changes in the environment interact to affect the structure and functioning of ecosystems at a range of spatial and temporal scales, including those functions that can in turn influence regional and global climate?**
- **What options does society have to ensure that desirable ecosystem goods and services will be sustained or enhanced in the face of potential regional and global environmental changes?**

Global environmental changes are altering the structure and functioning of ecosystems, affecting in turn the flow of ecosystem goods and services. Research during the last decade focused on the vulnerability of ecosystems to global change and contributed to assessments of the potential impacts of global change on ecosystems at multiple scales. We now know that impacts of environmental changes and variability may be manifested in complex, indirect, and conflicting ways. For example, warming may enhance tree growth by extending growing season length, but pathogens able to survive the winter because of higher temperatures may decrease forest productivity and further increase vulnerability to disturbances such as fire. Subtle changes in the salinity or temperature of ocean currents may alter the ranges and population sizes of fish species and increase or decrease fish catches. Whether environmental changes are anthropogenic or natural in origin, human societies face substantial challenges in ensuring that ecosystems sustain the goods and services on which we depend for our quality of life and, in some cases, for survival itself.

Ensuring the provision of ecosystem goods and services needed and valued by a growing human population requires understanding the interactions among basic ecosystem processes and developing approaches to reduce the vulnerabilities or take advantage of opportunities that arise within ecosystems as a result of global change. Scientific research can contribute to this societal goal by addressing three questions that will provide information to determine linkages and feedbacks between ecosystems and drivers of global change, identify important consequences for ecosystems on which societies depend for crucial goods and services, and identify options for how society might respond to sustain and enhance ecosystem goods and services as environmental conditions change.

Question 1: What are the most important linkages and feedbacks between ecosystems and global change (especially climate), and what are their quantitative relationships?

STATE OF KNOWLEDGE

Biological, chemical, and physical processes occurring in ecosystems affect and are affected by weather and climate in many ways. For example, ecosystems exchange large amounts of greenhouse gases with the atmosphere, including water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Moreover, the reflection (or absorption) of solar radiation by ecosystems is important to the temperature of Earth's surface, and several ecosystem processes affect this reflection. Linkages among the physical, chemical, and biological components of ecosystems are important on short time scales (minutes to days) as well as over the long term (years to millennia). Global change has the potential to alter ecosystem structure (e.g., amount of leaf area, plant height, or species composition) and ecosystem functioning (e.g., rate of evapotranspiration, carbon assimilation, or nitrogen cycling), and those potential ecosystem changes might themselves alter linkages between ecosystems and the global chemical and physical environments and therefore contribute to global change through numerous feedback mechanisms.

The most important feedbacks (either positive or negative) are likely to involve:

- Altered ecosystems exchanges of greenhouse gases (e.g., water vapor, CO_2, CH_4, N_2O);
- Altered ecosystem exchanges of aerosols (such as black carbon and sulfur resulting from controlled and uncontrolled ecosystem burning);
- Altered releases of volatile organic compounds;
- Changes in ecosystem/surface albedo; and/or

- Changes in the fraction of absorbed solar radiation that is "used" to evaporate water compared to directly heating the plants and soils in ecosystems.

Better understanding of ecosystem feedbacks on climate and atmospheric chemistry is needed to predict future climate and to inform policy decisions. Achieving this understanding will require collaboration with the Carbon Cycle (Chapter 9), Water Cycle (Chapter 7), and Land Use/Land Use Change (Chapter 8) research elements.

Feedbacks

A feedback from ecosystems to global change occurs when a change in the environment causes a change in the ecosystem (either its structure or functioning) that in turn alters the rate of the environmental change. A *positive feedback* intensifies the environmental change whereas a *negative feedback* slows the change. Both positive and negative feedbacks could be brought about in many ways. A positive feedback could occur, for example, if warming and drying (caused by rising atmospheric CO_2) of high latitude ecosystems containing large amounts of carbon in plants and soils (e.g., tundra and peatland) resulted in greater ecosystem respiration. That increase in respiration would accelerate the atmospheric CO_2 increase, which could accelerate the warming and drying. A negative feedback might occur if, for example, rising atmospheric CO_2 increased the geographic expansion of ecosystems into presently unfavorable environments and the increased areal extent of those ecosystems resulted in greater transfer of CO_2 from the atmosphere into the expanded ecosystems where it was stored in plants or soils. Complex feedbacks could occur if climatic change (perhaps accompanied by modified human activities in response to such changes) leads to land cover changes (e.g., ice/snow cover; balance between greenness, desertification, and urbanization; plant community changes) that alter the Earth's albedo, which itself could further modify climate.

ILLUSTRATIVE RESEARCH QUESTIONS

- How might various global and regional environmental changes (e.g., temperature and precipitation) affect net ecosystem exchanges (or timing or geographic distribution of those exchanges) of greenhouse gases?
- How might changes in climate and greenhouse gas concentrations, in combination with other factors such as land use/cover changes, affect nutrient cycling, ecosystem albedo, and energy exchange?
- How might changes in regional air quality, including chemicals and aerosols released from disturbances such as wildfires and crop residue burning, in combination with other global changes, affect ecosystem albedo and exchange of greenhouse gases?
- How might changes in ecosystems (particularly in the Arctic) alter ocean circulation, and could this contribute to abrupt changes in regional climates?
- How might various human activities, including redistribution of nutrients and water, affect the release or uptake of greenhouse gases by various ecosystems (e.g., wetlands, croplands, deserts, tundra, pastures and rangeland, coastal/estuarine systems, forests, lakes and rivers, and urban areas)?

RESEARCH NEEDS

Ecosystems research needs include ecological experimental facilities, improved ecosystem models, and enhanced ecosystem monitoring capabilities and programs (at different scales) to link point observations with remote sensing data to scale up. New research and monitoring programs may be too expensive, so the major efforts might be directed at enhancing existing capabilities. Specific research needs include:

- Large-scale field experiments and long-term ecological monitoring facilities required to understand ecosystem-environment interactions (focusing on ecosystem greenhouse gas and energy exchanges) to develop data needed to parameterize, calibrate, and evaluate models of ecosystem-climate-atmospheric chemistry feedbacks;
- Models that link remote sensing of land surface albedo to changes in the spatial distribution of ecosystems and exchanges of mass, energy, and momentum for implementation in general circulation models; and
- Spatially explicit ecosystem models capable of representing complex interactions between diverse ecosystems and the physical/chemical environment.

PRODUCTS AND PAYOFFS

- Reports presenting a synthesis of current knowledge of observed and potential (modeled) feedbacks between ecosystems and global/climate change, to aid understanding of such feedbacks and identify knowledge gaps for research planning (2 years).
- Identification of indicators of ecosystem change that are most important to feedbacks to climate and atmospheric chemistry, to help identify early responses and focus on important potential consequences (3 years).
- Definition of the initial requirements for monitoring of ecosystems to quantify feedbacks to climate and atmospheric chemistry, to guide enhancement of existing environmental monitoring programs, and possibly create new ones (4 years).
- Quantification of important long-term relationships between potential global change (especially multiple factors), linkages between ecosystems and climate, and resulting feedbacks to the atmosphere and ocean, to improve the accuracy of climate projections (> 4 years).

Question 2: What are the potential consequences of global change for ecosystems and the delivery of their goods and services?

STATE OF KNOWLEDGE

There is considerable evidence that ecosystems are already responding to global change, including climate change and variability and changes in atmospheric chemistry. For example, responses to changes in a single property (e.g., rising or extreme temperatures) have been linked to longer growing seasons (period of leaf display), grass species decline, changes in lake acidity, and coral bleaching. Climate change variables also interact. For example, increased temperatures in the tropics may increase coral bleaching and expand the range of corals poleward. These and other observations have come from long-term ecological research and monitoring, as well as from shorter-term, individual investigations. The few programs that support long-term observations (e.g., forest productivity, ultraviolet (UV) radiation fluxes, nitrogen deposition, and the spread of invasive species) have unambiguously established that large-scale ecological changes are occurring.

Most ecosystems are subject to multiple changes at any given time. Recent reviews have summarized the range of observed and potential undesirable consequences of combinations of climate and other local and shorter-term drivers (e.g., invasive species, nutrient pollution, and physical habitat modification) on coastal and marine ecosystems. In terrestrial systems, increased primary productivity driven by increased CO_2 depends in part on soil fertility, and warming has the potential to alter the effects of rising CO_2 on primary production processes. Interactions among temperature change, precipitation, and fire regimes can influence ecosystem vulnerability to invasive species. Survival and spread of pathogens and their vectors (carriers) are highly dependent on climate and weather, thus, climate change and increased weather variability can be expected to affect disease-causing organisms that can alter population sizes and genetic diversity of humans, animals, and plant hosts.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are the effects of multiple environmental changes on the structure, functioning, and biodiversity of terrestrial and aquatic ecosystems, particularly changes in CO_2, ozone, temperature, nitrogen cycling, UV radiation, sea level rise, precipitation patterns, and regional and global ocean circulation?
- How do changes in climate, climate variability, or weather variability intensify or mitigate the effects of other ecosystem stresses (e.g., pollution, invasive species, and changes in land and resource use)?
- What impacts will global environmental change have on the delivery of ecosystem goods and services such as forest and agricultural productivity, groundwater recharge, flood protection, fisheries, and recreation, and which will have the greatest socioeconomic impacts on humans?
- How do changes in climate and weather (both variability and extremes) affect the ecology and epidemiology of infectious pathogens, dissemination by their vectors, and the susceptibility of the humans, animals, and plants that are their hosts?

RESEARCH NEEDS

Identifying and quantifying the consequences of global change for ecosystems is essential for accurately assessing options for responding to ecosystem changes. Determining the most important and societally relevant ecosystem responses to global change will require collaboration among the physical, biological, and social science communities and an improved understanding of complex interactions between natural and human disturbances and climate variability. Some specific research needs to support this effort include:

- Investigations of the link between biodiversity and ecosystem functions and flows of services;
- Experiments on intact natural ecosystems to study the interactive effects of climate change, elevated CO_2, nutrient/pollution deposition, and other factors on key species and ecosystems;
- Remote sensing data to quantify key characteristics (e.g., vegetation composition and structure, biomass amount, and disturbance patterns) of present ecosystems, monitor trends in ecosystem changes, and link these observations to known processes;
- Studies to connect contemporary and historical changes in ecosystem structure and functioning; and
- Maintenance and enhancement of basic remotely sensed terrestrial, atmospheric, and ocean monitoring systems and networks to monitor trends and provide necessary data to observe changes, parameterize models, and verify model projections.

PRODUCTS AND PAYOFFS

- Reports describing the potential consequences of global and climate change on a range of terrestrial, freshwater, and marine ecosystems (e.g., Arctic and estuarine ecosystems; fire-susceptible ecosystems; Great Lakes) based on available research findings, to alert decisionmakers to the most likely consequences to ecosystems (2 years).
- Summaries of information to identify indicators of ecosystem change most important to the delivery of goods and services, and summaries of requirements for monitoring and modeling those ecosystems to enable tracking and forecasting changes to societally-relevant aspects of ecosystems (4 years).
- Spatially explicit ecosystem models at regional to global scales, based on data from experimental manipulations focused on the effect of interactions among global change variables, to improve our capacity to observe contemporary, historical, and long-term changes in ecosystem structure and functioning (> 4 years).

Question 3: What are the options for sustaining and improving ecosystem goods and services valued by societies, given projected global changes?

STATE OF KNOWLEDGE

As described previously, experiments and observations have demonstrated linkages between climate and ecological processes that indicate that possible future changes in climate could alter ecosystems in ways that might disrupt the flow of ecosystem services. Research has identified and evaluated some specific adaptation measures, including integrated land and water management; selection of plants and livestock for many intensive systems; multiple cropping systems; multiple-use systems for freshwater and land systems; protection programs for key habitats, landscapes, and/or species; intervention programs (e.g., captive breeding and/or introduction programs); efficient use of natural resources; and institution and infrastructure mechanisms (e.g., market responses, crop insurance, and water flow and supply management).

