Evaluating Progress of the U.S. Climate Change Science Program: Methods and Preliminary Results

Committee on Strategic Advice on the U.S. Climate Change Science Program, National Research Council

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Division on Earth and Life Studies
Division of Behavioral and Social Sciences and Education
National Research Council

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Adrian R. Chamberlain, Parsons Brinckerhoff Inc., Fort Collins, Colorado
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Sharon A. Cowling, University of Toronto, Canada
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Aristides A.N. Patrinos, Synthetic Genomics, Inc., Rockville, Maryland
David A. Randall, Colorado State University, Fort Collins, Colorado
Robert A. Weller, Woods Hole Oceanographic Institution, Massachusetts

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Kenneth H. Brink**,** Woods Hole Oceanographic Institution, appointed by the Divison on Earth and Life Studies, and George M. Hornberger, University of Virginia, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

The U.S. Climate Change Science Program (CCSP) was created in February 2002 under a new cabinet-level management structure designed to improve government-wide management of climate and related environmental science. The CCSP integrated the then-existing U.S. Global Change Research Program (USGCRP) with the administration's Climate Change Research Initiative. The CCSP was formed with an ambitious, but practical, guiding vision: *a nation and the global community empowered with the science based knowledge to manage the risks and opportunities of change in the climate and related environmental systems.*

Although the U.S. government has sponsored research on climate and related environmental change through the CCSP or USGCRP for more than 15 years, the progress of either program has never been evaluated. Such evaluations are important for identifying strengths and weaknesses and determining what adjustments should be made to achieve program goals. At the request of Dr. James Mahoney, then director of the CCSP, the National Research Council (NRC) established the Committee on Strategic Advice on the U.S. Climate Science Program to carry out three tasks over a three-year period. The first task—an evaluation of program progress—is the subject of this report:

> *Task 1. The committee will assist the CCSP in evaluating progress toward program goals. The CCSP Strategic Plan and the guidelines given in the 2005 NRC report* Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program *will provide a starting point for this examination. The report will address two subtasks:*
>
> *1a. Findings and recommendations on the process for evaluating progress toward the five goals in the CCSP strategic plan. The recommendations should be practical and consider the trade-offs between strategic utility and program costs associated with implementing metrics.*
>
> *1b. A preliminary assessment of progress made toward the program's goals. The results will serve as an interim report for a more comprehensive analysis of the program's progress to be completed in subsequent years.*

The focus of this report is on progress made over the past four years—the lifetime of the CCSP. How the program should evolve to address gaps and weaknesses or to respond to new needs is the subject of the committee's second task and report.

The CCSP's structure, activities, and time line for delivering products are laid out in a 2003 strategic plan. Thirteen federal agencies participate in the CCSP, which has an annual budget of about $1.7 billion. The budget is provided and managed by the participating agencies, which also help set the direction of the program through interagency committees at various levels. The overall program is guided by a director (currently an acting director) and carried out by the agencies and a small program office.

The CCSP is divided into three main components: (1) overarching goals, which represent what the overall program is trying to achieve (e.g., scientific understanding, reduction of uncertainties, risk management); (2) research elements (e.g., atmospheric composition, carbon cycle, human contributions and responses), which lay out the research agenda in the form of 33

questions to be answered; and (3) cross-cutting issues (e.g., observations, decision support resources, communications), which are common to all of the research elements. A method for evaluating the progress of all three components and conclusions from the committee's preliminary evaluation are described below.

METHOD FOR EVALUATING PROGRESS

Recommendation. CCSP progress should be evaluated in two stages: (1) a broad overview of the entire program based on the knowledge of the reviewers, and (2) a more in-depth analysis of areas in which progress has been inadequate, using the process and input metrics from NRC (2005).

A 2005 NRC report proposed a framework of 24 metrics that could be used to evaluate the CCSP from end to end—from program processes (e.g., strategic planning, peer review) to inputs (e.g., resources), to short-term outputs (e.g., publications), to long-term outcomes (e.g., improved understanding, use of science to support decision making) and impacts (e.g., improved public policy). The committee found that this framework yields a wealth of information on CCSP progress, but the detailed budget and management information necessary to score the process and input metrics is not readily available, even to CCSP agencies. Consequently, the committee developed an alternative two-stage evaluation approach that balances practicality and strategic utility. The first stage would be a high-level assessment of strengths and weaknesses of the entire program, based mainly on the reviewers' knowledge of program results. The entire program can be evaluated using a matrix of the 33 research questions in the research elements (rows of the matrix) versus five categories of outputs and outcomes (columns of the matrix):

A: Improve data sets in space and time, and improve estimates of physical quantities
B: Improve understanding and representation of processes
C: Improve predictability, predictive capabilities, or assessment of uncertainty
D: Improve synthesis and assessment to inform
E: Improve assessment and management of risk, and improve decision support for management and policy making

The rows of the matrix (research questions) are connected to the CCSP overarching goals, and the columns of the matrix overlap with the cross-cutting issues. In particular, category A includes observations and monitoring, category C includes modeling, category D includes communication, and category E includes decision support resources. By combining the scores of the cells of the matrix in different ways, it is possible to assess progress in the CCSP research elements, overarching goals, and cross-cutting issues.

The second stage of evaluation would be a careful analysis of areas identified as not meeting expectations. These areas would be evaluated with the process and input metrics from NRC (2005), which provide tools for diagnosing the reasons for program weaknesses and making strategic decisions about where adjustments should be made to improve outcomes.

PRELIMINARY ASSESSMENT OF PROGRESS

The committee used its matrix to carry out the first stage of the evaluation of CCSP progress. Findings based on that evaluation are given below.

The separation of leadership and budget authority presents a serious obstacle to progress in the CCSP.

Leadership to guide the program is generally required if a program is to succeed (NRC, 2005). The strength of the current CCSP leadership structure lies in its potential to engage the expertise found across U.S. government agencies and international partners to address climate science and applications. CCSP leaders can advocate for the program at higher levels in the government or with participating agencies when the decisions of a single agency adversely affect the entire program (e.g., cancellation of critical climate sensors) or when changing CCSP priorities would require changes in agency programs (e.g., a greater emphasis on supporting decision making). However, the CCSP director and agency principals lack authority to allocate or prioritize funding across the agencies, and the interagency working group members often have little budgetary authority to implement the research directions that they define. Such authority usually resides at higher levels in the participating agencies. As a result, progress is most likely when CCSP and agency interests coincide.

Discovery science and understanding of the climate system are proceeding well, but use of that knowledge to support decision making and to manage risks and opportunities of climate change is proceeding slowly.

Good progress has been made in documenting the climate changes of the past few decades and in unraveling the anthropogenic influences on the observed climate changes. The period has witnessed improved understanding of many aspects of the climate and related environmental systems, including aerosol direct forcing, land use change, sea ice retreat, glacier melting, and atmospheric warming. Predictive capabilities have also improved, especially of coupled ocean-atmosphere-land climate models used to evaluate the human impact on observed trends, although models that enable exploration of feedbacks, predictions at regional to local scales, or trade-offs of different resource management and mitigation options are still relatively immature. In contrast, progress in synthesizing research results or supporting decision making and risk management has been inadequate. Although the temperature trends assessment (CCSP, 2006b) was influential in the 2007 report of the Intergovernmental Panel on Climate Change, 19 other CCSP synthesis and assessment products scheduled to be released by now are still in the production stage. Also, only a few small programs (e.g., Regional Integrated Sciences and Assessments program, Decision Making Under Uncertainty centers) have been initiated to identify and engage decision makers.

Progress in understanding and predicting climate change has improved more at global, continental, and ocean basin scales than at regional and local scales.

Information at regional and local scales is most relevant for state and local resource managers and policy makers, as well as for the general population, but progress on these smaller spatial scales has been inadequate. Improving understanding of regional-scale climate processes and their impacts in North America, for example, would require improved integrated modeling, regional-scale observations, and the development of scenarios of climate change and impacts.

Our understanding of the impact of climate changes on human well-being and vulnerabilities is much less developed than our understanding of the natural climate system.

Progress in human dimensions research has lagged progress in natural climate science, and the two fields have not yet been integrated in a way that would allow the potential societal impacts of climate change and management responses to be addressed. This disparity in progress likely reflects the inability of the CCSP to support a consistent and cogent research agenda as recommended in previous studies. The level of investment ($25 million to $30 million) remains substantially lower than the level of investment in the other research elements, and funding is atomized across many agency programs. Few social scientists are in leadership positions in the federal agencies, which makes it difficult for the CCSP to increase program emphasis in this area or to establish links with the academic social science community. Finally, the research community is small and thus may be unable to advocate effectively for changing program priorities.

Science quality observation systems have fueled advances in climate change science and applications, but many existing and planned observing systems have been cancelled, delayed, or degraded, which threatens future progress.

Knowledge of climate variability and change rests on consistent long-term observations that are broadly disseminated and archived for future generations of scientists. The contribution of remote sensing and in situ observations and their associated information systems to Earth system science and applications has been a major achievement of the CCSP-USGCRP agencies. However, a number of planned satellite sensors critical to the long-term (multidecadal) data record have been cancelled or seriously delayed (e.g., National Polar-orbiting Environmental Satellite System climate instruments, Hydros, Landsat, Global Precipitation Measurement mission), and long-standing (decades to a century or longer) in situ networks are deteriorating (e.g., stream gauge network, Snowpack Telemetry snow observation system) because of funding shortfalls. The loss of existing and planned satellite sensors is perhaps the single greatest threat to the future success of the CCSP. Without a wide array of continuous satellite and in situ observations, the U.S. capability to monitor trends, document the impacts of future climate change, and further improve prediction and assimilation models through comparison with observations will decline even as the urgency of addressing climate change increases.

Progress in communicating CCSP results and engaging stakeholders is inadequate.

The program has had some successes interacting with scientists, federal government agencies, and water resource managers. However, efforts to identify and engage in a two-way dialogue with state and local officials, nongovernmental organizations, and the climate change technology community have generally been limited and ad hoc. As a result, the program is not gaining the input it needs on what scientifically based CCSP products to create, and opportunities to inform decision making are being missed.

The committee notes that differences in the rates of program progress between the natural and social sciences and between science and communications and decision support are not surprising, given the long history of support of fundamental research through the USGCRP and the allocation of CCSP funding. Only a small fraction of the CCSP budget is devoted to decision support resources and communication (CCSP, 2006a). However, if the program is to achieve its vision of producing information that can be used to formulate strategies for preventing, mitigating, and adapting to the effects of climate change, adjustments will have to be made in the balance between science and applications.

1
Introduction

The U.S. government has sponsored a substantial coordinated research program on global climate and related environmental change for more than 15 years, initially under the U.S. Global Change Research Program (USGCRP) and currently under the Climate Change Science Program (CCSP). Research carried out under these programs has led to numerous scientific advances, but evidence of progress is largely anecdotal. A formal evaluation of program performance would (1) demonstrate that investments in research and applications are generating returns, and (2) identify where adjustments should be made to improve results.

The CCSP has been considering ways to evaluate progress since 2003. However, assessing progress has proved challenging for a program which comprises activities ranging from research, observations, and modeling on the atmospheric, ocean, and land systems; to human contributions and responses to climate change; to tools to support decision making (e.g., scenarios of possible impacts of climate change on North America). A National Research Council (NRC) report *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program* (NRC, 2005) provided a framework that would enable CCSP managers to make strategic decisions about the entire program, and CCSP asked this committee for guidance in building from it.

The Committee on Strategic Advice on the Climate Change Science Program was established to carry out three tasks for the CCSP. The first task—to develop a process for evaluating progress and to make a preliminary assessment of CCSP progress (Box 1.1)—is the subject of this report.