Research has investigated how management practices may affect climate-related ecosystem services. For example, ecosystems emit greenhouse gases such as CH_4, N_2O, CO_2, water vapor, and aerosols; they store carbon, nitrogen, phosphorus, and other elements in soils, plants, wetlands, and oceans; and they reflect solar radiation. Management practices may result in positive or negative feedbacks to the climate system by altering emissions, carbon and nutrient storage, or reflectivity of the Earth's surface. However, while specific management strategies have been investigated, society's knowledge and ability to manage the broad array of ecosystem services in the context of increasing and potentially conflicting demands is extremely limited.

ILLUSTRATIVE RESEARCH QUESTIONS

- How could aquatic ecosystems (e.g., rivers and coral reefs) be managed to balance the production and sustenance of ecosystem services across multiple demands (e.g., management of rivers to supply freshwater for drinking, irrigation, recreation, and aquatic species; and management of coral reefs for tourism, erosion protection, refugia for commercially and recreationally important species, recreational and cultural activities, and biodiversity), considering the future effects of interacting global changes?
- How might terrestrial ecosystems such as rangelands, forests, woodlands, and agricultural lands be managed to balance the production and sustenance of ecosystem services across multiple demands (e.g., food, fiber, fuel, fodder, recreation, non-wood forest products, biodiversity, biogeochemical cycles, tourism, and flood and storm control), considering the future effects of interacting global changes?
- What options exist for society to preserve genetic diversity, respond to species migrations or declines, and manage changing disease incidence and severity in the face of environmental change?
- What are the effects of management techniques on global or regional environments (e.g., atmospheric chemistry; water supply quantity and quality), nitrogen cycling, and the maintenance of health, productivity, and resilience of ecosystems?
- What dependency, use and value do societies have for non-market services provided by terrestrial and aquatic ecosystems?

RESEARCH NEEDS

There is a need for evaluations of the influences of societal needs and demands on ecosystems and the values that societies place on ecosystem goods and services. Precise understanding of effective options to maintain and enhance the supply of critical goods and services will require substantial improvements in modeling capabilities to project impacts of interacting environmental changes on ecosystem services and to evaluate the effectiveness of alternative management responses. Specific research needs include:

- Exploring the causal mechanisms that create the complex changes in ecosystem services across multiple scales, including development of genetic and molecular tools to better understand, manage, and predict ecosystem/environment interactions;

- Integrated analyses of how ecological information, technology, forecasts, and scientific uncertainties may affect human behavior and be incorporated into environmental decisionmaking;
- Development of local to regional decision support tools linked to fully interactive ecosystem-climate models capable of simulations to evaluate climate change scenarios; and
- Development of methods, tools, and management approaches to sustain ecosystem services, coupled with an assessment of the direct and indirect effects of these approaches.

PRODUCTS AND PAYOFFS

- Data for preliminary comparisons of the effectiveness of selected forestry and agricultural management practices (e.g., fuel management, silviculture, timber harvesting, crop and tree genetics, nutrient management, tillage systems, irrigation, and crop rotations) in selected regions focusing on N_2O emissions, trace gas fluxes, and health and productivity of the targeted ecosystems and their services under changing environmental conditions (2 years).
- Data for preliminary comparisons of the effectiveness of selected management practices in other types of ecosystems (e.g., wetlands, fisheries, boreal forests, tundra, and coral reefs) in selected regions focusing on N_2O emissions, trace gas fluxes, and health and productivity of the targeted ecosystems and their services under changing environmental conditions (4 years).
- Data and spatially explicit models for examining the impact of management and policy decisions on a wide range of ecosystems, to predict the efficacy and tradeoffs of management strategies at varying scales relevant to the decisions at hand (> 4 years).

Key Linkages

Given the nature of the drivers of ecosystem change, research must span spatial scales (from small experimental plots to global satellite image mosaics), time scales (taking data from ice cores, tree rings, and fossil pollen to near-real-time forecast models), and the scientific elements of this plan. Monitoring systems at multiple spatial scales are needed to develop a consistent record of environmental change over time. Data from such observation systems would provide inputs to models and also allow evaluation and improvement of model performance. The resulting large collections of environmental data will necessitate large databases. Interagency facilities and mechanisms must be in place to process, archive, and distribute the data collected and generate relevant products.

Future observation systems may rely on networks of terrestrial and aquatic ecosystem observatories within particular biomes or larger ecoregions. They should link together and build on existing networks of field stations, experimental forests and ranges, environmental and resource monitoring programs, and long-term ecological research sites sponsored by many different government and academic organizations, many of which have lengthy records of environmental and ecological data.

For the ecosystems research community to make significant contributions to our understanding and management of global change, explicit scenarios and information to drive ecosystem models must be obtained from other research elements under this plan, including Scenario Development and Applied Climate Modeling (Chapter 4), Atmospheric Composition (Chapter 5), Climate Variability and Change (Chapter 6), Carbon Cycle (Chapter 9), Water Cycle (Chapter 7), Land Use/Land Cover Change (Chapter 8), and Human Contributions and Responses (Chapter 11). In turn, products from studies of the linkages between global change and ecosystems can be expected to improve the scientific products of these other plan elements. Collaboration with appropriate international efforts will involve programs and organizations such as several sponsored wholly or in part by the International Geosphere-Biosphere Programme (IGBP), including the Global Climate and Terrestrial Ecosystems (GCTE) project, the Global Environmental Change and Food Systems (GECaFS) project, or the Biospheric Aspects of the Hydrological Cycle (BAHC) project. Scientists conducting research under the Ecosystems element of this plan will participate in the planning of international collaboration activities.

CHAPTER 11

HUMAN CONTRIBUTIONS AND RESPONSES TO ENVIRONMENTAL CHANGE

This chapter's contents…

Human activities play an important part in virtually all "natural" systems and are changing the environment at local, regional, and even global scales. Social, economic, and cultural systems also are changing in a world that is more populated, urban, and interconnected, increasing the resilience of some groups while increasing the vulnerability of others. A more integrated understanding of the complex interactions of human societies and the Earth system is essential to identify vulnerable systems and pursue options to take advantage of opportunities and enhance resilience.

The need for research on human contributions and responses—sometimes referred to as the "human dimensions" of global change—motivates research questions throughout this plan. Human dimensions research includes studies of potential technological, social, economic, and cultural drivers of global change, and how these and other aspects of human systems may affect adaptation and the consequences of change for society. Much of this research is "cross-cutting"—integral to explorations of causes and impacts of changes in atmospheric composition, climate, the water cycle, the carbon cycle, ecosystems, land use and land cover, and other global changes. Research on human contributions and responses also is an area of study in its own right. Common forcing scenarios must be developed that integrate information from different research elements. The interacting impacts of multiple environmental stressors on human activities must be examined. New hypotheses, methods, and models must be developed and tested.

A series of national and international reports has identified a broad research agenda addressing human contributions and responses (including adaptation) to global change. The National Research Council (NRC) has issued several reports that identify key research issues, most recently including *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1999a), which includes a chapter on "Human Dimensions of Global Environmental Change," and *Under the Weather: Climate, Ecosystems and Infectious Disease* (NRC, 2001c). The NRC report *Climate Change Science: An Analysis of Some Key Questions* (NRC, 2001a) concluded that, “In order to address the consequences of climate change and better serve the Nation’s decisionmakers, the research enterprise dealing with environmental change and environment-society interactions must be enhanced.” This enterprise should include (among other elements), “support of interdisciplinary research that couples physical, chemical, biological, and human systems.” This chapter draws from these reports and from priority areas identified by the research community through federal research programs.

Two overarching questions for research on the human contributions and responses to global change are:

- **How do humans and human societies drive changes in the global environment?**
- **How do humans respond to global environmental change?**

These questions are addressed through research focused on the following areas:

- Human forcing of the climate system, changes in land use and land cover, and other global environmental changes;
- Impacts of global change on societies and societal vulnerability, resilience, and adaptive capacity in responding to the impacts;
- Decisionmaking under conditions of complexity and uncertainty; and
- The potential effects of global change on human health.

In all of these areas of research, there is a particularly strong need for the integration of social, economic, and health data with environmental data. This will require data from physical, biological, social, and health disciplines on compatible temporal and spatial scales, to support the integration of the data for research and to support decisionmaking.

Question 1: What are the magnitudes, interrelationships, and significance of the primary human drivers of change in atmospheric composition and the climate system, changes in land use and land cover, and other changes in the global environment?

STATE OF KNOWLEDGE

The influence of human drivers of global environmental change may be greater, yet be modeled with more uncertainty, than the influence of some factors studied in the natural sciences. For example, as difficult as it might be to predict the response of tropical forests to increasing levels of carbon dioxide (CO_2), it is probably more difficult, yet might be more important, to project the rates and patterns of global deforestation and the potential effectiveness of policies to control it.

The subject of potential human drivers is very broad. Research has been conducted for many years in many fields and for many reasons. However, the level of understanding achieved to date is quite uneven. Researchers who need to model human actions in order to project future conditions and consequences often find the foundation for quantitative models lacking.

ILLUSTRATIVE RESEARCH QUESTIONS

What are the key processes and trends associated with population growth and demographic change, technological change, and trade and global economic activity, and how can improved understanding of these issues be used to improve scenarios and projections of global change?

Population growth and demographic change

- What are the relationships among demographic changes, migration, and other related variables such as economic productivity, energy use, and ecosystem services?
- How do people use information and form perceptions about potential changes in health status to make decisions about migration, compared to information and perceptions about other factors, such as economic status?

Technological change

- What induces technological innovation and adoption of new technologies?
- What affects the transfer of technology from country to country?
- What can be predicted about the future of energy technologies, carbon sequestration options, and agricultural productivity?
- How do food production decisions (including land use, technology choice, and exposure to chemicals) affect environmental change?

Trade and global economic activity

- What influences the movement of goods and services domestically and from one country to another, and how do operational and technological changes affect economic productivity and energy use?

- How are environmental risks to health affected by structural economic changes, such as shifts from rural to urban lifestyles, changing modes of transportation, and openness to international trade?
- How is growth in economic productivity and increasing energy use related to emissions of contaminants and changes in land and water use?

RESEARCH NEEDS

Key needs have been identified, including:

- Development of integrated assessment models with the ability to analyze the effects of measures directed at the reduction of urban air pollution and greenhouse gas emissions;
- Development of integrated assessment models that introduce new energy and carbon sequestration technologies;
- Comprehensive studies of greenhouse-relevant emissions and potential climate change that include carbon aerosols in an integrated assessment model and the appropriate specification of emissions, costs of control, and chemical and radiative characteristics of those aerosols;
- The development of the capability to study the economic and trade effects of control measures that differ in complex ways, both within and among countries, including broad policy approaches (e.g., emissions targets, technology subsidies, voluntary national goals) and means of implementation (e.g., voluntary programs, taxes, cap and trade systems, and quantity constraints).
- Assessment of the full costs and benefits (including productivity impacts) of environmental policy and technology choices that affect human health at the individual or household level; and
- Analysis of how social, cultural, and economic factors affect the discounting of future health and environmental costs and benefits.

PRODUCTS AND PAYOFFS

Users of the results of this research will have an improved understanding of the variables affected by human actions. For example, the preparation of scenarios will be strengthened by an improved understanding of the interdependence among economic growth, population growth, energy consumption in different sectors (e.g., electricity, transportation), pollutant emissions, and migration. Research will provide a basis for improving the development and evaluation of those scenarios.

Question 2: What are the current and potential future impacts of global environmental variability and change on human welfare, what factors influence the capacity of human societies to respond to change, and how can resilience be increased and vulnerability reduced?

STATE OF KNOWLEDGE

Research has shown that the extent to which global environmental change can affect societies depends as much on the social systems that lead to vulnerability as on the biophysical systems that cause environmental change. This is the case, for example, in understanding how climate variability in the past has affected societies. According to the NRC *Pathways* report (NRC, 1999), "a major conceptual advance occurred in moving from impact assessments based on climate model scenarios to analyses based on an understanding of vulnerability. For example, rapid increases in water demand have increased drought vulnerability, and the spread of urban settlements into coastal and flood-prone regions has increased vulnerability to sea level rise and severe storms." Moreover, the capacity of society to prepare for climate impacts will be influenced in part by the capacity of individuals and institutions to respond to improved scientific information.