BOX 1.1 Committee Charge for Task 1

The committee will assist the CCSP in evaluating progress toward program goals. The CCSP *Strategic Plan* and the guidelines given in the 2005 NRC report *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program* will provide a starting point for this examination. This report will address two subtasks:

1a. Findings and recommendations on the process for evaluating progress toward the five goals in the CCSP strategic plan. The recommendations should be practical and consider the tradeoffs between strategic utility and program costs associated with implementing metrics.

1b. A preliminary assessment of progress made toward the program's goals. The results will serve as an interim report for a more comprehensive analysis of the program's progress to be completed in subsequent years.

The committee began by examining evaluation approaches tried by CCSP managers as well as the comprehensive framework laid out in *Thinking Strategically* (NRC, 2005). Based on this analysis, it developed an evaluation approach that would both identify strengths and weaknesses of the entire program and be practical to implement. The committee's approach was used to carry out the preliminary evaluation of CCSP progress (task 1b). Input for the evaluation was gathered from CCSP reports, the scientific literature, briefings and responses to questionnaires from CCSP managers, and a community workshop. Although the assessment identified gaps and weaknesses in the program, no recommendations were made on ways to address them. Identifying future priorities for the CCSP is the subject of the committee's second task.

CLIMATE CHANGE SCIENCE PROGRAM

The CCSP integrates the USGCRP and the Climate Change Research Initiative (CCRI). The USGCRP, the first federally coordinated program supporting climate change research, began as a presidential initiative in 1988 and received congressional support in 1990 under the Global Change Research Act.[1] The act called for the development of a research program "to understand, assess, predict, and respond to human-induced and natural processes of global change," and it guided federally supported global change research for the next decade. In 2001, President Bush launched the CCRI to investigate uncertainties and set new research priorities in climate change science.[2] The CCRI also gave priority to research that could yield results within a few years, either by improving decision-making capabilities or by contributing to improved public understanding. The two programs were merged the following year, and a cabinet-level management structure was introduced to improve coordination between the CCSP, a parallel program to promote the development of new technologies for monitoring or eliminating greenhouse gas emissions (the Climate Change Technology Program), and the Office of the President.

The CCSP is divided into three major components: overarching goals, research elements, and cross-cutting issues (Figure 1.1). The CCSP overarching goals differ from previous USGCRP goals by placing a greater emphasis on uncertainties and the use of research results in decision making. The five overarching CCSP goals follow:

1. Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.
2. Improve quantification of the forces bringing about changes in the Earth's climate and related systems.
3. Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future.
4. Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.
5. Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change (CCSP, 2003).

Some of the research elements have also changed since the inception of the CCSP. In particular, paleoclimate research under the USGCRP was apparently folded into the CCSP climate variability and change research element, and a new research element on land use and land cover change was added. Finally, the CCSP has identified six issues (e.g., modeling, observations) that cut across the research elements (Figure 1.1).

[1] Public Law 101-606(11/16/90) 104 Stat. 3096-3104.
[2] See <http://www.climatescience.gov/>.

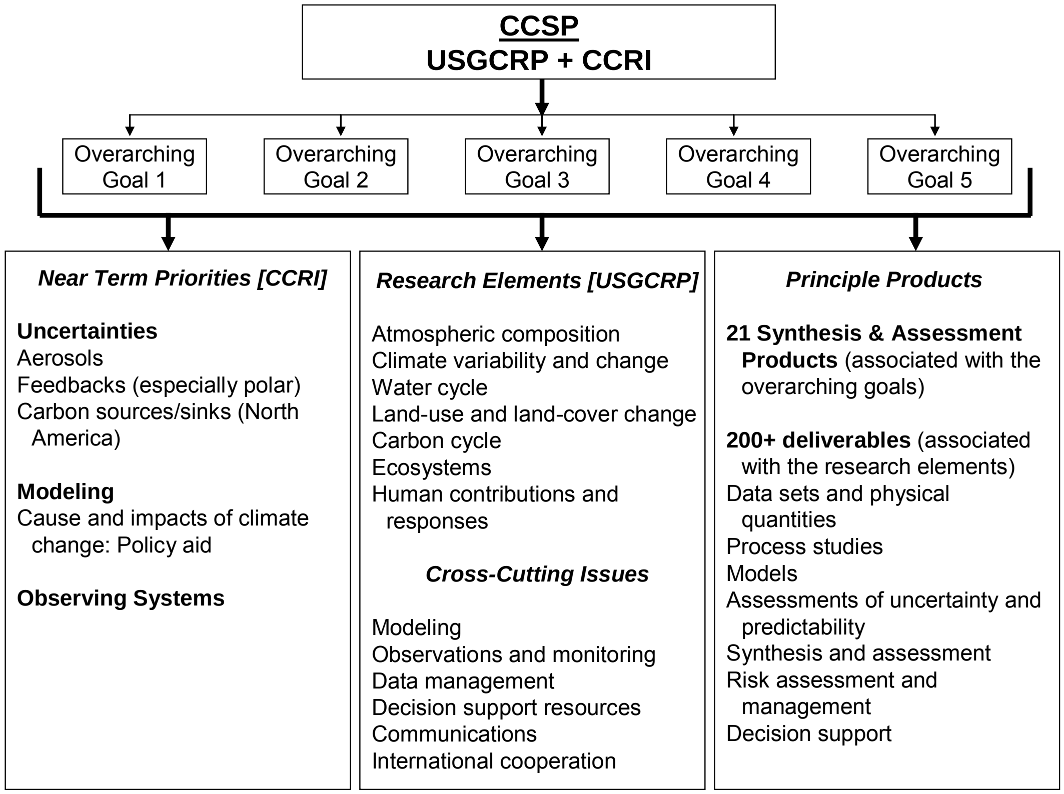

FIGURE 1.1 CCSP road map.

The USGCRP supported long-term research results, but the CCSP also committed to create hundreds of products within two to four years (Table 1.1), beginning in July 2003. This ambitious plan is not likely to be met. For example, only two of the 21 planned synthesis and assessment products have been published and only three others are in the final draft stage (Appendix A). Apparently, unforeseen delays were caused by new requirements to develop guidelines for peer review of federal government information and to prevent federal and nonfederal participants from serving on the same authoring committees, as had been planned originally.[3]

Thirteen agencies participate in the CCSP, which has an annual budget of about $1.7 billion (CCSP, 2006a). Coordination within the CCSP takes place at several levels (Figure 1.2). The program has a director (currently an acting director) appointed by the Department of Commerce. Strategic planning for the program as a whole is overseen by principals from each participating agency and liaisons from the Executive Office and related programs. Planning within the major components of the program is done through 11 interagency working groups, some of which have external advisory committees. A program office with about 14 staff members provides management and coordination support.[4]

[3] Presentation to the committee by James Mahoney, CCSP director, on April 27, 2006. See Public Law 106-554, (Information Quality Act) and Public Law 92-463 and amendments (Federal Advisory Committee Act).
[4] See <http://www.climatescience.gov/about/staff/default.htm>.

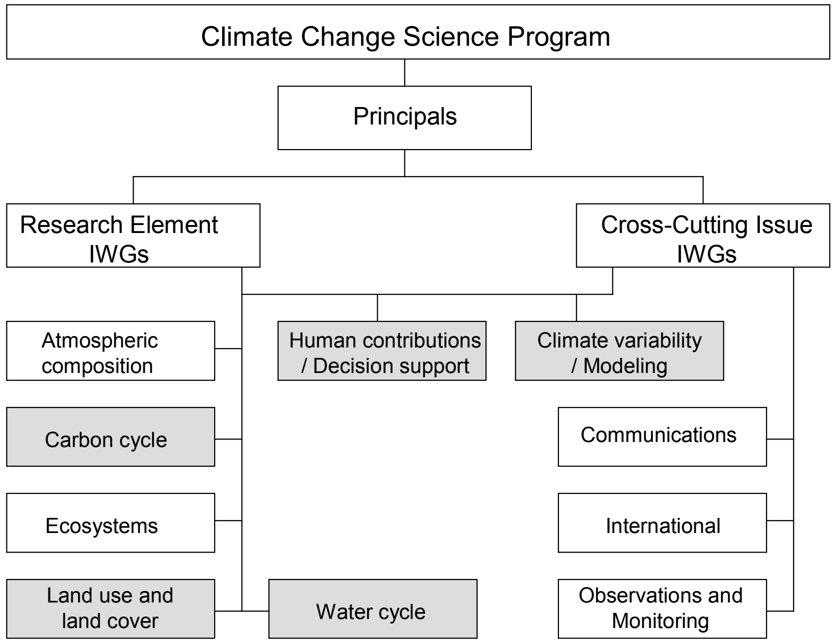

FIGURE 1.2 Interagency coordination structure for the Climate Change Science Program. Interagency working groups (IWGs) shaded in gray have access to an external advisory group. Two of the IWGs (human contributions and responses/decision support resources and climate variability and change/modeling) cover both a research element and a cross-cutting issue. There is also an IWG for financial operations. The CCSP Office supports coordination at all levels of the program.

ORGANIZATION OF THE REPORT

This report describes a method for evaluating progress of the CCSP and provides a preliminary assessment of progress over the last four years. The report is divided into two parts. Part I (Chapters 2 and 3) recommends an evaluation method and provides overarching conclusions from the preliminary assessment of CCSP progress. The strengths and limitations of different evaluation approaches are analyzed in Chapter 2. The evaluation of CCSP progress was structured around a matrix developed by the committee (Appendix C). Chapter 3 describes how the cells of the matrix were scored and presents conclusions on where the most and least progress has been made in the program. Detailed supporting analysis for these conclusions appears in Part II (Chapters 4 and 5) for reference. Chapter 4 evaluates progress in the seven research elements (e.g., carbon cycle, ecosystems) and part of an overarching goal, and identifies challenges and opportunities to maintaining or speeding progress in the future. Progress in the cross-cutting issues (e.g., modeling, communications) is assessed in Chapter 5. Input for the evaluation was gathered from CCSP reports and presentations, the scientific literature, responses to a questionnaire on funding and programs under the human contributions and responses research element (summarized in Appendix B), and a committee-organized workshop (see Appendix D).

TABLE 1.1 Budgets, Products, and Advisory Structure for CCSP Research Elements

	Atmospheric Composition	**Climate Variability and Change**	**Carbon Cycle**	**Water Cycle**	**Ecosystems**	**Land Use and Land Cover Change**	**Human Contributions and Responses**
Fiscal Year 2006 Budget (million dollars)[a]							
Research	\$170.1	\$286.9	\$113.2	\$137.9	\$115.8	\$32.5	\$25–30[b]
NASA satellites	\$62.9	\$136.9	\$89.4	\$119.4	\$49.0	\$42.7	\$0.0
Products							
< 2 years	0	3	3	5	1	13	3
2-4 years	11	37	20	19	8	12	12
≥ 4 years	5	11	23	14	7	17	4
Coordination or Advisory Structure							
Interagency working group	9 agencies	6 agencies and U.S. CLIVAR Project Office; also covers modeling	9 agencies and U.S. Carbon Cycle Program Office	9 agencies	9 agencies	8 agencies	8 agencies; also covers decision support resources
Science advisory committee	No	Use NRC committee (CRC)	Yes, active	Being reconstituted	No	Yes, met once in October 2005	Use NRC committee (CHDGC)

NOTES: CHDGC = Committee on the Human Dimensions of Global Change; CLIVAR = Climate Variability and Predictability; CRC = Climate Research Committee; NASA = National Aeronautics and Space Administration

[a] Budgets from CCSP (2006a). Research budget includes National Oceanic and Atmospheric Administration satellite costs, but not NASA satellite costs or CCRI activities.

[b] The CCSP-reported budget is \$147.6 million, including \$62.8 million for NASA programs on decision support and \$57.2 million for National Institutes of Health programs on the health effects of ultraviolet radiation, neither of which are social science research. Finding devoted to human contributions and responses research is probably \$25 million to \$30 million (see Appendix B).

Part 1
Methods and Results

2
Process for Evaluating Progress: Task 1a

The first part of the committee's charge (task 1a) was to develop a process for evaluating progress in the Climate Change Science Program (CCSP). The objective was to design an evaluation that (1) would encompass the major components of the program at a sufficient level of detail to enable program managers to make any necessary adjustments, and (2) would be practical for the CCSP to implement. A number of approaches have been proposed, ranging from the comprehensive evaluation framework laid out in *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program* (NRC, 2005) to simply tracking completion of CCSP products. This chapter examines the strengths and limitations of these approaches and recommends a methodology to evaluate the progress of the CCSP. The committee's preliminary assessment (task 1b), based on this methodology, is summarized in Chapter 3 and presented in more detail in Part II.

WHAT CAN BE EVALUATED

A key step in designing any evaluation is to divide the program into meaningful pieces against which progress can be measured (NRC, 2005). Too coarse a division of the program will capture many disparate elements and will both be difficult to evaluate and yield ambiguous results. Too fine a division will be costly and time consuming to evaluate, and the evaluation results may not be useful to program managers. Because progress has to be assessed in the context of applied resources, the pieces being analyzed should have associated budgets. Some natural divisions in the CCSP and the information available for the evaluation are described below.

Organizing the Evaluation

The CCSP has three major components: overarching goals, research elements, and cross-cutting issues (Figure 2.1). Any of these could serve as themes for organizing the evaluation, and all have advantages and disadvantages. The overarching goals (e.g., reduction of uncertainty) represent what the program is trying to achieve, but they are broad, some of them overlap (especially goals 1, 2, and 3), and progress in one goal usually depends on progress in another goal. The research elements (e.g., water cycle, ecosystems) represent a research agenda agreed on by multiple agencies with a time line for the delivery of specified milestones and products (Table 1.1). As such, they represent the strongest connection to the programs of participating agencies, where climate research activities are funded and managed. However, they offer only limited insight on the more applied aspects of the program. Finally, the cross-cutting issues (e.g., modeling, observations and monitoring) cover the types of activities the program supports, but their breadth makes them difficult to evaluate. For example, observation goal 1 is "design, develop, deploy, integrate, and sustain observation components into a comprehensive system" (CCSP, 2003), which applies to some extent to the entire program.

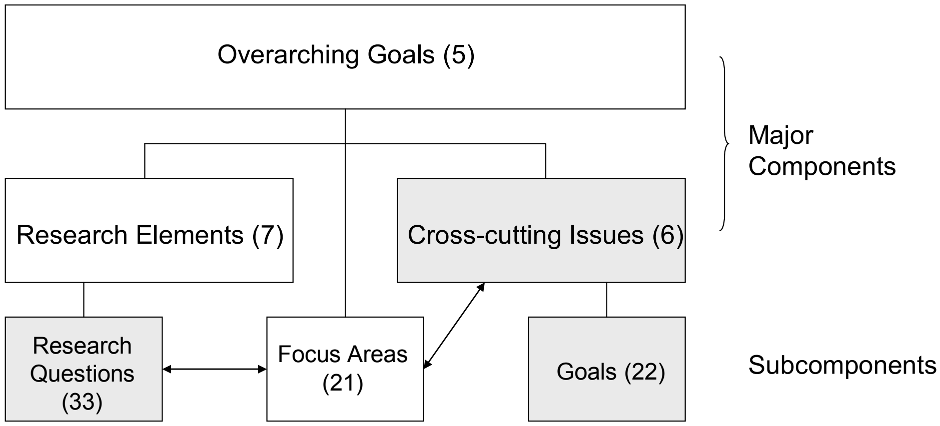

FIGURE 2.1 Hierarchical structure of CCSP components. The focus areas of the overarching goals are linked with both the research questions and the cross-cutting issues. The CCSP does not report budgets for boxes shaded in gray.

Each of the major components of the program has a subcomponent: the overarching goals are divided into 21 focus areas, the research elements are divided into 33 research questions, and the cross-cutting issues have 22 goals (Figure 2.1). Although the program can be analyzed at both hierarchical levels, the committee generally found it most fruitful to evaluate the program at the subcomponent level.

Information for the Evaluation

The information required to carry out a credible evaluation includes a list of program activities and results and the amount of funding devoted to these activities. None of these are available for the CCSP in useful forms. The activities included in the program are designated by the participating agencies and vary from year to year (GAO, 2006). Results are reported in many places, including the CCSP web site and publications and the scientific literature, but they are not linked directly to the major components or subcomponents of the program. The most unambiguous source of information on program progress is found in the CCSP's annual report to Congress, *Our Changing Planet*, which provides selected examples of progress and plans each year. *Our Changing Planet* also tallies agency budgets into some CCSP categories (overarching goals, focus areas, and research elements; see Figure 2.1), but this is primarily an accounting exercise, rather than a true allocation of funding to achieve CCSP objectives. Indeed, in response to a questionnaire prepared by the committee, agency managers had difficulty matching their programs to the CCSP overarching goals.[5]

Uncertainties about what activities are included in the program and how much they cost makes an in-depth evaluation of program progress difficult, if not impossible, for an external review committee. However, the available information is sufficient in most cases to test different

[5] Presentation to the committee on June 15, 2006, by Don Anderson (NASA, goal 1), Jay Fein (NSF, goal 1), Phil DeCola (NASA, goal 2), Roger Dahlman (DOE, goal 2), Bill Hohenstein (USDA, goal 5), and Jerry Elwood (DOE, goal 5). Written responses to a committee questionnaire were also provided by Anjuli Bamzai (DOE, goal 3), Chet Koblinski (NOAA, goal 3), and DeWayne Cecil (NASA, goal 4).

approaches to evaluating progress and to draw some high-level conclusions about CCSP progress to date.

The one case in which additional information was needed to even test evaluation approaches concerns the human contributions and responses research element. Although a research program on human contributions and responses is outlined in the CCSP strategic plan, the CCSP now manages it with the decision support resources cross-cutting issue (see CCSP, 2005). Consequently, it is no longer clear what research activities on human contributions and responses are supported by the CCSP. In response to a committee request, the CCSP Interagency Working Group on Human Contributions and Responses/Decision Support Resources sent out a questionnaire to eight participating agencies. The resulting list of programs and budgets is given in Appendix B and was used in the committee's evaluation.

This inquiry showed that few agency programs are aimed explicitly at human contributions and responses research, so detailed estimates of expenditures could not be generated. Relevant research may or may not be counted as CCSP, and some research that is clearly peripheral to research element objectives is included in the program accounts. For example, the National Institutes of Health (NIH) program on health effects of stratospheric ozone constitutes more than two-thirds of the reported human contributions and responses budget, yet it is only tangentially concerned with climate change or social science research. Another large fraction of the funding goes to decision support activities, most of which lack a human dimensions research component (see Chapter 5). Including such programs paints a distorted picture of CCSP human contributions and responses research. Funding for human dimensions research is likely on the order of $25 million to $30 million per year, excluding NIH research on the health effects of ozone and National Aeronautics and Space Administration (NASA) decision support activities (Appendix B).

APPLICATION OF THE NRC (2005) EVALUATION FRAMEWORK

The National Research Council (NRC, 2005) report *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program* lays out a comprehensive framework for evaluating the progress of the CCSP. The report identified five categories of metrics that could be used to measure progress and guide strategic thinking across the entire CCSP:

1. Process metrics: measure a course of action taken to achieve a goal
2. Input metrics: measure tangible quantities put into a process to achieve a goal
3. Output metrics: measure the products and services delivered
4. Outcome metrics: measure results that stem from use of the outputs and influence stakeholders outside the program
5. Impact metrics: measure the long-term societal, economic, or environmental consequences of an outcome

Specific metrics within these categories are listed in Table 2.1, and key conclusions from the report are summarized in Box 2.1. Both CCSP managers and the committee have tried to apply the metrics to a major component of the program (overarching goals and research elements, respectively), as described below.

BOX 2.1 Key Conclusions from *Thinking Strategically*

Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program (NRC, 2005) found that progress can be assessed for most aspects of the CCSP, from enhancement of data networks to improved public awareness of climate change issues. The key to promoting progress is to consider the program from end to end, starting with program processes (e.g., planning and peer review) and inputs (e.g., resources) and extending to outputs (e.g., assessments, forecasts), outcomes (e.g., near-term results for science and society), and long-term impacts. Metrics for evaluating all of these stages are given in Table 2.1. Of these, the most appropriate will be the subset that enables managers to identify and monitor program strengths and weaknesses. These measures will become apparent from even rough scores or yes-no answers to the metrics. Detailed analysis and tracking can then be focused on the parts of the program for which better results are desired. The process and input metrics provide clues about why scores on program results (outputs, outcomes, and impacts) might be low. For example, a project may not have succeeded because it lacked a leader with authority to direct sufficient resources to the effort. As the agencies gain experience, this subset of metrics will be refined until only the most useful remain.

Overarching Goals

In 2006, a few CCSP managers tried applying the NRC (2005) metrics to the five CCSP overarching goals. Their rough evaluation found that nearly all of the metrics were relevant to the CCSP and that quantitative scores could be assigned with a reasonably high level of confidence for most metrics.[6] Scoring was most difficult for metrics dealing with impacts, communication of results, and use of results by stakeholders.

CCSP managers have neither pursued this process nor made other efforts to use the NRC metrics. Resources are scarce, and the agencies are seeking a cost-effective, practical approach to assessing progress (see task 1a, Box 1.1). Consequently, they are weighing the extent to which they should adopt the type of broad, strategic evaluation framework recommended by the NRC (2005) against developing CCSP-wide and/or agency-specific metrics related to the CCSP (see “CCSP Approaches” below).

Research Elements

The committee tested the NRC (2005) evaluation framework on the research elements, the component of the program that it knows best. Two contrasting research elements were chosen for the trial: one well established (carbon cycle) and one emerging (human contributions and responses). The evaluation was conducted only at the top hierarchical level (e.g., carbon cycle) because the committee lacked the budget and management information to score the process and input metrics at subcomponent level (i.e., research questions).

As recommended in NRC (2005), scores to the metrics were assigned using only the committee’s knowledge of the research elements, and programmatic and budget information provided in CCSP reports and by the relevant interagency working groups (IWGs). This exercise enabled the committee to gain familiarity with the concepts presented in NRC (2005) and to see how the evaluation framework might be implemented. The results, which are presented for

[6] Presentation to the committee by Jack Kaye, NASA, on April 28, 2006.

illustration purposes only, appear in Table 2.1. Definitive conclusions about progress in these research elements will require additional programmatic information and peer review.

The committee found that this type of preliminary analysis is useful for identifying strengths and weaknesses within a particular research element and for comparing research elements to one another. For example, the carbon cycle research element is well funded and has a long history of strategic planning and science community involvement. Its primary outcomes are scientific advances. Other stakeholders have had little involvement to date, and nonscientific types of societal benefits (e.g., carbon management) are only beginning to be realized. In contrast, the human contributions and responses research element has had relatively little funding, multiagency coordination, or science community participation. However, nonscientist stakeholders are more engaged in selected agency initiatives, and as a result the program has had some successes in informing resource management and decision making, as well as in advancing science. Analyses of the differences among research elements would enable more strategic decisions to be made about where additional investments might best accelerate progress.

Overall, the committee found the evaluation framework laid out in NRC (2005) to be a viable method for assessing progress and making strategic decisions about the CCSP. However, available information on program planning and resource allocation was insufficient for a rigorous evaluation of the process and input metrics. Consequently, the committee sought an alternative method that would be based on readily available information for its preliminary assessment of CCSP progress.