ILLUSTRATIVE RESEARCH QUESTIONS

- How may methods be refined to accurately assess the combined impacts of climate change, changes in water quality and availability, land use change, sea level rise, and ecosystem change?
- How does vulnerability in human systems to global environmental change develop and how can it be reduced?
- What are the determinants of and processes associated with the capacity for adaptation?
- How can society use improved information about the climate system and its potential impacts to adapt more effectively to possible future changes?

RESEARCH NEEDS

Associated research needs include empirical studies, field campaigns, and model-based simulation studies of the influence of social and economic factors on vulnerability and adaptive capacity in households, organizations, and communities; analyses of the consequences of rapid climate changes in the past and the ability of hazard and resource management institutions to respond to surprising shifts in climate and to seasonal forecasts; and studies analyzing the factors that affect adaptive capacity in the context of multiple social and natural system stresses (climate change, land use change, population change and movements, sea level rise, and changes in political institutions).

PRODUCTS AND PAYOFFS

Research on these questions can be expected to improve analytical methods and models of how climate variability and change, land use change, population change, sea level rise, and other global environmental changes affect decisionmaking in public health, water management, agriculture, transportation infrastructure, urban areas, coastal areas, and other climate-sensitive sectors. Improved communication and dissemination of accurate climate information, including characterization of uncertainty, is being developed that attempts to meet the needs of decisionmakers in these sectors.

Question 3: How can the methods and capabilities for societal decisionmaking under conditions of complexity and uncertainty about global environmental variability and change be enhanced?

STATE OF KNOWLEDGE

Research suggests that the potential social and economic impacts of global climatic variability and change may be very large. Much less research has been devoted to examining how individuals, organizations, and governments can make better decisions to reduce risks and take advantage of opportunities related to global climatic variability and change.

ILLUSTRATIVE RESEARCH QUESTIONS

How can methods or approaches be improved:

- For representing, propagating, analyzing, describing, and communicating uncertainties?
- For understanding the economic costs and opportunities (societal, organizational, and individual) from global climatic variability and change?
- For representing how individuals, organizations, and societies make choices regarding threats whose consequences are long-term and uncertain?
- For evaluating and comparing the effectiveness of different approaches to modeling decisionmaking?
- For understanding the role of private, governmental, and social decisionmaking affecting health and environmental outcomes?

RESEARCH NEEDS

Associated research needs include research to determine what information is required by individuals, organizations, and governments to make better decisions regarding global environmental variability and change; what individuals, organizations, and governments know (and do not know), including uncertainties, about the state of scientific knowledge regarding global environmental change; and what decision resources would be most useful for different decisionmakers in different positions.

PRODUCTS AND PAYOFFS

Research on these questions will enable the development of assessments of the kind of knowledge and information needed by different decisionmakers and stakeholders in order to enhance decisionmaking associated with climate change, and will produce decision support resources.

Question 4: What are the potential human health effects of global environmental change, and what tools and climate and environmental information are needed to assess and address the cumulative risk to health from these effects?

STATE OF KNOWLEDGE

It is well established that human health is inextricably linked to the environment, and that changes in the natural environment may have a subtle, or even dramatic, effect on health. Over the past decade, several research and agenda-setting exercises have called for continued and expanded research and development of research methods in this area. Given the complex interactions among physical, biological, and human systems, this research must be highly interdisciplinary, well integrated, and span the breadth from fundamental research to operations. An interdisciplinary research program to examine the linkages across these sectors is being initiated in 2003. Focusing on global and developing country impacts, it will begin to improve understanding of how human health is affected by simultaneous environmental and economic shifts.

Federally supported research has thus far provided information on a broad range of health effects of global change, including the adverse effects of ozone, atmospheric particulates, ultraviolet (UV) radiation, and heat-related illnesses. Research continues to improve understanding of the impact of climate variability on certain infectious diseases, and researchers are developing tools and information products for anticipating and managing these impacts that capitalize on the enormous protections afforded by wealth and the public health infrastructure. However, many questions remain unanswered.

ILLUSTRATIVE RESEARCH QUESTIONS

- What are the impacts of changes in water quantity and quality, temperature, ecosystems, land use, and climate on infectious disease, and can the capacity for prevention, early detection, and effective response be improved?
- What are the impacts of atmospheric and climatic changes on the health effects associated with ambient air quality and UV radiation?
- What are the health effects and effective response strategies associated with temperature extremes and with extreme weather events?
- What are the best methods for assessing climate-related health impacts and for developing useful tools and information products to enhance public health?
- What effects will new technologies for global change mitigation and adaptation have on human health?

RESEARCH NEEDS

Research needs include:

- Work on improved understanding of the health effects of UV radiation, including exposure across regions and populations, risk awareness, and early detection;
- Initiation of a temporally and spatially compatible long-term field study, empirical analysis, and integrated modeling effort of the physical, biological and social factors affecting the impact of climate on public health issues of national importance;
- The effect of temperature on air quality, particularly in urban heat islands, and the potential public health consequences;

- Research on the climate, environment, and atmospheric interactions related to asthma, allergic disorders, and other acute and chronic respiratory disorders and deaths;
- Research on preventing and reducing the adverse health impacts of extreme weather events;
- Research on prevention and control of infectious diseases that might increase in incidence as a result of climate change;
- Research on the control and treatment of vector- and water-borne diseases; and
- Research on the health effects of production and use of alternative fuels and new energy technologies.

A parallel need exists to develop additional appropriate tools and methods for assessing and adapting to potential health outcomes; and for evaluating the impact of research, the effectiveness of Earth science information and products, the methods for communicating that information, and the systematic identification of knowledge gaps and feedback to the research communities.

PRODUCTS AND PAYOFFS

Products from this area include operational tools, research to support innovative institutional arrangements and processes, and fundamental research results that may be used by decisionmakers. Expected products include:

- Tools for preventing and managing the public health threat of infectious diseases, especially those that are vector-borne.
- Assessments of the health effects of combined exposures to climatic and other environmental factors (e.g., air pollution).
- Multiagency joint award for competitive multiyear grants to support research on climate variability and health.
- Next phase of health sector assessments to understand the consequences of global change for human health in the United States, especially for at-risk demographic and geographic subpopulations.

Key Linkages

The study of human contributions and responses to global change has ties to all of the Climate Change Science Program (CCSP) research elements, and in many cases needs to be an integral component of collaborative research within these elements. For example, research to identify options for increasing the resilience of national water systems to climate variability and to long-term socioeconomic and climate trends is linked to Water Cycle research (Chapter 7). Similarly, an evaluation of local- and regional-scale factors that condition impacts of land use and land cover change on economic welfare and human health is equal parts Land Use/Land Cover Change research (Chapter 8) and Human Contributions and Responses research. Research on human disease vectors is linked to the study of Ecosystems (Chapter 10).

Comparable examples can be cited for Atmospheric Composition (Chapter 5), Climate Variability and Change (Chapter 6), and the Carbon Cycle (Chapter 9).

Questions from other research elements that are related to Question 1 above include:

- What natural processes and human activities control carbon emissions and uptake around the world? (from Carbon Cycle)
- How do social, political, and economic forces influence human decisions regarding land use and resource management, and how might changes in these forces affect the carbon cycle? (from Carbon Cycle)
- What are the environmental, institutional, policy, technological, demographic, and economic drivers of land use change? (from Land Use/Land Cover Change)

Questions from other research elements that are related to Question 2 above include:

- What are the multiple stresses that climate change, ozone layer depletion, and regional air quality exert on humans and ecosystems? (from Atmospheric Composition)
- What are the current patterns of water consumption and how are they likely to change as a result of potential changes in temperature, land cover and land use, demographics, and water policies? (from Water Cycle)
- How will the combined effects of land use and climate change affect agriculture, aquatic ecosystems, rangeland, and forest extent and productivity, and what are the implications for land management and economics? (from Land Use/Land Cover Change)
- What is the impact of future changes in land use and land cover on water supply and quality, considering climate-induced changes in the patterns and characteristics of water resources? (from Land Use/Land Cover Change and Water Cycle)
- What are the most likely vulnerabilities and opportunities arising from climate variability and potential future climate changes, and what climate indicators would be of the most benefit in assessing climate vulnerability and resilience in sectors such as agriculture, water, and other environmental resources, and for assessing other potential societal impacts (positive and negative), including human health? (from Climate Variability and Change)

Questions from other research elements that are related to Question 3 above include:

- What are the implications of water cycle research for managing conflicting demands on transboundary waters? (from Water Cycle)

Research on Human Contributions and Responses to Environmental Change is linked to the International Human Dimensions Programme and to a variety of other international efforts, including the International Research Institute for Climate Prediction (see Chapter 14).

References:

NRC, 1999a. Committee on Global Change Research, National Research Council, *Global Environmental Change: Research Pathways for the Next Decade* (Washington, DC: National Academy Press).

NRC, 2001a. National Research Council, Committee on the Science of Climate Change, *Climate Change Science: An Analysis of Some Key Questions* (Washington, DC: National Academy Press).

NRC, 2001c. Committee on Climate, Ecosystems, Infectious Diseases, and Human Health, Board on Atmospheric Sciences and Climate, National Research Council, *Under the Weather: Climate, Ecosystems, and Infectious Disease* (Washington, DC: National Academy Press).

CHAPTER 12

GRAND CHALLENGES IN MODELING, OBSERVATIONS, AND INFORMATION SYSTEMS

This chapter's contents…

1. Observations
2. Modeling capabilities
3. Data and Information Management

Research into the basic processes of global environmental change provides the foundation of knowledge required to improve projections and understand the consequences of interacting stresses on natural resources and human activities. However, the seven research elements described in Part II cannot meet the Climate Change Science Program (CCSP) objective for the coming decade. Even the first part of the objective—extending knowledge of the Earth system and improving projections of global change at scales relevant to decisionmaking—cannot be met without more extensive integration, regional synthesis, advances in modeling capabilities, and sustained commitment to observations and data information systems.

Observations, modeling, and data and information dissemination have been thought of as crosscutting, "enabling" activities since the US Global Change Research Program's (USGCRP) inception—hence these are already tightly coupled to the seven research elements. These are needs that are particular to a given research area and must be planned and implemented in close association with the research that they support or draw on. However, they also need to be managed in a focused manner because they provide essential infrastructure that must serve multiple purposes within the CCSP—enabling fundamental research, as well as supporting assessment and decisionmaking—and because they depend on the distributed assets of CCSP agencies, some of which were originally developed to serve other needs.

These activities are of the highest priority for the CCSP. Because of their crosscutting nature, these capabilities are also particularly challenging to foster. The sections that follow outline new objectives and approaches that will improve CCSP implementation of these areas and contribute to the evolution of the program into one that successfully integrates research and responds to the needs of the next decade.

1. Observations

The study of global change requires a strong base of observations. The Global Change Research Act of 1990 specifically calls for "global measurements, establishing worldwide observations necessary to understand the physical, chemical, and biological processes responsible for changes in the Earth system on all relevant spatial and time scales," as well as "documentation of global change, including the development of mechanisms for recording changes that will actually occur in the Earth system over the coming decades." The program continues to respond to this call by following a strategy to address observations on appropriate space and time scales. The strategy includes guiding principles, identification of priorities, and effective management of available resources.

The development of new space-based global observing capabilities was a primary focus of the program's first decade. Several new Earth-observing satellites—including TOPEX/POSEIDON, Jason-1, TRMM, QuikSCAT, SeaWiFS, EOS-Terra, EOS-Aqua, and Landsat-7—are now producing unprecedented amounts of high-quality global data for the research community and other users, and new data from satellites soon to be launched are not far behind. There have also been advances in programs that provide additional important data for global change research such as the Global Climate Observing System (GCOS) Surface Network (GSN), the Tropical Atmosphere-Ocean moored array (TAO), Argo, the Joint Global Ocean Flux Study, the Global Terrestrial Network for Permafrost (GTN-P), and the Ameriflux network. Many new ground-based and ocean observing technologies have also been developed and demonstrated.