EVALUATING PROGRESS BASED ON PROGRAM RESULTS

Evaluations of progress commonly focus on program results, such as publications and services delivered. The CCSP is considering using annual evaluations of agency-specific performance metrics, which focus on outcomes, and tracking completion of CCSP products to assess progress. The committee developed a “matrix” evaluation approach that focuses only on program results. Program results are relatively well known to external reviewers, so a peer review evaluation, which is important for assessing quality (NRC, 2005), is possible. The agency and committee approaches are described below.

TABLE 2.1 Application of NRC (2005) Metrics to Two CCSP Research Elements

Metric	Carbon Cycle	Human Contributions and Responses
Process Metrics		
1. Leader with sufficient authority to allocate resources, direct research effort, and facilitate progress	Leadership exists in IWG members, who have agency budget authority	The IWG has been expanded to cover decision support tools, which makes it difficult to assess the effectiveness of leadership on human contributions and responses
2. A multiyear plan that includes goals, focused statement of task, implementation, discovery, applications, and integration	CCSP strategic plan as well as North American Carbon Program and Ocean Carbon and Climate Change plans have scientific community input and review	CCSP strategic plan contains good research questions, but little information on implementation. A science community plan with common research goals also exists under the International Human Dimensions Programme on Global Environmental Change, but its connection with CCSP is unclear
3. A functioning peer review process in place involving all appropriate stakeholders, with (a) underlying processes and timetables, (b) assessment of progress toward achieving program goals, and (c) an ability to revisit the plan in light of new advances	Program peer review through the IWG's science advisory group	Peer review takes place within agency programs, but there is no peer review process for the research element
4. A strategy for setting priorities and allocating resources among different elements of the program (including those that cross agencies) and advancing promising avenues of research and applications	Science advisory group is one input for priority setting	Much of the supported research appears to be motivated by natural science research needs, rather than by a prioritization of what questions need to be addressed to solve problems
5. Procedures in place that enable or facilitate the use or understanding of the results by others (e.g., scientists in other disciplines, operational users, decision makers) and promote partnerships	Minimal development of procedures to facilitate communication or partnerships; workshop on the state of carbon cycle research attempted to identify and engage stakeholders on carbon management	Little effort to communicate results beyond a few individual projects (e.g., Knowledge Systems, Decision Making Under Uncertainty [DMUU], Regional Integrated Sciences and Assessments [RISAs])
Input Metrics		
1. Sufficient intellectual and technologic foundation to support the research	Science questions are mature; a research pool actively pursuing these questions and technological tools exist; progress is not primarily limited by technology	Intellectual, technological, and financial support are insufficient to build the research community and carry out research on CCSP goals

2. Sufficient commitment of resources (i.e., people, infrastructure, financial) directed specifically to allow the planned program to be carried out	Implementing the complete carbon science plan requires more resources than currently available	Resources are inadequate to carry out the stated research program
3. Sufficient resources to implement and sustain each of the following: (a) research enabling unanticipated scientific discovery, (b) investigation of competing ideas and interpretations, and (c) development of innovative and comprehensive approaches	Opportunities for basic research cut across agencies; new approaches have been identified within the current structure	With the exception of a few focused programs, research is ad hoc and scattered across the agencies, making it difficult to build comprehensive approaches
4. Sufficient resources to promote the development and maintenance of each of the following: (a) human capital; (b) measurement systems, predictive models, and synthesis and interpretive activities; (c) transition to operational activities where warranted; and (d) services that enable the use of data and information by relevant stakeholders	Funds largely used for basic science, observations, and modeling rather than for developing stakeholder linkages	No apparent coordination of resources to build capacity in the human dimensions or to facilitate the transfer of knowledge to stakeholders
5. The program takes advantage of existing resources (e.g., U.S. and foreign historical data records, infrastructure)	Syntheses of existing and historical data sets have been used to reconstruct forest inventory and land cover changes. Strong links exist to international carbon cycle research efforts	Little evidence that existing social and economic databases have been used by the CCSP, or that the CCSP is emphasizing the creation of new databases necessary to advance human contributions and responses research
Output Metrics		
1. The program produces peer-reviewed and broadly accessible results, such as (a) data and information, (b) quantification of important phenomena or processes, (c) new and applicable measurement techniques, (d) scenarios and decision support tools, and (e) well-described and demonstrated relationships aimed at improving understanding of processes or enabling forecasting and prediction	Large number of peer-reviewed publications and data products for all except (d)	A number of successful initiatives have been undertaken, but they appear to be insufficient to address the research element
2. An adequate community and/or infrastructure to support the program has been developed	Research community exists; infrastructure includes observation networks and modeling. However, planned expansion of networks has not materialized	The research community is small and may be insufficient to meet the requirements of the research element

3. Appropriate stakeholders judge these results to be sufficient to address scientific questions and/or to inform management and policy decisions	Work benefits and is benefited by research in other science fields (e.g., land use and land cover, ocean acidification and ecosystems). Links to carbon management communities are weaker—best links are with U.S. Department of Agriculture's Agricultural Research Service and Forest Service inventory, but less interaction with carbon emissions scenario building (carbon markets)	Little documented interaction with stakeholders except possibly the RISAs and the International Research Institute for Climate and Society (IRI)
4. Synthesis and assessment products are created that incorporate these new developments	CCSP synthesis and assessment product 2.2 is under review (more or less on schedule; see Appendix A)	Synthesis and assessment products are focused mostly on decision support
5. Research results are communicated to an appropriate range of stakeholders	Some uncoordinated efforts exist to link land management to carbon and net climate effects	A few programs (e.g., RISAs, DMUU centers) have created structures for communication with and transfer of knowledge to stakeholders
Outcome Metrics		
1. The research has engendered significant new avenues of discovery	New science questions (e.g., role of fire or disturbance, ocean acidification) have been engendered by research	Program initiatives have pointed toward new avenues of discovery, such as characterizing irreducible uncertainties about climate change and its impacts, assessing vulnerabilities, and understanding the role of institutions in climate-related decision making
2. The program has led to the identification of uncertainties, increased understanding of uncertainties, or reduced uncertainties that support decision making or facilitate the advance of other areas of science	Scientists still cannot balance the global carbon budget, although uncertainties in some areas have narrowed. Feedbacks remain important areas of research (coupled modeling advances)	Program initiatives (e.g., DMUU centers) are beginning to lead to increased understanding of uncertainties and development of decision strategies and tools that incorporate uncertainties, which could inform decision making at several scales and sectors
3. The program has yielded improved understanding, such as (a) more consistent and reliable predictions or forecasts, (b) increased confidence in our ability to simulate and predict climate change and variability, and (c) broadly accepted conclusions about key issues or relationships	Coupled climate-carbon models have been developed, although they are in the early stages	Investment in scenarios and economic modeling has yielded limited knowledge useful for informing policy making

4. Research results have been transitioned to operational use	Carbon management is in the early stages of operations	Some valuable outputs have been transferred to users (e.g., by RISAs and IRI) in areas such as drought response, fire management, and fisheries management
5. Institutions and human capacity have been created that can better address a range of related problems and issues	Links to carbon markets are weak; no institutions have been established	Little human capacity has been created
6. The measurements, analysis, and results are being used (a) to answer the high-priority climate questions that motivated them, (b) to address objectives outside the program plan, or (c) to support beneficial applications and decision making, such as forecasting, cost-benefit analysis, or improved assessment and management of risk	Inadequate progress beyond basic science	Activities to achieve these outcomes have taken place on a very limited scale
Impact Metrics		
1. The results of the program have informed policy and improved decision making	Science advances are informing assessments of the Intergovernmental Panel on Climate Change	Some programs (e.g., RISAs) appear to have informed policy making, although not to the extent envisioned in the CCSP strategic plan
2. The program has benefited society in terms of enhancing economic vitality, promoting environmental stewardship, protecting life and property, and reducing vulnerability to the impacts of climate change	Carbon management is being addressed at the state or regional level, if at all	Positive societal benefit, especially if measured against the level of investment
3. Public understanding of climate issues has increased	Improved public understanding of the links between CO_2 and warming	Insufficient data to measure the effect of initiatives to increase public understanding of climate

CCSP Approaches

Agency-Specific Metrics

The 1993 Government Performance and Results Act requires federal government agencies to set strategic goals and to measure performance against them on an annual basis.[7] Every federal agency has metrics to measure performance, and CCSP program managers are trying to determine whether the metrics of participating agencies can also be used to assess CCSP progress as a whole.[8] However, the aggregate of agency metrics reflects neither the level of agency involvement in CCSP programs nor the breadth of the CCSP, a conclusion also reached in NRC (2005). For example, five agencies (Department of Energy [DOE], NASA, National Oceanic and Atmospheric Administration [NOAA], National Science Foundation, and U.S. Geological Survey) have research projects and initiatives to address CCSP overarching goal 3: reduce uncertainty in projections of how the Earth's climate and related systems may change in the future (CCSP, 2006a). Yet, only three of these agencies have metrics related to this overarching goal (Table 2.2), and these miss key aspects of climate predictions (e.g., droughts) and interagency contributions (e.g., an integrated Earth system analysis capability).

TABLE 2.2 Metrics of Participating Agencies Related to CCSP Overarching Goal 3

Agency	Multiyear Performance Goals and Annual Performance Measures
NOAA	Understand climate variability and change to enhance society's ability to plan and respond. Annual performance measures: • U.S. temperature forecasts (cumulative skill score computed over the regions where predictions are made) • Reduce uncertainty in the magnitude of the North American carbon uptake • Reduce uncertainty in model simulations of the influence of aerosols on climate • Determine the national explained variance (%) for temperature and precipitation for the contiguous United States using U.S. Climate Reference Network stations
DOE	Deliver improved climate data and models for policy makers to determine safe levels of greenhouse gases for the Earth's system. By 2013, substantially reduce differences between observed temperature and model simulations at subcontinental scales using several decades of recent data. Annual performance measure: • Improve climate models: Produce a new continuous time series of retrieved cloud properties at each Atmospheric Radiation Measurement site and evaluate the extent of agreement between climate model simulations of water vapor concentration and cloud properties and measurements of these quantities on time scales of 1 to 4 days
NASA	Progress in understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition. Annual performance measure: • Demonstrate that NASA-developed data sets, technologies, and models enhance understanding of the Earth system, leading to improved predictive capability in each of the six science focus area road maps Progress in quantifying global land cover change and terrestrial and marine productivity, and in improving carbon cycle and ecosystem models. Annual performance measure: • Demonstrate that NASA-developed data sets, technologies, and models enhance understanding of the Earth system, leading to improved predictive capability in each of the six science focus area road maps

[7] Public Law 103-62.
[8] Presentation to the committee by Jack Kaye, NASA, on April 28, 2006, and by Mary Glackin, NOAA, on September 15, 2006.

Progress in quantifying the key reservoirs and fluxes in the global water cycle and in improving models of water cycle change and freshwater availability. Annual performance measures:

- Demonstrate that NASA-developed data sets, technologies, and models enhance understanding of the Earth system, leading to improved predictive capability in each of the six science focus area road maps
- Complete Global Precipitation Measurement confirmation review

Progress in understanding the role of oceans, atmosphere, and ice in the climate system and in improving predictive capability for its future evolution. Annual performance measures:

- Demonstrate that NASA-developed data sets, technologies, and models enhance understanding of the Earth system, leading to improved predictive capability in each of the six science focus area road maps
- Complete Operational Readiness Review for the NPOESS Preparatory Project

SOURCE: DOC, 2006; DOE, 2006; NASA, 2006; <http://www.mbe.doe.gov/budget/06budget/Start.htm>.

Some of NOAA's goals are aligned with CCSP goals, but the other agencies are committed to several different objectives that may or may not have a specific climate component. The mismatch between CCSP and agency goals suggests that it may be difficult to make more than limited progress in the program overall.

Product Status Reports

Tracking the status of products is the simplest way to monitor one kind of program result. The CCSP is tracking the 21 synthesis and assessment products associated with the overarching goals, and participating agencies are tracking the 208 milestones, products, and payoffs associated with the research elements. Reporting whether each milestone, product, or payoff is completed; on or behind schedule; or discontinued responds directly to Office of Management and Budget directions in the Fiscal Year 2006 federal budget plans (OMB, 2005).

The status of synthesis and assessment products is also monitored and the products are evaluated for quality, which makes the metric more useful. All synthesis and assessment products undergo three stages of development: (1) development of a prospectus, (2) preparation and revision of the product, and (3) final approval by the National Science and Technology Council and publication. Product quality is evaluated via peer review and public comment during development of the prospectus, during drafting of the product, and at the request of lead authors, just before final approval. Changes in the status of the products are announced through community e-mails, the *Federal Register*, and web site updates.

Whether or not a planned product was created on time is a useful metric. However, use of this measure alone would suggest that progress of the CCSP is inadequate, given that only two synthesis and assessment product have been completed in the scheduled time (Appendix A).

Committee's Matrix Approach

The committee developed a new evaluation approach, which uses a matrix to evaluate the 33 research questions in the research elements (rows of the matrix) against outputs and outcomes (columns of the matrix). The columns of the matrix were derived from five categories of CCSP products and results, themselves generalized from categories identified in NRC (2005):

Category A: improve data sets in space and time, and improve estimates of physical quantities
Category B: improve understanding and representation of processes
Category C: improve predictability, predictive capabilities, or assessment of uncertainty s
Category D: improve synthesis and assessment to inform
Category E: improve assessment and management of risk, and improve decision support for management and policy making

These product categories provide a measure of the maturity of the program, starting from data collection, to predictions of future climate changes, to improved use of information to better serve society. The complete matrix is given in Appendix C.

The research questions were chosen for evaluation because nearly all of the CCSP's milestones, products, and payoffs are associated with them. Moreover, they are linked to the focus areas of the overarching goals (Figure 2.1). The product categories overlap with the cross-cutting issues. In particular, category A includes observations and monitoring, category C includes modeling, category D includes communication, and category E includes decision support. Consequently, the matrix enables a reasonably broad assessment of CCSP progress.

The committee used the matrix to make a preliminary assessment of CCSP progress (task 1b). Scores for the rows of the matrix provide information on progress in the research questions, research elements, and overarching goals (see Chapters 3 and 4). Scores for the columns of the matrix provide a measure of the maturity of the research element as well as an indication of progress in the cross-cutting issues (see Chapters 3 and 5).

CONCLUSIONS

Recommendation. CCSP progress should be evaluated in two stages: (1) a broad overview of the entire program based on the knowledge of the reviewers, and (2) a more in-depth analysis of areas in which progress has been inadequate, using the process and input metrics from NRC (2005).

Agency approaches to monitoring progress (i.e., compiling agency metrics, tracking milestones and products) are useful, but open only a narrow window onto the program. More information about the program as a whole can be obtained from the matrix approach developed by the committee. Overall, the committee found that the matrix can be used to assess progress toward the research elements and overarching goals, although it is unwieldy to evaluate the goals in this manner. The matrix also provides information on progress in the cross-cutting issues, to the extent that these issues overlap with the product categories (i.e., the columns of the matrix). However, this method provides little insight on why good progress has or has not been made. Diagnosing the causes of strengths and weaknesses requires knowledge of planning, leadership, and resources in addition to program results. The process and input metrics from the NRC (2005) framework offer a means to evaluate these issues.

An evaluation of CCSP progress using either the committee's matrix or the NRC (2005) evaluation framework can be daunting. The matrix contains 165 cells, but more than 165 scores are necessary since many of the research questions cover a complex set of issues. A similar number of scores would be required to evaluate the major components of the program (five overarching goals, seven research elements, and six cross-cutting issues) using the 24 metrics identified in NRC (2005). Evaluating the research questions by this method would require nearly 800 scores.

The evaluation process can be made more practical by breaking it into stages, with the initial evaluation aimed at identifying successes and finding weaknesses. Preliminary scores can be assigned using only the knowledge of the reviewers and information on programs and results in readily available publications. A community workshop, such as the one organized by the committee, is one way to obtain the breadth of knowledge required to carry out the first stage. A stage 1 evaluation of the entire program might be necessary only when there is a major change in the program, such as a new strategic plan.

The second stage of evaluation can focus exclusively on areas identified in the first stage as not meeting program objectives and expectations. These areas would be evaluated with the process and input metrics from NRC (2005), which provide tools for diagnosing the reasons for the weakness. Detailed programmatic and budgetary information would be required to carry out this stage of evaluation, which should continue until outcomes improve.

3
Preliminary Assessment of CCSP Progress

Chapter 2 recommends dividing the evaluation of Climate Change Science Program (CCSP) progress into two stages: (1) a broad overview of the entire program and (2) an in-depth analysis of areas in which progress has been inadequate. The committee addressed task 1b—a preliminary analysis of CCSP progress—by carrying out the first stage of the evaluation. The first stage is focused on major issues that are relatively easy to identify, so it can be carried out using mainly the knowledge of the evaluators. Because the program is so broad, however, the committee supplemented its knowledge with input from a workshop, consultation with CCSP program managers, and reference to the literature. Qualitative scores and commentary from the first stage of the evaluation appear in Part II, and overall conclusions and a discussion of key areas that should undergo the second stage of the evaluation are given below.

EVALUATION APPROACH

The committee's preliminary (stage 1) assessment was structured around a matrix of 33 research questions versus five categories of outputs and outcomes (see Appendix C). Scores were assigned to each cell of the matrix. The scores of the cells were then combined and analyzed to draw conclusions about progress in the research elements, cross-cutting issues, and one of the overarching goals.

At the request of the CCSP, progress was assessed for the last four years of effort—the lifetime of the program. Nearly all of the milestones and products in the CCSP strategic plan were to have been completed within four years, although in several cases this objective has not been met. Where longer periods were required to demonstrate progress of fundamental research (e.g., see NRC, 2005), the committee's assessment extends beyond four years.

Program results were gleaned from accomplishments listed in *Our Changing Planet* (CCSP, 2005, 2006a) and the scientific literature. It is generally not possible to distinguish between accomplishments that result from agency-sponsored activities (1) that are carried out to address CCSP or related objectives and are counted in the CCSP budget, or (2) that are relevant to the CCSP, but are not considered part of the program (e.g., National Polar-orbiting Operational Environmental Satellite System [NPOESS]). Only CCSP workshops, coordinated activities (e.g., interagency working groups [IWGs] and their science advisory committees), and synthesis and assessment products can be linked unambiguously to the program. In the absence of information to make this distinction, the committee treated all U.S. government-sponsored climate science as part of the CCSP. However, a final evaluation of CCSP progress would focus ideally only on areas attributable to the program.

A significant source of input for the evaluation was a workshop of CCSP stakeholders (listed in Appendix D) organized by the committee in September 2006. Stakeholders that generate or use CCSP information and products include research scientists; private companies and nongovernmental organizations in the insurance, agriculture, energy, forestry, transportation, water resources, public health, and emergency response sectors; federal, state, and local government agencies; and policy makers (NRC, 2005). Their insights are particularly important for assessing program quality and outcomes. However, about 80 percent of the workshop attendees were scientists, making the exercise more of a peer review than a broad stakeholder assessment. Although chosen for their expertise in different aspects of the CCSP, no small group of individuals can represent the scope of the CCSP. Nevertheless, their collective insights enabled nearly all of the cells in the matrix to be scored.

Because the stage 1 assessment focused on identifying major strengths and weaknesses, the committee chose to score progress on a scale of good, fair, and inadequate. The objective was to assign five scores to each research question, one for each column of the matrix. However, in some cases a score was not applicable. For example, not all research questions follow the same progression from improving data sets to informing policy. Some will lead simply to new research directions. Other research questions mirror the matrix columns (e.g., question 3.1 focuses on data and physical quantities). In such cases it did not make sense to score all columns of the matrix.

Many of the research questions are broadly written and include multiple components, each of which may have progressed at a different rate. Where this was the case, multiple scores were assigned to the cell and described in the commentary. A score for progress in the overall research question was assigned based on the scores of the five cells and the judgment of the committee about which cells were most significant.

Overall, the committee and workshop participants found that they were able to use the matrix to score progress in all of the research questions. The primary difficulty in scoring the left columns of the matrix (columns A, B, and C) was that data, processes, and predictions can overlap significantly, sometimes making it difficult to differentiate progress in one area from progress in another. The most difficult cells to score were those concerning synthesis and assessments, and risk managements and decision support (columns D and E). Any CCSP accomplishments in these areas are not yet widely published or known in the community. In many cases, the committee was able to gather additional information to adjust or verify the initial scores. However, a larger number of social scientists and state and local decision makers would ease future evaluations.

RESULTS OF THE STAGE 1 EVALUATION

Few of the CCSP research questions scored good or fair on all five columns of the matrix. Below is a summary of which areas of the research elements are proceeding as well as or better than expected, and which areas should undergo careful (stage 2) evaluation to diagnose problems and improve CCSP outcomes. In selecting the areas for stage 2 analysis, the committee strove for both practicality, which limits the number of issues that can reasonably be evaluated and monitored, and breadth. Although not all of these areas have equal potential to improve program results, progress in each would advance CCSP objectives.

Atmospheric Composition

Good progress has been made in understanding the factors that alter atmospheric composition and how these alterations affect climate, humans, and ecosystems. Examples include much better knowledge of the direct and indirect effects of aerosols, air quality, and tropospheric ozone and the impacts of pollutants on human health. However, limiting factors still exist, and these could benefit from a stage 2 evaluation. For example, inclusion of aerosol interactions, including aerosol-cloud interactions, in coupled climate change models has been slow, and the CCSP may be able to improve this by fostering better coordination between observational, process modeling, and coupled model development groups. The CCSP has also not undertaken a coordinated effort to evaluate future scenarios of changes in worldwide aerosol emissions, which is critical for projections of future climate, decision support systems, and policy actions.

Climate Variability and Change

Significant advances have been made in understanding the Earth's climate system components, their interactions, their variability, and the mechanisms driving current changes. For example, the CCSP synthesis and assessment report on atmospheric temperature trends resolved the discrepancy between in situ balloon observations and satellite microwave observations and confirmed that tropospheric warming is consistent with surface warming (CCSP, 2006b). Likewise, observations of ocean heat content confirmed that the warming has penetrated to deeper layers of the ocean. Proxy records have expanded our knowledge of past abrupt climate changes, including the relationship between climate variability and droughts or wildfires. Improved understanding has led to state-of-the-art climate models that now reproduce many aspects of the climate of the past century, and simulations of the evolution of global surface temperature over the past millennium are consistent with paleoclimate reconstructions, thus improving confidence in future projections.

However, progress in some key areas has been inadequate, and the second stage of evaluation might show why. Ice sheet dynamics remains a major uncertainty in future climate projections because of the need for longer observations and the development of more advanced models. Observations are also insufficient to substantially advance understanding and modeling of cloud and aerosol processes. In addition, even the best models are deficient in their ability to represent extreme events (e.g., hurricanes, heat waves), abrupt climate changes, and smaller-scale (regional to local) processes. The CCSP does not have a coordinated strategy to collect and archive climate observations, and this may be slowing the understanding of some climate processes as well as the improvement of models that must be initialized with estimates of the observed state of the climate system. Finally, little information on climate variability and change is being used by resource managers and planners, perhaps because sufficient bridging or translating functions are not available.