Yet despite these major achievements, many serious observing-system challenges remain for the CCSP. Several fundamental challenges for the next decade include:

- Completing the development and deployment of systematic space-based and *in situ* global climate and ocean observing components that are needed for long-term climate change research and the accurate characterization of global change and its causes and consequences.
- Implementation of observing systems, such as a terrestrial observing system to obtain crucial climate measurements related to carbon cycles, surface hydrology (including precipitation, evaporation, runoff, stream-flow, and soil moisture), ecosystems, and the cryosphere (including snow cover, glaciers, and permafrost).
- Regular assessment of and response to the observational priorities of the program's research elements and the scientific community.
- Establishment of a linkage between observation and assimilation technology and between surface and space-borne sensors with regular whole-atmosphere column measurements made from the ground and especially suborbital platforms.
- Development of a comprehensive system integrating remote sensing and *in situ* measurements designed to observe the Earth's climate change and climate variability.

- Development of explorer class satellite observations to measure missing variables in order to enhance discovery and improve understanding of climate processes.
- Continuous improvement of state-of-the-art measurements within the atmosphere (on aircraft and/or balloons) to validate the new space-borne measurement capabilities, to supply essential information not obtainable from space or surface networks.
- Long-term investment in the maintenance of our terrestrial, ocean, and atmosphere observing systems.
- Developing more effective cooperation with operational observing programs that are not part of the CCSP, including high-level agreements and a process for effective transition of research measurements to operational status.
- International cooperation.

OBSERVATIONAL PRIORITIES

A range of observational requirements are identified in the CCSP research elements described in Part II of this plan, including both existing measurement programs that must be maintained and enhanced, and new measurements that must be initiated (see box). A key lesson learned over the past decade is that observing systems and networks must be implemented in a way that allows flexibility as both requirements and technology evolve. Therefore, the program will regularly assess the evolving science requirements and priorities and propose modifications to the observing systems that are required for the CCSP to execute its research plans. This process must involve the scientific community and program managers working on each research element, as well as those involved in modeling, scientific assessment, and other integrative activities.

Observational Priorities in CCSP Program Elements

Atmospheric Composition (Chapter 5)

- Continue global observation of ozone distribution and trends, and a representative sample of source, reservoir, and tracer molecules that govern stratospheric chemistry.
- Develop and implement global observations of aerosol distribution and properties.
- Improve surface-, aircraft-, and space-based measurements of global and regional troposphere pollutants, and atmospheric chemistry.

Climate Variability and Change (Chapter 6)

- Maintain and improve long-term space-based and *in situ* observations of temperature, humidity, wind strength and direction, clouds, precipitation, pressure, sea ice, snow cover, glaciers, and ice sheets.
- Develop and maintain an Integrated Ocean Observing System, combining *in situ* and satellite observations, to monitor ocean topography and circulation, heat content, salinity, sea level, and ocean-atmosphere exchange of momentum, heat, and freshwater.
- Maintain and improve space-based and *in situ* measurements of key climate forcings (greenhouse gases, aerosols, solar radiation, and land cover change)

Water Cycle (Chapter 7)

- Develop and maintain the continuity and consistency of climate-quality observations of atmospheric temperature, water vapor, and clouds by operational environmental satellites.
- Develop and implement space-based global measurements of precipitation, continental soil moisture, soil freezing/thawing, and snow accumulation.
- Maintain and expand surface-based operational measurements of precipitation, soil moisture, snow accumulation, river discharge, groundwater levels, water chemistry, and other hydrologic variables.
- Develop and implement systematic regional hydrologic, climate, and radiation measurement test beds, and advanced technologies involving ground based remote sensing and water isotope analysis.

Land Use and Land Cover Change (Chapter 8)

- Maintain high-resolution observations of rapid changes in global land cover and land use.
- Maintain the research quality of long-term, global observations of land cover and land use at low and moderate resolution through the transition to operational observing systems.
- Develop *in situ* ecosystem observations and the collection of relevant local and regional socioeconomic data.
- Improve links between ground-based and remote-sensing land use and land

management data systems.
- Maintain and expand a research program to evaluate the utility of existing and planned sensing systems to assess their utility for land use/land cover change applications.

Carbon Cycle (Chapter 9)
- Strengthen and ensure the continuity of continental inventories of forests, other ecosystems, and major land uses, and derived estimates of soil carbon storage.
- Continue and enhance a national carbon dioxide (CO_2) flux measurement network that covers all major ecosystem types, and promote the development of a worldwide network of cooperating sites.
- Strengthen and ensure the continuity of global oceanic chlorophyll observations, and derived estimates of oceanic primary productivity and carbon budget.
- Strengthen and ensure the continuity of surface-based measurement of ocean carbon and air-sea carbon flux.

Ecosystems (Chapter 10)
- Expand age, size, and vertical structure measurements of forests with known management histories.
- Develop satellite remote sensing capabilities to determine terrestrial ecosystem productivity.
- Increase collection of ground truth data at Long Term Ecological Research and similar sites in all major natural and managed ecosystem types.

The National Research Council (NRC) has specified six attributes of the Earth's climate system that are especially important to society: (1) precipitation and water availability, (2) temperature, (3) storms, (4) solar radiation, (5) sea level, and (6) ecosystem structure and functioning. Developing a better understanding of natural and human-induced climate changes is dependent on accurate long-term measurements of the mean state or condition, variability over time scales, geographic variability, and the frequency and persistence of extreme values of each of these variables. The CCSP has expanded this initial inventory to encompass the needs of research on and applications to the global cycles of carbon, water and biogeochemical constituents, atmospheric composition, and changes in land use. The need to characterize the vulnerability and resilience of society and of natural and managed ecosystems to change, and thus to develop a more complete understanding of the potential impacts of global change, adds yet another dimension to observational requirements.

Observing systems are currently in place within both research and operational programs that partially fulfill the requirements for meeting these objectives. Other key sensors and observing networks still need to be developed and implemented. Priorities for these augmentations will be determined by the scientific needs of the research elements and a set of agreed criteria (see box). The management of the program will recommend these augmentations in consultation with the scientific community. The continued development and deployment of new technology that can improve the accuracy and lower the costs of space-based observing systems and suborbital measurements (i.e., those within the atmosphere, at Earth's surface, and below it) is also critical. Careful calibration and overlapping operation of new and old technology during transitions is a necessity for maintaining the quality control of data records.

Observing System Prioritization Criteria

The following prioritization criteria should be considered in selecting CCSP observing program initiatives:

- **Scientific Return:** significance of the expected increase in fundamental knowledge.
- **Benefit to Society:** extent to which the outcome may be utilized for great societal benefit.
- **Mandated Programs:** support of programs mandated by law.
- **Partnership Opportunities:** the extent to which needed work can be carried out with partners in the United States and abroad.
- **Technology Readiness:** the extent to which current technology enables a question to be productively addressed.
- **Program Balance:** distribution of resources to ensure scientific progress is not impeded by the lack of key information.

Integration and transition of experimental and operational systems

There is an immediate need to work with US Government agencies to prevent the further deterioration of operational observing systems that provide essential data for global change research. In some cases, it may be cost effective to invest in stabilizing and upgrading existing operational systems rather than in the creation of new systems. In other cases, the transition of proven research systems to operational status may help fill both operational and research requirements in a more cost effective way. More effective integration of the planning and development of research and operational systems will benefit both communities.

A Global Observing System

The need for dedicated observing systems for climate change research is well established, and the CCSP is poised to assist agencies to build on the successful deployment of many elements of such systems over the last five years. Thus a near-term priority for the program is augmentation of existing observations to initiate the Global Climate Observing System (GCOS), as described in Chapter 3. There is a clear consensus on a core set of long-term measurement requirements for GCOS, many of which are parts of existing operational observing systems and many of which need to become parts of operational systems. A system to meet requirements for long-term continuous data must be coupled with ongoing opportunities, such as explorer satellites, to initiate shorter-term measurements of key processes and forcing factors. The major near-term challenge is to seek every opportunity to improve and maintain the coverage, quality, and consistency of land, ocean, and atmosphere measurements to complement the research observation capabilities that have been initiated by the USGCRP in the past and new capabilities developed over the next decade. Additionally, provisions must be made for observations that do not necessarily require continuity, e.g. monitoring changes of ice sheets and glaciers over time. Such observations, which must be particularly well calibrated, differ from many others in that they do not directly feed into routine climate-related models and do not fit the "transition to operational" paradigm. They are necessary, however, for addressing critical elements of the CCSP plan.

Opportunities for international collaboration

The creation of US networks is a valuable step in creating an observing system; however the overarching need is for *global* networks and systems. The CCSP will continue to support the international development of the Integrated Global Observing Strategy, and the Global Climate, Ocean, and Terrestrial Observing Systems. As the largest supporter of global change research and observations, the United States has a special responsibility to lead the development of an integrated global Earth observing system, but this task cannot be accomplished without active international support and participation. The CCSP will continue or expand efforts to assist and support developing nations in improving their observing networks.

The Road Forward

It is the responsibility of the CCSP to ensure that decisions on the implementation and maintenance of important space-based and in situ observing system components are based primarily on scientific needs. However, many important observing systems are developed and operated by organizations that are not formal participants in the CCSP, making the development of strong cooperative relationships that extend beyond the current CCSP a necessity. The CCSP will work with observing system partners and the scientific community to identify requirements and set priorities in light of available resources and competing needs, in order to develop the observing system priorities identified in the table “Observational Priorities in CCSP Program Elements.” Near-term CCSP observing system objectives include:

- **Stabilize existing observational capabilities.** Maintain and improve basic data center archives and research observing facilities, networks, and systems (both space-based and *in situ*), including extension of the moored, drifting, and ship-based networks to all oceans.
- **Identify and implement critical measurement improvements.** Maintain a sustained research and development program to address major deficiencies in observing systems (e.g., missing carbon sinks, closing the budgets of the regional and global water cycles, and integrating the coastal ocean monitoring systems). To the extent possible, new observational capabilities should be integrated into existing networks so as to minimize redundant operations and costs.
- **Incorporate climate and global change observing requirements in operational programs at the appropriate level.** Operational observation

networks continue to be the backbone of climate measurements. These networks, with only modest incremental costs, could satisfy significant parts of the climate observing requirements. Providing essential additional research capability to operational observing systems, and continuing to improve mechanisms for transition of research and experimental observing systems to operational platforms, are both important.

- **Continue intensive field missions.** Integrate airborne (*in situ*), surface, and satellite observations over regional scales and durations from days to several weeks. These intensive observation periods provide valuable data for testing and validating satellite retrieval algorithms, and for the fine scale resolution necessary to test, validate, and constrain climate models. These coordinated observation efforts will need to become even more sophisticated as satellites evolve towards formation flying, onboard processing, and smart sensor technology.
- **Continue a vigorous program in data reanalysis to ensure the time consistency and spatial homogeneity of global change data sets.** Fully exploit the information value of historical data series using the latest technologies, quality control and assurance, and processing methodologies. This involves continuing mining of historical records.

2. Modeling capabilities

Modeling is one of the most important components of the CCSP. Models are an essential tool for synthesizing observations, theory, and experimental results to investigate how the Earth system works and how it is affected by human activities. Such models can be used in both a retrospective sense, to test the accuracy of modeled changes in Earth system forcing and response by comparing model results with observations of past change, and in a prognostic sense, for calculating the response of the Earth system to projected future forcing. Models provide the only quantitative means to integrate scientific understanding of the many components of the climate system and, thus, are the only tools available for making quantitative projections. Comprehensive climate models represent the major components of the climate system (atmosphere, oceans, land surface, cryosphere, and biosphere) and the transfer of water, energy, organic chemicals, and mass among them, but are still in their formative stages. Comprehensive climate models are complex and require "high-end" computer resources to run.

The current organizational structure of the US modeling effort has not fully supported the product-driven modeling that is especially important for making climate model information more usable and applicable to the broader global change research community. The NRC (1999b and 2001b) reports provide valuable guidance on how to improve US climate modeling efforts. They emphasize:

- The recognized US leadership in basic climate science research;
- The shortcomings of US efforts to integrate the basic climate research into a comprehensive climate modeling capability;

- The challenges, including software, hardware, human resources, and management issues, of routinely producing comprehensive climate modeling products; and most importantly,
- The need to establish a dedicated capability for comprehensive climate modeling activities, including the global climate observations and data that underpin them.

In the next decade, the CCSP modeling component must expand beyond the simulation and prediction of the physical climate system to include the complex and interrelated nature of the many processes that make up the Earth system, including dynamic ecosystems and biogeochemistry. Previously, the focus in model development has been primarily on the largest spatial scales (especially global). It is clear that many emerging modeling needs, especially for predictive applications, are at the regional scales at which most societal and environmental resource decisions are made. It is thus increasingly important that models have the capacity to integrate across the multiple components and processes needed to describe the Earth system in sufficient complexity, while simultaneously providing reliable information on increasingly refined spatial scales. In addition, the computational capability, software, and model physics must be developed to allow for model resolutions at the smaller scales that support regional decisions. These are two immense challenges. Over the long term, the CCSP must define a path that leads from comprehensive climate modeling as a research activity alone to the point where it can routinely produce high quality, but standard products, on demand. Further, the CCSP must guarantee that a productive partnership is maintained between product-driven modeling activities and the discovery-driven modeling research program that will underpin its credibility and future success.

The CCSP strategy envisions two complementary climate-modeling activities. The first will be principally a research activity. It will maintain strong ties to the research communities in both global change and computational science to incorporate new knowledge rapidly into a comprehensive climate and Earth-system modeling capability. Although the mission of this activity is research, it will be "product driven" in the sense that it must make models and model products available to the broader community. Tightly connected research institutions with complementary areas of expertise can form the core of a distributed modeling program that maintains collaborations with perhaps hundreds of external contributors. Areas of research emphasis would include model development, computational science, and data assimilation.

Closely associated with the research activity, but distinct from it, will be a prediction capability responsible for sustained and timely delivery of model products that are required for assessment and other needs. This "quasi-operational" capability should maintain a research component that is an integral part of the research modeling activity described above. Additionally, the "quasi-operational" entity would be charged with producing, on demand, the required modeling products for policy analysis and assessment. This activity might include both operational forecasts of seasonal-to-interannual variability (e.g., El Niño-Southern Oscillation (ENSO)), because we can model these shorter-term variations at a level of skill appropriate to operations, as well as quasi-operational decadal- to centennial-scale modeling, because there are operational needs, such as scenario preparation for sensitivity studies of impacts, that we can meet with existing skill levels. The addition of product-driven model research to a strong base of discovery-driven research, together with strong links between them will result in a suite of CCSP modeling activities that will better support and drive the interdisciplinary research objectives of the CCSP.

These two activities are complementary and both are required for a successful modeling program. They should both employ a common modeling framework and maintain constant interaction. Full implementation of such a strategy will take several years. Key to the success of the strategy are substantial and continuing investments in high-end computing, archival storage, collaboration technology, and associated information technology infrastructure.

The approach toward a having a comprehensive climate and Earth-system modeling capability will be to incorporate the modeling needs of the seven CCSP elements (see box).

1

Modeling Priorities and Linkages in CCSP Program Elements

Atmospheric Composition (Chapter 5)

- Carry out chemical transport modeling activities, with emphasis on cross-tropopause processes, the role of particles in accelerating ozone-loss chemistry, and stratospheric transport.
- Use models to describe the interactions of various types of aerosols and to estimate the net sign, magnitude, and uncertainty in the cooling–warming role of aerosols.
- Build and evaluate diagnostic/prognostic models of the coupled climate, chemistry/transport, and ecological systems (in collaboration with other elements of the program).

Climate Variability and Change (Chapter 6)

- Refined estimates of the role of climate feedback processes in affecting climate sensitivity and improvements in their representation in climate models.
- Predictions of regional patterns of different modes of climate variability.
- Improved predictions of ENSO, particularly the onset and decay phases, and assessment of potential predictability beyond ENSO, e.g., the Pacific Decadal Oscillation, the Arctic Oscillation, monsoons.
- An improved ability to separate the contributions of natural versus human-induced climate forcing to climate variations and change, resulting in more credible answers to "what if" policy-related questions.
- More advanced knowledge about the changes in natural variability that may result from anthropogenic forcing.
- Improved understanding of the primary natural and forced mechanisms for abrupt climate changes.
- Models of the full three-dimensional circulation of the global ocean.
- Time dependent models of ice sheet changes to assess underlying mechanisms and their contributions to future sea level rise.
- Climate monitoring and forecast capabilities for regional applications and risk reduction.

Water Cycle (Chapter 7)

- New parameterizations for water vapor, clouds, and precipitation processes for use in climate models, using new cloud-resolving models created in part as a result of field process studies.
- New models capable of simulating the feedbacks between the water cycle and the climate system (including biogeochemical cycles).
- Models that partition precipitation among surface and subsurface pathways, route flows, and quantify physical and chemical interactions for evaluating climate and pollution impacts.

- Integrated models of total water consumption for incorporation into decision support tools that identify water-scarce regions and efficient water use strategies.

Land Use and Land Cover Change (Chapter 8)

- Urban growth models.
- Identification of the regional components of a US land use and land cover change model.
- National- and global-scale land use and land cover change projection models.
- Climate models incorporating land use and land cover data.
- National- and global-scale models with a coupled climate-land use system.

Carbon Cycle (Chapter 9)

- Carbon cycle models including data assimilation customized for North America (developed under part I).
- Models of ocean carbon cycling based on linkages between carbon and nitrogen in coastal environments, and of ocean carbon sequestration that incorporate biogeochemistry, ocean circulation, and the potential impact on ecosystems.
- Global maps of carbon storage derived from model-based analysis of actual land cover (cooperative effort with the Land Cover element).
- Advanced carbon models that include the long-term effects of actual land use history and are able to simulate interannual variability at ecosystem and landscape scales.
- Improved projections of climate change forcings and quantification of dynamic feedbacks among the carbon cycle, human actions, and the climate system, with better estimates of uncertainty and errors, from prognostic carbon cycle models.

Ecosystems (Chapter 10)

- Spatially explicit ecosystem models at regional to global scales, based on data from experimental manipulations focused on the effect of interactions among global change variables, to improve our capacity to observe contemporary, historical, and long-term changes in ecosystem structure and functioning.
- Data and spatially explicit models for examining the impact of management and policy decisions on a wide range of ecosystems, to predict the efficacy and tradeoffs of management strategies at varying scales relevant to the decisions at hand.

Human Contributions and Responses to Environmental Change (Chapter 11)

- Development of integrated assessment models with the ability to analyze the effects of measures directed at the reduction of urban air pollution and greenhouse gas emissions.
- Development of integrated assessment models that introduce new energy and carbon sequestration technologies.
- Model-based simulation studies of the influence of social and economic factors on vulnerability and adaptive capacity in households, organizations, and communities.
- Analyses of the consequences of rapid climate changes in the past and the ability of

hazard and resource management institutions to respond to surprising shifts in climate and to seasonal forecasts.
- Model-based simulation studies of the influence of demographic, social, economic and climate change factors on the incidence and distribution of infectious diseases.

LINKAGES

The grand challenge modeling components will ultimately result in a multidisciplinary approach toward the Earth system climate model, which couples the chemical and ecological systems to atmospheric processes and incorporates:

- Reduced uncertainties such as ozone-layer responses to climate change and the role of aerosols in cooling and warming.
- Better prediction of modes of variability based on results from Chapters 4 and 6.
- Sensitivity analysis.
- Natural versus human-induced climate forcing.
- Land use and land cover parameterizations.
- Knowledge gained under Chapter 4 about important climate feedback processes and their improved representation in climate models will be applied, leading to significantly reduced uncertainties in climate projections.

Outcomes will span a wide range of options, such as sets of ensemble global simulations projecting possible climate change at continental and regional scales from various emissions scenarios; and comprehensive studies of greenhouse-relevant emissions and potential climate change that include carbon aerosols in an integrated assessment model and the appropriate specification of emissions, costs of control, and chemical and radiative characteristics of those aerosols.

3. Data and Information Management

Providing access to distributed and varied forms of data, products, and information is a central objective of CCSP data systems. Researchers, planners, and decisionmakers need seamless access to information produced not only by CCSP efforts, but also the larger scope of information produced by other federal, non-federal, regional, and international programs and activities. These users should be able to focus their attentions on the information content of the data, rather than how to find and access the data. The vision of the future CCSP system is one where the user experience will change fundamentally from the current process of locating, downloading, reformatting, and displaying to one of accessing information, browsing, and comparing data in the form of basic scientific graphics through a standard Web browser, GIS tools, and scientific visualization/analysis systems, without concern for data format, data location, and data volume.

This vision can only be achieved by harnessing advanced technologies and developing frameworks for interoperability between heterogeneous systems, which are part of a common collective. Such a framework, with established metadata and quality control/quality assurance standards, mechanisms of transport, protocols, and requirements, would permit federal and non-federal data and product providers to contribute their information to the common collective as well as allow users to query and access the system for relevant information. The system will call for each cooperating system to conform to such protocols enough to ensure that it will interface seamlessly with the overall climate information system thereby maintaining a distributed architecture.

Such a data management strategy is being pursued for the ocean observing system (i.e., Ocean.US) and holds great promise. Much of the technology required to make this vision a reality exists already; however, significant challenges remain that require short-term as well as strategic investments. The challenge to CCSP will be pursuing unprecedented levels of cooperation across current data management systems and programs and a commitment to mapping the future development and execution of a suitable strategic plan.

Opportunities lie ahead for the evolving data and information systems of the CCSP. Evolving new technologies for data collection and management, new science and applications, and new institutional and organizational possibilities indicate that a robust and open data and information system spanning the environmental and socioeconomic realms is achievable in the coming decade. This vision needs to incorporate careful attention to the need for continuity in global change data, for long-term data stewardship, and for equitable access across social or "digital" divides. The CCSP will need to provide leadership both within the US Government and across a diversity of partners to ensure that the Nation's global change data and information capabilities support the achievement of its 10-year objectives and the realization of their full potential benefits to the Nation and the world.

CHALLENGES

At present, data are not integrated, making them difficult for policymakers—and even scientists—to use. They are often not consistently calibrated in space or time to permit simple identification by site or scientifically sound integration of the multiple data sets needed for multidisciplinary research. Moreover, the US Government has limited resources to support long-term electronic data management beyond the life of individual investigators' projects or programs. Scientific data that are not institutionally managed are likely to vanish when the scientist-data collector turns to other projects or retires.

Ongoing advances in information technology will for the first time enable development of a distributed data and information system in which

- Data will be collected and managed in multiple locations, including federal, state, and local agencies, academic institutions, non-governmental organizations, and private companies. Long-term archiving of the data will be the responsibility of federal data centers;

- Users will be able to find and access these data via the Internet, utilizing sophisticated systems for data search and retrieval;
- New techniques for enabling interoperability between databases and data systems will not only support the needs of global change research but also practical applications related to environmental and resource management, disaster mitigation and emergency response, and other data-dependent activities; and
- Historical data are preserved through aggressive data rescue activities enabling a transfer of data from manuscripts and individual scientists to digital databases.

RESEARCH NEEDS

To advance these goals, the CCSP priorities will be to:

- Expand the current data management infrastructure, based on the strong foundation provided by existing distributed systems to:
    - Encompass the data centers established by federal science agencies, such as the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, Department of Energy, and US Geological Survey data centers.
    - Provide a means of identifying and using socioeconomic data collected by federal statistical agencies, such as the Census Bureau and the Bureau of Economic Affairs, by resource management agencies such as the US Army Corps of Engineers, the US Bureau of Reclamation, the US Bureau of Land Management, and the US Fish and Wildlife Service, and by state and local agencies. This socioeconomic data may need to be georeferenced and collected in ways to ensure that it is compatible on temporal and spatial scales with data collected in the physical and natural sciences so that integrated studies may be undertaken.
    - Include partnerships with foreign governments, intergovernmental agencies, and international scientific bodies and data networks to provide data that are needed to address the international character of research and decisionmaking.
- Continue to develop a framework to respond to the need for integration and communication of information across disciplines and among scientists and policymakers. Multi-agency and multidisciplinary institutional and data resources will be a part of the efforts to develop standards and processes for sound data management.
- Identify the data requirements of the program on a regular basis, including visualization, analysis, and modeling requirements.
- Identify and rescue data that are at risk of being lost due to either media deterioration or in the hands of data collectors who may retire or move to other projects.