Water Cycle

Understanding of the mechanisms that control water fluxes among the components of the Earth system has improved over the last several years. Good progress has been made in quantifying water fluxes and budgets from multiple data sources, and in understanding and modeling processes such as cloud formation, air-sea interaction, and land-atmosphere interaction. However, additional work needs to be done on feedbacks that cut across disparate physical processes (e.g., aerosol and moist processes; coupled water, energy, and carbon fluxes) and physical-human processes (e.g., accounting for managed ecosystems and water transfers in climate models). Fair progress has been made on understanding long-term change and decadal variability, but future progress will require investments in sustained and global observing systems and in the development of robust coupled models. Progress toward understanding the consequences of water cycle variability for human societies and ecosystems has been inadequate, as has progress in understanding how information about such consequences can be used to inform decision making. A rigorous stage 2 evaluation of research activities related to water cycle questions 4 (consequences) and 5 (information) could reveal whether this assessment of progress is accurate and, if it is, whether inadequate progress to date reflects low agency priorities or poor interaction with relevant stakeholder communities. A stage 2 evaluation could also gauge whether a synthesis and assessment product targeted specifically at the water cycle might focus agency and community efforts in a way that spurs progress across the entire research element.

Land Use and Land Cover Change

Good progress has been made in the quantification and characterization of land use and land cover change. The availability of high-resolution (30 m) satellite data has enabled regional estimation of rates of land cover change. Improved understanding of the processes of change is enabling predictive modeling of future land cover changes. However, less progress has been made on the land use aspects of this research element. Areas that would benefit from a stage 2 evaluation include land use modeling and the societal impacts of land use and climate change and their interactions. Land use modeling is in its infancy, with social, economic, and biophysical processes only beginning to be incorporated. Researchers are just starting to quantify the impacts of land use change on climate and to understand the impacts of climate change on land use (e.g., on agriculture, forest, and rangeland distribution and productivity). The absence of a national review of land use models to guide the development of global, spatially explicit, dynamic land use models for integration with global climate models may be slowing progress in this area. Finally, considerable growth potential exists for research on climate and land use interactions. The inadequate progress to date likely reflects limited CCSP support for the social science aspects of land use and land cover change research and analysis.

Carbon Cycle

Good progress has been made in developing strategies for evaluating the spatial distribution of, and processes responsible for, current carbon sources and sinks. However, the fate of carbon dioxide from fossil fuels and land use emissions is still not completely determined. Thus, priorities for a stage 2 evaluation are the current carbon budget and our ability to predict and manage future CO_2 levels.

Major uncertainties remain in the magnitude and even the sign of the feedbacks between climate change and the distribution of carbon among atmosphere, ocean, and land reservoirs. Coupled carbon-climate models and observation networks emphasize seasonal-to-interannual variations in surface-atmosphere CO_2 exchange, and areas of uncertainty for the feedbacks they address are well known. However, potentially critical processes are difficult to assess or predict given current understanding, including the role of disturbances (e.g., fire, pollutant deposition, vegetation change) in land carbon balance and the potential for changes in ocean ecosystems and thermohaline circulation to affect ocean carbon exchange. A stage 2 evaluation could focus on finding ways to balance process studies, data collection, and modeling that would yield the greatest improvements in predictions of future CO_2 levels.

Predicting how current land and ocean carbon sinks will behave in the future is a key area of uncertainty. However, the greatest uncertainty in predicting future atmospheric CO_2 levels involves the choices that people make about energy, carbon management, and land use. Inadequate progress has been made in supplying scientific information to inform these choices, perhaps because social science investigations of human choices have not been incorporated into scenarios on which predictions are based.

Ecosystems

Good progress has been made in understanding the potential consequences of natural and anthropogenic climate change for ecosystems. Knowledge of carbon cycling processes has improved, and better estimates of carbon inventories in marine and terrestrial ecosystems have been made. High-quality integrated data sets have been acquired from satellite and in situ measurement programs, and long-term sites for measuring carbon have been established. Coupled ecosystem-climate models for marine and terrestrial systems have advanced as a result of improved understanding of carbon processes and advances in computation. However, progress has been inadequate in two key areas that would benefit from a stage 2 evaluation. First, quantitative understanding of potential feedbacks among ecosystem components, especially those that cross boundaries (e.g., land-ocean), may be hindered by insufficient coordination among CCSP programs that focus on different parts of the marine and terrestrial ecosystem. A coordinated effort to develop a carbon model that includes land, marine, and atmospheric components could also foster projections of future climate states and the development of management policies to deal with these future states. Second, the effects of climate change on marine and terrestrial ecosystems cannot yet be predicted reliably, perhaps because of shortcomings in coordinated community efforts, computational resources, and/or sustained measurement programs.

Human Contributions and Responses

Although some gains have been made in understanding stakeholder needs and characterizing the impact of uncertainty on decision making, overall progress has been inadequate given the breath and depth of issues encompassed by the research questions. Achievements have been particularly insufficient regarding human drivers of ecosystem change; the nature, magnitude, and value of climate change impacts; and the cost of mitigation and adaptation. These issues would benefit from a stage 2 evaluation because of their importance in preparing for and responding to climate change stressors. Inadequate progress may reflect the absence both of a conceptual framework to understand the diverse human-ecosystem interactions that work over time and of a research agenda to characterize and measure impacts, vulnerability, and adaptive capacity. These in turn depend in part on leadership to foster and coordinate research efforts across agencies. The United States risks lagging behind other developed countries in understanding these issues.

OVERARCHING CONCLUSIONS

Discovery science and understanding of the climate system are proceeding well, but use of that knowledge to support decision making and to manage risks and opportunities of climate change is proceeding slowly.

Good progress has been made in documenting climate changes and their anthropogenic influences and in understanding many aspects of how the Earth system works (e.g., aerosol direct forcing, glacier melting). Coupled ocean-atmosphere-land climate models have also improved, although models that enable exploration of feedbacks, assessment of human driving forces, or trade-offs of different resource management and mitigation options are still relatively immature. The program has made a significant contribution to international climate research, particularly to Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC). CCSP research and the temperature trends report (CCSP, 2006b) have also played a role in the findings of the recently released IPCC (2007) report.

In contrast, inadequate progress has been made in synthesizing research results, assessing impacts on human systems, or providing knowledge to support decision making and risk analysis. Reports on temperature trends (CCSP, 2006b) and scenarios of greenhouse gas emissions (CCSP, 2007) were the only CCSP synthesis and assessment products completed in the last four years; most synthesis activities have been small, focused, community efforts. A previous review of the CCSP strategic plan found that decision support activities were underdeveloped (NRC, 2004). The committee's preliminary assessment of progress (Chapters 4 and 5) shows that decision support has been incorporated into some aspects of the ecosystems research element (i.e., management strategies that consider the effect of climate variability on fisheries) and the human contributions and responses research element (e.g., Decision Making Under Uncertainty [DMUU] centers). However, these programs are small, and decision support is treated primarily as a service activity, rather than a topic that requires fundamental research. As a result, decisions about climate and associated environmental change have had to be made without the benefit of a strong scientific underpinning.

Progress in understanding and predicting climate change has improved more at global, continental, and ocean basin scales than at regional and local scales.

The disparity in progress is partly a result of the site-specific nature of impacts and vulnerabilities and the much greater natural variability on smaller scales. For example, the interannual variability of surface temperature is an order of magnitude greater on the scale of an individual town than the global average. It is these smaller spatial scales that are most relevant for state and local resource managers, policy makers, and the general public. Future projected land cover changes and changes in the distribution of continental water due to dams and irrigation, for example, are just beginning to be included in climate models. However, improving understanding of regional-scale climate processes and their impacts in North America would require improved integrated modeling, regional-scale observations, and the development of scenarios of climate change and impacts. Improved predictions of climate change at local levels should help the CCSP bridge the gap between science and decision making.

Our understanding of the impact of climate changes on human well-being and vulnerabilities is much less developed than our understanding of the natural climate system.

The greatest progress in the CCSP has been made on basic climate science associated with overarching goals 1, 2, and 3 (although human driving forces have lagged) and the least has been made on the interaction of climate change with human systems (overarching goals 4 and 5). Improved progress toward overarching goals 4 and 5 will require stronger connections with the social science community and a more comprehensive and balanced research program. Indeed, a review of the draft CCSP strategic plan recommended accelerating efforts in human dimensions, economics, adaptation, and mitigation by strengthening science plans and institutional support (NRC, 2004). Yet only a small percentage of the CCSP research and observations budget is devoted to the human contributions and responses research element (Table 1.1), making it difficult to carry out even the limited research agenda outlined in the CCSP strategic plan. The bundling of human dimensions research and decision support tools further deemphasizes the importance of social science research and is detrimental to both parts of the program.

Another reason for inadequate progress is that no agency has a program focused on the human dimensions of climate. A consequence is that expertise in the human dimensions of climate change is in short supply in the participating agencies, which in turn makes it difficult for the CCSP to exert leadership and forge the necessary links between these agencies and the academic social science community. The connections that the National Science Foundation established for its DMUU centers may provide a model for other CCSP social science research. Finally, the human dimensions research community is small and unorganized and thus may be unable to advocate effectively for changing program priorities. However, the good quality of work achieved with the low level of investment to date suggests that the community is capable of supporting a more substantial program.

Science quality observation systems have fueled advances in climate change science and applications, but many existing and planned observing systems have been cancelled, delayed, or degraded, which threatens future progress.

Much of the progress in understanding the climate system has been fueled by the availability of a wide range of data (e.g., NRC, 1999, 2007). A rich resource of satellite and in situ observations has been collected, disseminated, and archived by agencies participating in the CCSP. However, the number and diversity of satellite observations are expected to diminish significantly with the cancellation or delay of several planned National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) satellite missions (e.g., Hydros, Global Precipitation Measurement mission, Landsat Data Continuity Mission, Geostationary Operational Environmental Satellite Series-R) and the elimination of climate instruments from NPOESS. By the end of the decade the number of operating sensors and instruments on board NASA platforms is expected to decrease by approximately 40 percent (NRC, 2007). In addition, a number of long-standing in situ networks (e.g., U.S. Geological Survey stream gauge network, U.S. Department of Agriculture Snowpack Telemetry snow observation system) are deteriorating, and planned carbon cycle field campaigns may be cancelled because of funding shortfalls. The anticipated decline in U.S. capability to monitor global- or regional-scale environmental changes and the degradation of climate data records that provide the baseline for measuring change will severely hamper future progress in climate change research. Indeed, the reduction in remote sensing capability is perhaps the single greatest threat to the future progress of the CCSP. Yet the CCSP has no strategy for implementing, sustaining, and evolving an observing system to address crucial questions on climate and related environmental changes (NRC, 2004). It is also not clear what role the CCSP might play in cooperating with other countries to obtain necessary data. This is particularly worrisome, given the IPCC (2007) prediction that the large warming trend of the last two decades will continue for at least the next few decades.

Progress in communicating CCSP results and engaging stakeholders is inadequate.

One of the most important differences between the CCSP and the U.S. Global Change Research Program (USGCRP) is the increased emphasis on communicating research results to stakeholders and encouraging the use of science-based products to support decision makers. Indeed, using CCSP knowledge to manage risks and opportunities related to climate variability and change is an overarching goal of the program. However, a coherent communications strategy, informed by basic social science research, has not yet been developed. Most efforts to carry out the two-way dialogue envisioned in the CCSP strategic plan appear to be ad hoc and to rely more on communicating research results—especially to federal agencies and, to a lesser extent, the scientific community—than on hearing what others need from the program. NOAA's Regional Integrated Sciences and Assessments program has been effective in communicating research results to stakeholders in particular sectors (e.g., impact of seasonal-to-interannual climate variability on water resources) or regions, but this program is small and has limited reach. Other efforts to identify and engage state and local officials, nongovernmental organizations, and the climate change technology community are still in the early stages. Building and maintaining relationships with stakeholders is not easy and requires more resources in the CCSP Office and participating agencies than are currently available. Yet a well-developed list of stakeholders, target audiences, and their needs is essential for educating the public and informing decision making with scientifically based CCSP products.