PRODUCTS AND PAYOFFS

Requirements from the seven CCSP elements will be incorporated as part of the data and information management plan to provide products such as:

- Improved access to climate information and products for addressing regional concerns and issues. This includes both observations and model results.

- Beginning to identify the regions, sectors, and users who are using climate projections for management and policy decisions.
- Beginning to solicit the climate information requirements from the users.
- Reliable, commensurate data sets at the watershed scale that scientists from the several disciplines will use to examine critical water-Earth interactions for improved integrated watershed management.
- Determining what information is required by individuals, organizations, and governments to make better decisions regarding global environmental variability and change; including what individuals, organizations, and governments know (and do not know), including uncertainties, about the state of scientific knowledge regarding global environmental change

In the next five years the data management program will focus on improving the interoperability and usability of agency data sets by the various working groups and researchers. This includes:

- Establishing data and metadata documentation, standards, and formatting policies that will make possible the combined use of targeted data products taken at different times, by different means, and for different purposes.
- As funding is available, creating special, tailored portals for data products of interest and use by the various CCSP working groups. These portals will use the emerging web metadata clearinghouse technology to allow researchers to locate and access coincident data of interest from various observation systems.
- Implementing the national climate observing system architecture developed in Chapter 4.

LINKAGES

The focus of the CCSP plan is to advance our capability for understanding and predicting past, present, and future impacts of our changing climate. Every step in this process, from understanding the variability in climate change through the use of models and observations, to ensuring the continuance of quality long-term records, interpretation of the model and observation results, and communication of and access to these results for resource managers and decisionmakers will rely on the existence of a flexible, accessible, and user-friendly data and information system. The transfer of research information to policymakers and resource managers will require interactions between customers and data system managers including research and operational efforts, and close links to international programs such as the World Climate Research Programme and the International Geosphere-Biosphere Programme.

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PART III

COMMUNICATION,

COOPERATION,

AND MANAGEMENT

CHAPTER 13

REPORTING AND OUTREACH

This chapter's contents…

1. Inventory of Existing Agency Activities
2. Reporting and Outreach for Decisionmakers
3. Reporting and Outreach for the Public
4. Outreach for K-12 Education

The Climate Change Science Program (CCSP) focuses on establishing and applying priorities for climate change research so the Nation can address and evaluate global and climate change risks and opportunities. Improved coordination, reporting, and outreach among federal agencies are required to make research results and decision support resources more readily available and useful to stakeholders. This reporting and outreach plan consists of working with two kinds of stakeholders. The first includes those who need or are affected by climate information, including policymakers, resource managers, the scientific community, the private sector, non-governmental organizations (NGOs), and the international community. The second kind of stakeholder includes those involved in education—whether it is the general public, K-12 students, or those who communicate information (i.e., media, educators). As users of climate information, the needs of the stakeholders for reliable, accurate, and easily understood data should be taken into account in research planning and execution of this strategic plan.

With many near-term products identified in the CCSP strategic plan, especially in the Climate Change Research Initiative (CCRI) elements, it is especially important to integrate public information and outreach considerations at an early stage. In particular, an interagency inventory of outreach activities is required along with an interagency working group to address outreach issues and coordinate a plan.

1. Inventory of Existing Agency Activities

Education and outreach on global change research occurs at many levels of the federal government. However, there is no routine and comprehensive interagency assessment of public information and outreach efforts. A relatively small portion of the overall public information and outreach effort occurs at the interagency level. An example is the Global Change Research Information Office (GCRIO) (www.gcrio.org), which responds to a large volume of inquiries and contributes to the distribution of documents such as *Our Changing Planet*. The US Global Change Research Program (USGCRP) coordination office also has sponsored limited outreach activities that have included a monthly Congressional seminar series (May 1995 through July 2000), a website (www.usgcrp.gov), and responses to frequent information requests from stakeholders. A significant amount of interagency outreach activity also is associated with the working groups of the CCSP. In particular, numerous stakeholders, especially within the research community, have been engaged in the preparation and reviews of long-term strategic plans.

Reporting and outreach efforts are also individually pursued by each agency. Efforts include activities in which agencies:

- Respond directly to inquiries from the public and other stakeholders;
- Maintain websites and listservs;
- Produce and distribute hardcopy documents and multimedia products;
- Conduct or sponsor briefings, lectures, and press conferences;
- Testify before Congress or other government bodies;
- Finance scholarships, fellowships, and internships;
- Support museum exhibits and other public displays;
- Sponsor, participate, or otherwise contribute to meetings attended by stakeholders;
- Provide scientifically-sound content for K-12 education activities; and
- Fund outreach efforts managed outside the federal government.

Overall, there is a need to survey the federal agencies so they can determine what is effective and how to best facilitate outreach without duplicating efforts. A strategy is needed for allocating responsibilities and ensuring participation, even when faced with competing agency priorities. The CCSP will facilitate interagency coordination of outreach efforts so information generated from federally-funded global change research is effectively disseminated and communicated. The CCSP will also coordinate plans to communicate research results so reporting and outreach activities produce more useful and timely information.

2. Reporting and Outreach for Decisionmakers

Information developed by the CCSP will be used by decisionmakers in debating and selecting possible strategies to mitigate and adapt to global change without unnecessarily compromising the economy or energy security. Decisionmakers as defined in Chapter 4 are those who are actively involved in policy at the national and regional level and those who are making operational decisions for natural resources based on climate information. Reporting and outreach for decisionmakers are a priority for the CCSP.

NATIONAL POLICYMAKERS AND THE INTERNATIONAL COMMUNITY

The Global Change Research Act of 1990 established the USGCRP and calls upon officials to "consult with actual and potential users of the results of the Program to ensure that such results are useful in developing national and international policy responses to global change." It requires a plan that will "produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change." The law furthermore mandates a Global Change Research Information Office (GCRIO) to disseminate useful scientific research information "to foreign governments, businesses, and institutions, as well as the citizens of foreign countries."

The communication of information on global and climate change research to Congress, the Administration, and our international partners is critically important to ensure well-informed discussion and decisions. In addition to publishing *Our Changing Planet* each fiscal year, the CCSP will facilitate agency coordination to:

- Provide Congressional briefings on research results and program accomplishments as needed;
- Provide a science and technology assessment report in cooperation with the National Climate Change Technology Initiative (NCCTI); and
- Provide information and briefings to international partners.

LOCAL/REGIONAL GOVERNMENTS, BUSINESSES, AND NGOS

Local and regional governments, businesses, and NGOs need an awareness and understanding of existing and planned resources and technologies available to support their decisions. They require familiarity with the integration of science and technology that will emerge from the coordination of the CCRI with NCCTI. National and regional decisionmakers need special analysis of scenarios, model outputs, and climate data. They require state-of-the-art observations of climate and climate variability. Researchers need to understand how uncertainty is used in decisionmaking so that uncertainties are effectively communicated.

To ensure that these stakeholders have research and decision support resources, the CCSP will facilitate agency coordination to:

- Supplement agency outreach with basic information (brochures, fact sheets) that links their initiatives to the broader Program activities;
- Produce hardcopy and digital materials and make them available in a timely fashion and indirectly through outreach activities sponsored by individual agencies and third parties;
- Coordinate outreach material by state to make the information more salient to each state's delegation; and
- Facilitate regional identification of key stakeholders through regional workshops, regional integrated research, and regional briefings.

3. Reporting and Outreach for the Public

The general public is the largest and the most important audience for the communication of reliable global change information. A well-informed citizenry is essential for responding appropriately to the challenges posed by climate change and other global change issues. Because it is critical that these audiences have access to clear, consistent, and accurate information about global change research and its findings, the CCSP will work closely with federal agencies to ensure reporting of relevant information in a useful and accessible format.

The CCSP and participating federal agencies will identify a range of activities and initiatives for reporting useful global change information to the public. Information will be provided either directly from the CCSP and federal agencies or indirectly (i.e., via media outlets) and will be used not only to respond to public inquiries, but also to inform key constituents about the importance that science can play in decision-making.

Many federal agencies already are effectively communicating with the media by providing information about global and climate change science. With improved strategic coordination, the CCSP and federal agencies can coordinate existing activities or identify new opportunities for more effective media coverage.

The CCSP will facilitate agency coordination to:

- Release coordinated press releases. US Government agencies, working together and/or with the CCSP, can develop joint media releases to report on new research projects and results;
- Organize workshops for science journalists. This includes joint projects to educate journalists so that they can provide more frequent and informed coverage of science topics;
- Provide briefings for the general public. Using innovative information and communications technologies, agencies can explore options to conduct virtual town hall meetings or other public forums on issues relating to global change;
- Provide briefings for public officials. Opportunities to improve understanding among officials from various levels of government would, in the long term, serve to stimulate and inform valuable public discussion;
- Organize and compile web sites, fact sheets, and other public information materials. There is a need for a centralized, Internet-based clearinghouse of reliable, accessible information about global change science generated by other agencies.
- Provide articles for mainstream business, policy, and general science journals. The CCSP could produce a series of articles, over the next 2-4 years, of potential interest to the public and end-users of climate information.

4. Outreach for K-12 Education

The importance of education has long been recognized by federal agencies, which individually have sponsored activities directed at teachers and students from kindergarten through twelfth grade (K-12). These range from the National Science Foundation's very extensive efforts directed at educators to the National Aeronautics and Space Administration's (NASA) Earth Science Enterprise (ESE) Education initiatives. They also include many websites such as those maintained by the Environmental Protection Agency (EPA). In addition, agencies have, to a limited extent, cosponsored collaborative K-12 educational initiatives such as the *Climate Change Partnership Education Program* initiated by the EPA, NASA, and the National Oceanic and Atmospheric Administration (NOAA).

Despite these programs, American school children are still not adequately educated in the sciences. According to the National Science Board's *Science and Engineering Indicators 2002* (NSB, 2002), in mathematics and science "few students are attaining levels deemed Proficient or Advanced by a national panel of experts." It furthermore says that "internationally, US student relative performance becomes increasingly weaker at higher grade levels." Evidence suggests the problem rests not so much on the amount of classroom time devoted to science, but on the quality of the curriculum and instruction. Any federal effort to significantly improve global change education therefore will have to be strategically focused on teachers and the instructional resources they have available. In addition, because so many children access the Internet at home and at school, K-12 education initiatives also can effectively reach children directly through that medium.

To ensure that students and educators have the required resources, the CCSP will facilitate agency coordination to:

- Improve the reliability and quality of agency and other program activities, especially web-based initiatives that already are heavily used by students and teachers;
- Identify opportunities for collaboration among agencies and with other organizations to educate children;
- Participate in dialogues with the National Science Teacher Association (NSTA) and professional societies with K-12 programs to identify basic curriculum content that needs to be provided to educators at all grade levels;
- Fund CCSP representation at key educator conferences and include development of exhibits and handouts; and
- Fund development of games and activities that familiarize children with basic climate facts and concepts.

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CHAPTER 14

INTERNATIONAL RESEARCH AND COOPERATION

This chapter's contents…

From the first days of research on climate science, it has been recognized that change occurs on many scales—from local to regional to global. Early research focused on change as it was manifest at the local level where scientific capabilities were also the strongest. The results of this early research indicated clearly to US scientists studying change that the processes that influence change at the local level could not be divorced from regional and global processes. To obtain first-hand knowledge and to develop comprehensive understanding of these processes—under a broad range of geophysical and biogeochemical conditions—requires scientists to cooperate across national boundaries on both a regional and global basis.

It was recognized that research and observational programs to study change at these levels should be carried out so as to assure the full and open exchange of data among participating scientists and between these scientists and the broader scientific community and those involved in the policy-making process. These research and observational programs also contribute substantively to the international assessment process, such as the Intergovernmental Panel on Climate Change (IPCC) and the Scientific Assessment of Ozone Depletion, as described in the preceding chapters of this plan. It is also important in conducting such programs, especially those involving developing countries, that ways be found to assist scientists in these countries to play a substantive role in the collection and analysis of data and to benefit from the results of these activities. Efforts in these areas have resulted in a comprehensive array of international global change research programs and projects that are steadily evolving as new scientific needs are identified.

When US scientists identify international collaboration necessary for them to address important scientific problems at the regional and global level, they are encouraged to address these to the maximum extent possible through direct scientist-to-scientist cooperation. US scientists studying global change thus work directly with colleagues in other countries in a number of key areas, as is highlighted in earlier sections of this plan.

1. Goals of International Cooperation in Climate Science

The broad scope and complexity of US climate science research often also requires that the United States develop a broad, well-organized international framework within which:

- Regional- and global-scale specific cooperative research and observational programs can be planned and implemented;
- US scientists and scientific institutions can interact effectively with scientists and scientific institutions with expertise in other geographic areas not normally accessible to US scientists;
- The full and open exchange of scientific observations and data needed for research results can be encouraged and the results of such research can be exchanged;
- Research needed to support decision-making can be identified and developed;
- Early warnings of emerging environmental issues can be obtained;
- Other countries, their agencies, institutions, and scientists, can be encouraged to become more actively involved in research and observational programs; and
- The research and observational capabilities of these countries, especially developing countries, can be improved.

2. The International Framework

US scientists, US funding agencies and the US Government and our colleagues and counterparts in other countries have developed such a framework to address both research and observational requirements.

This framework includes a series of global-scale research programs; non-governmental and intergovernmental international organizations at both the global and regional level; various networks for coordination of observing systems—both *in situ* and remote sensing—and data exchange and management; and organizations that focus on education, training, and capacity-building.

The United States is involved in numerous significant partnerships with other nations to develop and implement climate-related satellite programs. Such satellite remote-sensing systems require development of collaborative international ground-based networks, maintenance of these networks, and assurance of calibration relative to widely recognized standards. This cannot be accomplished only through collaboration of scientists from all nations. Such ground-based observations also form an important link for the calibration and validation of satellite data that are obtained by the space agencies that constitute the Committee of Earth Observing Satellites (CEOS).

A few illustrative examples include the following:

- French partnership with the United States was vital to the success of the TOPEX/POSEIDON mission over the past 10 years to measure ocean topography.
- Japan provided satellite and launch for the US ocean surface wind instruments (NSCAT on ADEOS I and SeaWinds on ADEOS II) and the precipitation radar and launch for the very successful Tropical Rainfall Measuring Mission.
- Japan also is providing the Advanced Microwave Sounding Radiometer (AMSR-E) on NASA's Earth Observing System (EOS) Aqua satellite mission.
- Brazil contributed the HSB atmospheric sounding instrument on Aqua.
- Canada has provided the MOPITT instrument on the EOS Terra satellite.
- German partnership was key to the successful recent launch of the GRACE satellite to measure time variations in the Earth's gravity field.

In addition to their fundamental contribution to the mission flight success, these partnerships have substantially broadened the science and end-user communities for climate-related satellite observations.

THE GLOBAL-SCALE INTERNATIONAL RESEARCH PROGRAMS

Within the global-scale research programs, scientists from many countries address: the physics and related chemistry of global change, with a special focus on climate, through the World Climate Research Programme (WCRP); the biology and chemistry and related geosciences of global change, through the International Geosphere-Biosphere Programme (IGBP); the human dimensions of global change, through the International Human Dimensions Programme (IHDP); and biodiversity science, through the Diversitas program.

These programs link to international scientific unions through the International Council for Science (ICSU) and with ICSU committees, such as the Scientific Committee for Ocean Research (SCOR); the Scientific Committee on Problems of the Environment (SCOPE); and the Scientific Committee on Antarctic Research (SCAR).

These programs also provide a framework within which major field campaigns can be organized involving ships, aircraft, satellites, balloons, surface-based measurements, and laboratory studies. One example of such a campaign is the Global Observation of Forest and Land Cover Dynamics program (GOFC-GOLD), an international effort to provide accurate, reliable, quantitative space-based and *in situ* observations of forests and other vegetation cover for sustainable development of terrestrial resources. This program also contributes to improving understanding of the terrestrial carbon budget.

3. Bilateral Cooperation in Climate Change Research and Technology

In response to an initiative of President George W. Bush, the United States has recently undertaken to develop bilateral cooperation with a number of other countries that share US interests and capabilities in specific areas of climate change research and technology. Efforts are well underway with Italy, Japan, and Australia. Discussions are in progress with the People's Republic of China, the Republic of Korea, Canada, India, seven Central American countries, and the European Union.

4. Multilateral International Cooperation in Research and Observational Programs

National agencies that fund global change research, satellite remote sensing systems, agricultural research, and development aid also coordinate their efforts with their counterpart agencies in other countries through a number of organizations and networks. These include the International Group of Funding Agencies for Global Change Research (IGFA); the Committee on Earth Observing Satellites (CEOS); and the Consultative Group on International Agricultural Research (CGIAR). Through IGFA, national agencies that fund global change research exchange information, identify issues of mutual interest, and develop approaches to resolving these issues that the agencies then implement nationally.

The United States is one of the largest donors to CGIAR, which sponsors sixteen international agricultural research centers devoted to improving food security, alleviating poverty, and improving the management of natural resources in developing nations. These centers are engaged in biological research that is intended to increase production of basic food crops and livestock and to maintain and enhance the natural resource base relating to soil, water, aquatic resources, agro forestry, and forestry.

The United States interacts at the intergovernmental level with partner countries in United Nations (UN) organizations that support global change research, both directly and indirectly. Preeminent among these are the World Meteorological Organization (WMO); the Intergovernmental Oceanographic Commission (IOC) of the UN Educational, Scientific and Cultural Organization (UNESCO); the UN Environment Programme (UNEP); the Food and Agriculture Organization (FAO); the UN Development Programme (UNDP); and the World Health Organization (WHO). Through its participation in UNEP, the UNDP, and the World Bank, the United States also participates actively in and supports the Global Environmental Facility (GEF), the primary international institution for transferring energy and sequestration technologies to the developing world.

Among other things, these agencies are involved in sponsorship of a number of the key scientific bodies involved in international cooperation in global change research, e.g., the World Climate Research Program. The WMO, UNESCO, IOC, UNEP and FAO, in cooperation with

ICSU, also sponsor and oversee coordination of many of the observational systems that support global change research, including the Global Climate Observation System (GCOS), Global Ocean Observation System (GOOS), and the Global Terrestrial Observation System (GTOS).

Of special note, the WMO and the IOC have established a new Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) to which the two organizations have entrusted development, maintenance, coordination, and guidance of the operation of their global marine meteorological and oceanographic observing systems.

5. Regional Cooperation In Global Change Research

The United States also participates in and supports regional cooperation in global change research, especially in the Americas, Asia and the Pacific, and Africa. In 1990 President George H.W. Bush hosted a ministerial-level *Conference on Scientific and Environmental Research Related to Global Change*. At this conference, the United States proposed—and the Conference agreed—to establish three hemisphere-scale regional global change research networks.

The first of these, the Inter-American Institute for Global Change Research (IAI), was set up in 1992, and the Asia-Pacific Network for Global Change Research (APN) soon followed. In Africa the SysTem for Analysis, Research, and Training (START) has established a Pan-African START Regional Committee (PACOM). START and PACOM are involved in designing and implementing regional cooperative research in such areas as climate variability and climate change; water and food security; and land use change, ecosystems, and biodiversity. Regional networks directed at GOFC-GOLD objectives have also been established in Central Africa and the Miombo region in southern Africa.

The United States hosts two organizations that emphasize cooperation with developing countries in global change research. The first is the START program cited above, an international non-governmental organization that was established under the aegis of ICSU. START is co-sponsored by the IGBP, the WCRP, and the IHDP. Its purpose is to build capacity in developing countries to conduct research on global environmental change and the challenges these changes pose for human health, agriculture, water, and food security, and to apply the results of such research in decision-making.

The second is the International Research Institute for Climate Prediction (IRI), an innovative science institution working to accelerate the ability of societies worldwide to cope with climate fluctuations, especially those that cause devastating impacts on humans and the environment, thereby reaping the benefits of decades of research on the predictability of the El Niño-Southern Oscillation phenomenon and climate variations.

The United States also actively promotes global change research in the Antarctic and Arctic, the former through cooperation with other parties to the Antarctic Treaty and SCAR, and the latter through the Arctic Council; the International Arctic Sciences Committee (IASC); and the Arctic Ocean Sciences Board (AOSB).

6. U.S. Plans and Objectives For Future International Cooperation

The overall framework for international cooperation in global change research and observations has been responsive to the needs of US global change science. However, this framework should be broadened and strengthened to keep pace with the evolving needs of this science with respect to both research and observations.

Climate modeling capabilities have improved dramatically in recent years and can be expected to continue to do so. As a result, US scientists are now able to model Earth system processes and their coupling on a regional and global scale with increasing precision and reliability. To continue to improve such modeling will require substantial expansion of Earth observing systems, both remote and *in situ*, in order to fill gaps in existing databases, especially in those areas of the world for which existing data is sparse. Such data-sparse regions include remote regions, especially those with harsh environments, and areas where existing capabilities to make observations and collect data are limited, such as the oceanic and interior land areas of the Southern Hemisphere and both polar regions.

To expand cooperation internationally, the President has announced that the United States intends to:

- Commit $25 million to support the implementation of climate observation and response systems in developing countries;
- Expand funding of the GEF;
- Support transfer of energy and sequestration technologies to developing countries to promote sustainable development while limiting their greenhouse gas emissions growth;
- Expand cooperation in climate change research and technology with a number of key countries and regional organizations; and
- Work with the IAI and other institutions to better understand regional aspects of climate change.

The Climate Change Science Program also intends to:

- Encourage regional cooperation in Africa, working in cooperation with ICSU, the Third World Academy of Science (TWAS), and START, possibly leading to a hemisphere-scale regional network for global change research in Africa;
- Promote further development and expansion of global observing systems through the Global Climate Observing System (GCOS) and the Argo program (a global array of free-drifting profiling floats that measure the temperature and salinity of the upper 200

meters of the ocean) for ocean observations, through further multilateral and bilateral cooperative efforts analogous to those already initiated;

- Encourage expanded cooperation in biodiversity research, especially through the Diversitas program;
- Enhance efforts to bring science and technology to bear on increasingly complex problems of natural resource development (e.g., the application of climate information for improved adaptation and disaster preparedness); and
- Work closely with the international global change research programs—the WCRP, IGBP, IHDP and Diversitas—to promote effective transition of a number of their present focused programs to cross-cutting programs (such as the Global Environmental Change and Food Security Program) that are intended to relate global change research more directly to major societal and economic factors.

CHAPTER 15

PROGRAM MANAGEMENT AND REVIEW

This chapter's contents…

1. Mechanisms for Successful Management: Scientific Guidance, Interagency Planning and Implementation, and Program Integration

The Climate Change Science Program (CCSP) oversees and coordinates the Climate Change Research Initiative (CCRI) and the US Global Change Research Program (USGCRP). The CCSP has joint membership with the Subcommittee on Global Change Research, the interagency body responsible for coordinating the USGCRP. In the CCSP, responsibility for implementation of different components of the research program is distributed across participating federal departments and agencies. The basic rationale for this distributed organization is that the issues of climate and global change are complex and wide ranging and thus extend beyond the mission, resources, and expertise of any single agency.

In June 2001, in response to evaluations of the USGCRP that raised questions about the ability of the existing interagency mechanism to develop adequate focus, President Bush requested that the Secretary of Commerce take the lead in reviewing the arrangements for coordinating climate and global change research. In February 2002, the President announced a new management structure for federal climate change science and technology development to improve the research support for decisionmaking and to increase accountability.