The separation of leadership and budget authority presents a serious obstacle to progress in the CCSP.

A principle in *Thinking Strategically* (NRC, 2005) is that a leader with authority to direct resources and/or research effort is essential if the program is to succeed. However, the CCSP is an interagency program in which responsibility for program management and budget allocation is shared among the participating agencies. As a result, effective coordination mechanisms are essential. Strong coordination at all levels of the program—within research questions, among closely related research elements and cross-cutting issues, and across the program as a whole—can create new avenues of investigation and should enable the CCSP to achieve more than its participating agencies could accomplish alone. Advances in characterizing the carbon budget, for example, have been attributed in part to an active IWG and scientific steering committee, community-established implementation plans, and a long history of interagency cooperation on carbon cycle research projects (see Chapter 4). Established coordination mechanisms exist at both the component level (IWGs for research elements and cross-cutting issues; see Table 1.1 and Figure 2.1) and the program level (CCSP principals and program office).

However, coordination of budgets has been less effective. In the early years of the USGCRP, the Office of Management and Budget worked closely with the program leadership to identify priorities and to communicate those priorities to the relevant agency heads (NRC, 1999). CCSP budget allocations are coordinated to a much lesser extent today. Budgets are reported for major components of the CCSP (e.g., overarching goals, research elements), although this is primary a post factum accounting exercise, not a true allocation of funds to carry out the program. The CCSP director and agency principals have only a small budget over which they have discretionary control, and they must rely on persuasion rather than authority to allocate or prioritize funding across the agencies. For example, the CCSP appears to have had little influence either on the decisions taken to cancel or delay satellite missions or on what resources should be allocated to expand or upgrade in situ networks, despite the importance of observing systems to achieving CCSP objectives. Instead, these decisions are made by the respective agencies. Similarly, the interagency working groups have few discretionary funds and little authority to implement the objectives that they define, unless these objectives coincide with their agency objectives. Even funding for the Climate Change Research Initiative is disbursed among agency programs. Such fragmented authority can only weaken coherent leadership and priority setting and slow progress in achieving the overall goals of the program.

Part I References

Climate Change Science Program (CCSP) and Subcommittee on Global Change Research, 2003, *Strategic Plan for the U.S. Climate Change Science Program*, Washington, D.C., 202 pp.
Climate Change Science Program and Subcommittee on Global Change Research, 2005, *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2006*, Washington, D.C., 215 pp.
Climate Change Science Program and Subcommittee on Global Change Research, 2006a, *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2007*, Washington, D.C., 264 pp.
Climate Change Science Program and Subcommittee on Global Change Research, 2006b, *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*, Synthesis and Assessment Product 1.1, T.R. Karl, S.J. Hassol, C.D. Miller, and W.L. Murray, eds., Washington, D.C., 164 pp.
Climate Change Science Program and Subcommittee on Global Change Research, 2007, *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations; and Review of Integrated Scenario Development and Application*, Synthesis and Assessment Product 2.1, L.E. Clarke, J.A. Edmonds, H.D. Jacoby, H.M. Pitcher, J.M. Reilly, R.G. Richels, E.A. Parson, V.R. Burkett, K. Fisher-Vanden, D.W. Keith, L.O. Mearns, H.M. Pitcher, C.E. Rosenzweig, and M.D. Webster, authors, Department of Energy, Washington, D.C., 260 pp.
Department of Commerce (DOC), 2006, *FY 2006 Performance & Accountability Report*, Washington, D.C., 360 pp.
Department of Energy (DOE), 2006, *Performance and Accountability Report: FY 2006*, DOE/CF-0012, Washington, D.C., 240 pp.
Government Accountability Office (GAO), 2006, *Climate Change: Greater Clarity and Consistency Are Needed in Reporting Federal Climate Change Funding*, Statement of John B. Stephenson, Director, Natural Resources and Environment, GAO-06-1122T, Washington, D.C., 23 pp.
Intergovernmental Panel on Climate Change, 2007, Summary for Policymakers, in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds., Cambridge University Press, Cambridge, 18 pp.
National Aeronautics and Space Administration (NASA), 2006, *FY 2006 Performance and Accountability Report*, NP-2006-11-451-HQ, Washington, D.C., 258 pp.
National Research Council, 1999, *Global Environmental Change: Research Pathways for the Next Decade*, National Academy Press, Washington, D.C., 595 pp.
National Research Council, 2004, *Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan*, National Academies Press, Washington, D.C., 96 pp.
National Research Council, 2005, *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program*, National Academies Press, Washington, D.C., 150 pp.
National Research Council, 2007, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, National Academies Press, Washington, D.C., in press.

Office of Management and Budget (OMB), 2005, *Analytical Perspectives: Budget of the United States Government, Fiscal Year 2006*, U.S. Government Printing Office, Washington, D.C., p. 65.

Part II
Detailed Supporting Analysis

4
Progress Toward the Research Elements

This chapter presents the committee's stage 1 analysis of the Climate Change Science Program (CCSP) research elements. The preliminary assessment was structured around the matrix (Appendix C), which evaluates progress of the 33 research questions in five categories: (1) data and physical quantities, (2) understanding and representation of processes, (3) uncertainty, predictability, or predictive capabilities, (4) synthesis and assessment, and (5) risk management and decision support. The goal was to highlight the most important issues, as identified by the peer-review workshop, not to provide an exhaustive analysis of every aspect of each research question. Consequently, although scores and commentary were assigned to all 165 cells in the matrix, this chapter reports only an overall qualitative score (good, fair, inadequate) and key comments for each research question. The scores are defined as follows:

- Good = The quality and contribution of work exceeds expectation.
- Fair = The quality and contribution of work merely meets expectation. Additional review may be warranted to increase effectiveness.
- Inadequate = The quality and contribution of work does not meet the needs of the program. Additional review to explain the poor results is required.

Recurring themes and trends are discussed under "Opportunities and Threats" for each research element. The chapter concludes with an example of how progress in the overarching goals can be evaluated, based on scores for the relevant research questions.

ATMOSPHERIC COMPOSITION

The composition of the atmosphere plays a critical role in connecting human welfare with climate changes because the atmosphere links the principal components of the Earth system. Emissions of gases and particles from natural sources and human activities enter the atmosphere and are transported to other geographical locations and often to higher altitudes. Some emissions undergo chemical transformation or removal while in the atmosphere or influence cloud formation and precipitation. Changes in atmospheric composition alter the greenhouse effect and the reflection and absorption of solar radiation, which modifies the Earth's radiative (energy) balance. Subsequent feedbacks and responses to this human-induced climate forcing influence human health and natural systems in a variety of ways. Observed trends in atmospheric composition are among the earliest harbingers of environmental change. Because the atmosphere acts as a long-term reservoir for certain trace gases, any associated global changes could persist for decades or even millennia, affecting all countries and populations.

The CCSP approach to understanding the role of atmospheric composition integrates long-term (multidecadal) systematic observations, laboratory and field studies, and modeling, with periodic assessments of understanding and significance to decision making. Most of the activities related to the atmospheric composition research element are carried out through national and international partnerships, partly because of the breadth and complexity of the science and policy issues and partly because the atmosphere links all nations. CCSP-supported research focuses on how the composition of the global atmosphere is altered by human activities and natural phenomena, and how such changes influence climate, ozone, ultraviolet (UV) radiation, pollutant exposure, ecosystems, and human health. Specific objectives address processes that affect the recovery of stratospheric ozone; properties and distributions of greenhouse gases and aerosols; long-range transport of pollutants and the implications for regional air quality; and integrated assessments of the effects of these changes. Interactions between atmospheric composition and climate variability and change, such as the potential effects of global climate change on regional air quality, are of particular interest.

Progress Toward Answering the Research Questions

In situ and satellite measurements and field campaigns have yielded rich data sets and improved estimates of physical quantities for all five questions under this research element. Gaps remain, however. Similarly, gains in our understanding and representation of many key physical processes have been substantial, although large uncertainties about the indirect effect of aerosols on climate, poor quantification of aerosol solar absorption, and the absence of aerosol-cloud-precipitation interactions in coupled models remain major shortcomings. Great uncertainties also remain in our knowledge of the radiative forcing of non-CO_2 gases (e.g., tropospheric ozone). Although predictions of air quality and ozone have improved, the predictability of the impact of pollutants on human health and especially on ecosystems is still limited. Finally, although we have sufficient understanding of some atmospheric species (e.g., sulfates and nitrates) to promote action, the same is not true for other aerosols (e.g., elemental and organic carbon) and non-CO_2 greenhouse gases.

Q 3.1. What are the climate-relevant chemical, microphysical, and optical properties, and spatial and temporal distributions, of human-caused and naturally occurring aerosols?

Good scientific progress has been made on several fronts (e.g., observationally constrained aerosol direct forcing), but large uncertainties remain (e.g., emission sources, indirect effect of aerosols on climate). Progress in aerosol observations has enabled the Intergovernmental Panel on Climate Change (IPCC) to quantify for the first time the net contribution of aerosols to anthropogenic forcing (IPCC, 2007). Significant CCSP investments in this question reflect growing recognition of the importance of aerosols and their role in climate. A plethora of new data from space and ground measurements have been used effectively to generate physical properties such as aerosol absorption and anthropogenic fraction on a global scale. These data sets provided the first information on how aerosols are transported from land regions to oceanic regions. For example, the CCSP sponsored field experiments on transport and transformation processes in aerosol plumes off the east coasts of Asia and North America. Data from ground stations in the western United States have shown that springtime background aerosol in that region is Asian in origin (Heald et al., 2006b). The Indian Ocean Experiment and the Asian Pacific Regional Aerosol Characterization Experiment field campaign revealed that satellite-derived maps of aerosol optical depth and aerosol mixture (air-mass type) extent, combined with targeted in situ component microphysical property measurements, can provide a detailed global picture of aerosol properties and distributions and their direct radiative forcing (Chung et al., 2005; Yu et al., 2006). Such investigations provided the first observationally constrained estimates of the effect of anthropogenic aerosols on climate. Another major advance is the first measurement of the effect of aerosols, including sunlight-absorbing black carbon (soot), on the inhibition of cloud formation by the Moderate-Resolution Imaging Spectroradiometer (MODIS) (Kaufman et al., 2005a, b).

There is still room for improvement, however. Large uncertainties remain about the emission sources of elemental and organic carbon, the indirect effect of aerosols on climate, and the extent of atmospheric solar absorption. Incorporation of aerosol-cloud interactions in coupled models has been slow. The CCSP has not undertaken a coordinated effort to evaluate future scenarios of changes in worldwide aerosol emissions, which seriously limits projections of future climate changes. Improved knowledge of aerosol forcing would have a major impact on decision support systems and policy actions: reductions in aerosols would reduce the aerosol masking effect on global warming and accelerate greenhouse forcing over the next few decades. However, no coordinated efforts to provide information to climate modelers or to policy makers are apparent. Finally, understanding of some types of aerosols (e.g., sulfates, nitrates, elemental carbon) is insufficient to evaluate and promote specific actions.

Q 3.2. What are the atmospheric sources and sinks of the greenhouse gases other than CO_2 and the implications for the Earth's energy balance?