At the highest level, the new structure includes the Executive Office of the President, with a combined National Security Council (NSC), Domestic Policy Council (DPC), and National Economic Council (NEC) panel responsible for program review. The Chair of this panel is the National Security Advisor or other Presidential appointee and reports to the President. The **Committee on Climate Change Science and Technology Integration** was developed to oversee the federal climate change science and technology programs. The Committee is a cabinet-level body that, in coordination with the Office of Management and Budget, provides recommendations concerning climate science and technology to the President and, if needed, recommends the transfer of funding and programs across agency boundaries.

The **Interagency Working Group on Climate Change Science and Technology** reports to the Committee. The Working Group is composed of departmental and agency representatives at the Deputy Secretary level. It will review all federal programs that contribute to climate change science and technology and will make recommendations to the Committee about the funding level and focus of these programs to advance a climate change science and technology program that contributes to the enhanced understanding needed to better support policy and management decisions.

The **Climate Change Science Program** (CCSP) reports to the Working Group. Its membership includes representatives from all agencies that have a research mission in climate and global change. The CCSP is responsible for effective management of the coordinated interagency research program, oversees the interagency groups responsible for each major research program element listed in this Strategic Plan (i.e., Atmospheric Composition, Climate Variability and Change, Water Cycle, Land Use/Land Cover Change, Carbon Cycle, Ecosystems, and Human Contributions and Responses to Environmental Change), and interacts with various external advisory groups. The **Climate Change Technology Program** (CCTP) is an interagency program that will coordinate and develop a comprehensive, multi-year, integrated climate change technology R&D program for the United States.

The USGCRP has a decade of experience and has established a number of successful methods for planning and implementing interagency programs to support research on complex climate and global change issues. While approaches used in the past provide a good foundation for the future, new mechanisms for improved coordination and integration are being developed. This section of the strategic plan provides a framework for management of climate and global change research by the CCSP in the next decade.

1. Mechanisms for Successful Management: Scientific Guidance, Interagency Planning and Implementation, and Program Integration

The CCSP incorporates three mechanisms for management of the program:

- Scientific guidance;
- Interagency planning and implementation; and
- Program integration by the CCSP.

The interaction of these three management elements is critical for improving the scientific planning, the effectiveness of interagency management, and the focus of climate and global change research to support governmental and non-governmental needs.

SCIENTIFIC GUIDANCE

The US and international science communities bring essential expertise to the CCSP activities. Relevant committees and boards of the National Academy of Sciences, in particular, will be asked to provide scientific guidance.

Scientific Steering Committees (SSCs) will be established for each research program element to assist the agencies by developing detailed science plans that describe in greater detail than is possible in this Strategic Plan the research that is required to address the questions in each of the research program elements. An example of a detailed science plan is the *U.S. Carbon Cycle Science Plan* (Sarmiento et al., 1999). This science plan was requested by several agencies participating in the USGCRP and was developed by a Carbon and Climate Working Group that drew on the expertise of the entire US carbon cycle science community through workshops. It was subsequently published and serves as detailed scientific guidance for USGCRP activities in this area. Scientific plans have been developed or are being developed for the other CCSP research program elements as well to guide research efforts.

The science review of implementation plans and progress towards achieving objectives is also essential. This will provide crucial information for both the program managers and the CCSP in evaluating whether the CCRI and USGCRP are making progress toward their goals.

INTERAGENCY PLANNING AND IMPLEMENTATION

The CCSP draws on the strengths of many agencies and departments. It requires a significant degree of coordination, however, to ensure that research planned and implemented across these departments and agencies supports agreed-upon scientific objectives.

At the level of individual research program elements, interagency committees of program managers work together to ensure that the science plans for each element inform departmental and agency budget priorities and are translated into implementation plans that explain how research efforts will achieve specific deliverables. The CCSP will oversee development of an interagency implementation plan for each research program element. The implementation plans will identify and prioritize the scientific programs necessary to meet the key science objectives and the roles of each participating agency. They will also provide generalized timelines and budget estimates for the investments necessary to carry out the activities, noting any critical dependencies. Each implementation plan will also prioritize the observations and/or observing systems necessary to meet the goals of the research as well as critical modeling efforts and/or information-management issues. These priorities will inform the choices that will need to be made by agencies and by CCSP as a whole.

Each implementation plan will be developed by an interagency working group, reviewed by external scientists, and approved by the CCSP. This process assures the agreement of agencies to the overall timelines and budget priorities as well as transparency and credibility to the planning process. This process also provides a mechanism for identifying any critical dependencies requiring action by the CCSP and by those responsible for agency budgets. The implementation plans will be updated and revised regularly in order to ensure that they reflect evolving scientific discovery, agency participation, and budget priorities.

These interagency working groups will also be responsible for providing program-level coordination for budgets, joint announcements of opportunity for the scientific research community, coordinated studies by agency staff, and periodic evaluation of progress toward the scientific goals.

The coordination of the CCSP is facilitated by the CCSP Office, consisting of a Director (a Department of Commerce detailee) and staff. The office is supported on a shared-cost basis by the participating agencies and by the allocated time of agency staff.

CCSP INTEGRATION

This draft Strategic Plan describes the important questions and goals for research over the next decade. The CCSP has responsibility for periodically reviewing these questions and goals and ensuring that program objectives are met. This responsibility includes an annual cycle of program and budget review.

The CCSP will adopt a problem-driven rather than a disciplinary approach in setting priorities and sequencing investments, identifying for early action and support those projects and activities that meet agreed-upon criteria in the following areas:

- Relevance/Contribution;
- Scientific Merit;
- Readiness;
- Deliverables;
- Linkages; and
- Costs.

Some projects and activities may be identified for early implementation because they lay the foundation for subsequent work in other areas or are ready for implementation due to prior planning. The CCSP will also ensure periodic program reviews and evaluations involving both internal and external partners, including the scientific research community and other users of climate and global change information. Individual agencies will enable external review of their research strategies and plans (e.g., by the National Research Council (NRC) and Federal Advisory Committee Act (FACA) advisory committees) to ensure quality, relevance, and timeliness of the CCSP and its agencies' goals.

Developing answers to the questions posed in the draft Strategic Plan will require integration of research conducted or supported by different departments and agencies. The past decade has shown that the research on climate and global change often includes components that do not fall neatly into the core mission of any one of the participating agencies, are entirely new program needs, or are key to the integration of separate agency activities. An example is the development of comprehensive climate and Earth-system modeling necessary for projecting climate change and assessing its impacts on natural and human systems. Other examples include developing decision support resources for natural resource management and policy decisions and preparation of integrated products such as the proposed periodic CCSP reports.

One necessary approach for addressing such integrating activities is to develop a mechanism that allows functions that are not central to the core missions of the participating agencies, but that are highly relevant, to be fostered. Some functions might be of short-duration but critical to integration. Others might be long-term efforts that eventually lead to the transition of multi-agency research activities to operational activities associated with a specific agency.

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Sarmiento et al., 1999. Sarmiento et al., Carbon and Climate Working Group of the USGCRP, *US Carbon Cycle Science Plan* (Washington, DC: USGCRP).

Acronyms

ADEOS. Advanced Earth Observing Satellite

AQRS. Air Quality Research Subcommittee of the Committee on Environment and Natural Resources. The CENR is one of the 9 committees organized under the National Science and Technology Council (NSTC).

AmeriFlux. American network of sites measuring fluxes of carbon and water vapor fluxes between terrestrial ecosystems and the atmosphere.

AMSR. Advanced Microwave Sounding Radiometer.

AO. Arctic Oscillation.

AOSB. Arctic Ocean Sciences Board.

APN. Asia-Pacific Network for Global Change Research

BAHC. Biospheric Aspects of the Hydrological Cycle project.

CCRI. Climate Change Research Initiative.

CCSM. Community Climate System Model.

CCSP. Climate Change Science Program.

CEOS. Committee on Earth Observation Satellites.

CGIAR. Consultative Group on International Agricultural Research.

CH_4. Methane.

CliC. Climate and Cryosphere project of the World Climate Research Programme.

CLIVAR. Climate Variability and Predictability.

COLA. Center for Ocean-Land-Atmosphere Studies.

CO_2. Carbon dioxide.

CPT. Climate Process Teams.

DPC. Domestic Policy Council.

ENSO. El Niño-Southern Oscillation.

EOS. NASA's Earth Observing System.

ESE. NASA's Earth Science Enterprise.

FAO. United Nations Food and Agriculture Organization.

G3OS. Combination of three observing systems:

1. Global Climate Observing System (GCOS)
2. Global Ocean Observing System (GOOS)
3. Global Terrestrial Observing System (GTOS).

GAW. Global Atmosphere Watch.

GCOS. Global Climate Observing System.

GCRIO. Global Change Research Information Office.

GCTE. Global Climate and Terrestrial Ecosystems.

GECAFS. Global Environmental Change and Food Systems project.

GEF. Global Environmental Facility.

GEWEX. Global Energy and Water Cycle Experiment.

GFDL. Geophysical Fluid Dynamics Laboratory.

GIS. Geographic Information System.

GISS. Goddard Institute for Space Studies.

GOFC-GOLD. Global Observation for Forest and Land Cover Dynamics program.

GOOS. Global Ocean Observing System.

GPS. Global Positioning System.

GRACE. Gravity Recovery and Climate Experiment.

GSN. Global Climate Observing System (GCOS) Surface Network.

GTN-P. Global Terrestrial Network for Permafrost.

GTOS. Global Terrestrial Observing System.

GUAN. GCOS (Global Climate Observing System) Upper-Air Network.

HELP. Hydrology for Environment, Life and Policy (United Nations Educational, Scientific and Cultural Organization).

HSB. Humidity Sounder of Brazil

IAI. Inter-American Institute for Global Change Research.

IASC. International Arctic Sciences Committee.

ICSU. International Council for Science .

IGBP. International Geosphere-Biosphere Programme.

IGAC: International Global Atmospheric Chemistry, a Core Project of the International Geosphere-Biosphere Programme.

IGFA. International Group of Funding Agencies for Global Change Research.

IGOS. Integrated Global Observing Strategy.

IHDP. International Human Dimensions Programme.

IOC. the Intergovernmental Oceanographic Commission of UNESCO.

IPCC. Intergovernmental Panel on Climate Change.

IRI. International Research Institute for Climate Prediction .

K-12. Kindergarten through grade 12.

MOPITT. Measurement of Pollution in the Troposphere

N_2O. Nitrous Oxide

NACIP. National Aerosol–Climate Interactions Program.

NACP. North American Carbon Program.

NAS. National Academy of Sciences.

NASA. National Aeronautics and Space Administration.

NCAR. National Center for Atmospheric Sciences.

NCCTI. National Climate Change Technology Initiative.

NEC. National Economic Council.

NGO. Non-governmental organization.

NOAA. National Oceanic and Atmospheric Administration.

NRC. National Research Council.

NSC. National Security Council.

NSCAT. NASA Scatterometer.

PAGES. Past Global Changes palaeoscience project of the International Geosphere-Biosphere Programme.

PDO. Pacific Decadal Oscillation.

PACOM. Pan-African Committee of START [SysTem for Analysis, Research, and Training].

QuikSCAT. NASA's Quick Scatterometer.

SCOPE. Scientific Committee on Problems of the Environment.

SCOR. Scientific Committee on Oceanic Research of the International Council for Science.

SCAR. Scientific Committee on Antarctic Research of the International Council for Science.

SeaWiFS. Sea-viewing Wide Field-of-view Sensor.

SPARC. Stratospheric Processes and their Role in Climate.

SSC. Scientific Steering Committee

START. SysTem for Analysis, Research, and Training.

TAO. Tropical Atmosphere-Ocean moored array.

TOPEX. Ocean Topography Experiment

TRMM. Tropical Rainfall Measuring Mission.

TWAS. Third World Academy of Sciences.

UN. United Nations.

UNDP. UN Development Programme.

UNEP. UN Environment Programme.

USAID. US Agency for International Development.

USGCRP. US Global Change Research Program.

WCRP. World Climate Research Programme.

WMO. World Meteorological Organization.

WHO. World Health Organization.

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