Good progress has been made on radiative forcing and sources and sinks of some greenhouse gases, such as methane, but uncertainties remain for other greenhouse gases, limiting progress on decision support. Good measurements exist of most non-CO_2 greenhouse gases (e.g., nitrous oxide, chlorofluorocarbons [CFCs], methane, carbon monoxide, ozone, hydrogen, hydrochlorofluorocarbons, hydrofluorocarbons, methyl halides, sulfur hexafluoride), although better measurements are required for some. Analyses have shown, for instance, that global methane abundances were constant for nearly seven years beginning in 1999, suggesting that methane may have reached a steady state in the atmosphere for reasons that are not yet known (Dlugokencky et al., 2003). The Aura satellite is providing the first-ever daily global measurements of tropospheric ozone and many other trace gases with unprecedented spatial resolution. A 350-year history of atmospheric carbonyl sulfide from an Antarctic ice core and firn air showed how atmospheric abundances of this gas have changed as a consequence of industrial sulfur emissions (Aydin et al., 2002). Researchers have also made good progress in understanding North American emissions of trace gases, which are precursors of the formation of aerosols and ozone (Heald et al., 2006a; Pfister et al., 2006).

However, although good measurements exist, large uncertainties remain in our knowledge of the radiative forcing of non-CO_2 gases. Similarly, while the sources and sinks of many of these gases are better understood, unanswered questions on emission and removal processes remain. Many non-CO_2 greenhouse gases are not yet included in global climate models.

Q 3.3. 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?

Good progress has been made in describing the fate of anthropogenic emissions in the global atmosphere through new measurement techniques and observational studies, yet

predictability is still limited. Considerable work has been done on this question. For instance, the National Aeronautics and Space Administration's (NASA's) Transport and Chemical Evolution over the Pacific mission demonstrated the value of global satellite and airborne observations for improving knowledge of emissions inventories (Streets et al., 2003; Wang et al., 2005). Broad-based initiatives to study anthropogenic emissions in megacities are now under way (Guttikunda et al., 2005; Madronich, 2006). Data from the Aura satellite are being used to help monitor pollution production and transport between cities, regions, and continents on a daily basis for the first time. The International Consortium for Atmospheric Research on Transport and Transformation carried out the largest climate and air quality study to date, with a focus on developing a better understanding of the factors involved in the intercontinental transport of pollution and the radiation balance in North America and the North Atlantic (Singh et al., 2006). Finally, a new technique that enables measurement of trace gases in the atmosphere has opened a new frontier on the atmospheric chemistry that occurs at night. Nighttime reactions involving nitrogen-containing trace gases can effectively remove these gases from the atmosphere, and "short-circuit" the chemical reactions that would have produced ozone the next day (Sillman et al., 2002; Ren et al., 2003).

Although the understanding of atmospheric chemistry processes and the impact of pollutants on human health has improved, a number of complexities, especially on the regional scale, limit predictability. Understanding of the heterogeneous chemistry from local to global scales is still not sufficient to include in global models and make predictions of future changes. Finally, uncertainties remain about longer-term trends (e.g., for tropospheric ozone) that are important for interpreting the historical global climate record (Lamarque et al., 2005).

Q 3.4. What are the characteristics of the recovery of the stratospheric ozone layer in response to declining abundances of ozone-depleting gases and increasing abundances of greenhouse gases?

The recovery of stratospheric ozone is a success story, where decisions were made despite some scientific uncertainty. Recent advances in understanding and modeling stratospheric transport and dynamics have since reduced these uncertainties. The *Scientific Assessment of Ozone Depletion* (WMO, 2003) summarizes current understanding of the ozone layer and the phenomenon of stratospheric ozone depletion. CCSP-sponsored work continues to improve knowledge of the atmospheric processes underlying ozone abundance at the poles and globally, to support satellite observations of ozone-depleting substances in the atmosphere, to revise expectations for recovery of the ozone layer, and to develop approaches to evaluate the impacts of very short-lived halogen-containing substances on the ozone layer. Ground-based measurements of ozone are now sufficiently accurate to validate the satellite data, and their temporal resolution is sufficiently fine to determine diurnal variations and understand observed trends over the last century or more. For example, nine years of radiometer data from the UV-B Monitoring and Research Program's observational network has been used to assess the geographic distribution, trends, and year-to-year variability of UV-B radiation in the United States (Grant and Slusser, 2004).

Progress is inadequate, however, on the critical exchange processes between the troposphere and the stratosphere, the feedback mechanisms between increasing concentrations of greenhouse gases and reduced levels of chlorofluorocarbons, and predictions of the amount of water vapor in the stratosphere.

Q 3.5. What are the couplings and feedback mechanisms among climate change, air pollution, and ozone layer depletion, and their relationship to the health of humans and ecosystems?

Improved decadal and longer term climate and ozone data have driven good progress in the description of the effects of long-term changes in stratospheric and tropospheric temperatures and circulation on ozone-layer depletion. However, predictability is still limited because of insufficient understanding of the couplings between air pollution and climate change. This broad and complex question is tailor-made for the CCSP because it is inherently interdisciplinary and requires strong interagency cooperation. Strong leadership has led managers of fragmented programs to pool resources in this arena. Resulting field programs engendered by the CCSP have yielded good results, and fair progress has been made in understanding processes that link long-term (several decades) changes in temperatures and circulation with ozone depletion. The impacts of pollutants on human health in New York City have been studied (Drewnick et al., 2004), yet significant gaps remain in understanding the connections between atmospheric composition and human health, and especially between atmospheric composition and ecosystem health (NRC, 2001c).

It is still not possible to model the full range of aerosol constituents in polluted areas, primarily because of the inherent complexity of the problem and secondarily because concentrations of organic aerosols in urban environments are still uncertain by a factor of ten. Local- to global-scale heterogeneity of cloud processing of aerosols and the subsequent modification of aerosol chemistry also remain very uncertain. Work in this area has not reached the stage where scientific understanding can support risk management and decision making.

Opportunities and Threats

A large amount of high-quality satellite and in situ data, increasing computational resources, and sophisticated models have led to good progress in understanding the factors that alter atmospheric composition and how these alterations affect climate, humans, and ecosystems. However, the absence of a well-coordinated national effort is limiting progress in improving aerosol emission strengths globally, estimating past histories of biomass burning, and determining the vertical distribution of aerosols and their solar absorption.

Another major issue is that while satellite data are currently a rich resource, primarily because of the investment that began in the 1990s with NASA's Earth Observing System, the future looks relatively bleak. The recent National Polar-orbiting Environmental Satellite System (NPOESS) downscale has eliminated several key climate instruments, such as the aerosol polarization sensor (NRC, 2007a). Moreover, since most climate records require overlapping intercalibration to ensure accurate climate monitoring, future gaps in high-quality data will in many cases restart the climate record (NRC, 1998, 2004b; Trenberth et al., 2006). Such gaps are now likely, and since satellites require 5 to 10 years of advance planning, the NPOESS downscale must be dealt with soon. The future degradation of the climate data system is a problem for most of the CCSP science questions.

CLIMATE VARIABILITY AND CHANGE

Much has been learned over the past few decades about the Earth's climate system components, the interactions among them and their variability, and how and why the climate system is changing. This improved understanding is continually translated into better models of climate system components and of the fully coupled system, and these models are being applied to important scientific and societal questions. For example, current models indicate that the observed global-, continental-, and ocean basin-scale temperature increases of the past several decades are outside the range of natural variability (IPCC, 2007).

Observations underlie many of the advances in our understanding of the climate system. Ground-, ocean-, and space-based observations of key climate variables (e.g., surface and atmospheric temperature, precipitation, atmospheric moisture, clouds, winds, aerosols, sea level) provide insight on climate forcings (e.g., variations in solar output), processes (e.g., clouds, precipitation), and feedbacks (e.g., surface cover, albedo). Their compilation into long-term climate data records enables regional details of changes that are occurring in the global environment and their connections to human activities to be discerned (Alverson and Baker, 2006; NRC, 2007a). Paleoclimate data sets enable assessment of longer-term variability within the climate system, and also place the global climate changes observed in recent decades within a longer context (NRC, 1990, 2006d).

The climate variability and change research element plays an integrative role in the CCSP and is therefore central to the entire enterprise (CCSP, 2003). Specific objectives of the climate variability and change research element include reducing uncertainties and improving model predictions of climate variability and projections of change and determining their limits, assessing the likelihood of abrupt climate changes, examining how extreme events may be linked to climate variability and change, and formulating this knowledge in a way that can be integrated with non-climatic knowledge to support management and policy making.

Progress Toward Answering the Research Questions

Progress has been made in addressing the five questions under this research element, although accomplishments have been uneven. Better, longer, and more data sets have contributed to improved documentation and attribution of climate variability and change and to better understanding of many key climate processes (e.g., the global carbon cycle). However, as a result of ocean sampling limitations, evaluations of the decadal variability in global heat content, salinity, and sea level changes can be made with only moderate confidence. Moreover, some processes (e.g., vertical ocean mixing, cloud feedbacks, the role of aerosols and ice sheet dynamics) are still relatively poorly understood. Although uncertainties remain in our understanding of climate processes and some processes need to be more fully represented (e.g., historical and likely future changes in land use; Feddema et al., 2005), state-of-the-art climate models are now able to reproduce many aspects of the climate of the past century, and simulations of the evolution of global surface temperature over the past millennium are consistent with paleoclimate reconstructions (IPCC, 2007). This achievement improves confidence in future projections.

Synthesis and assessment activities have also progressed (e.g., the release of *Temperature Trends in the Lower Atmosphere*; CCSP, 2006b), and some seasonal-to-interannual capabilities have been shared with stakeholders through the National Oceanic and Atmospheric Administration's (NOAA's) Regional Integrated Sciences and Assessments (RISA) program. However, although contributions to risk management and decision support have slowly increased, the individuals engaged have been few in number and many decisions have been made without strong scientific underpinnings.

Q 4.1. To what extent can uncertainties in model projections due to climate system feedbacks be reduced?

Investments in observation systems have paid off with improved understanding and reduced uncertainties about feedbacks, although progress has been uneven and contributions to risk management and decision support have been inadequate. The response of global temperature to a given small forcing is proportional to the climate sensitivity. Feedback processes operating in the atmosphere (e.g., changes in water vapor and cloud properties), ocean (e.g., efficiency of ocean mixing, changes in sea ice properties), and land (e.g., changes to surface cover, albedo, evapotranspiration, runoff, and biogeochemical cycles) collectively determine the climate sensitivity. The number and diversity of observations related to feedbacks have grown. For example, satellite data records over the past decade indicate that mass losses from the Greenland and West Antarctic ice sheets have contributed to global sea level rise (Velicogna and Wahr, 2006; Shepherd and Wingham, 2007) and that flow speed has been highly variable over short time intervals (a few years) for some Greenland outlet glaciers (Howat et al., 2007; Truffer and Fahnestock, 2007).

Some key climate feedbacks (e.g., water vapor; see Trenberth, 2005) are better constrained, although less progress has been made on other important feedbacks such as those involving ocean mixing (e.g., Wunsch and Ferrari, 2004), aerosol effects, and cloud processes. The initiation of climate process teams (CPTs) has encouraged much-needed collaboration between modelers and those involved in process- and observation-oriented research (see Chapter 5, "Modeling"), although CPT findings are just beginning to be incorporated into models (e.g., Danabasoglu et al., 2007). The availability of the suite of climate model simulations performed around the world to support the fourth IPCC assessment has resulted in a wider examination of climate system feedbacks, such as the sensitivity and response of polar systems to global climate change (e.g., Holland et al., 2006) and the possible slowdown of the thermohaline circulation (Schmittner et al., 2005). However, scientific contributions to risk management and decision support have only begun to emerge.

Q 4.2. How can predictions of climate variability and projections of climate change be improved, and what are the limits of their predictability?

Good progress has been made in improving the quality of climate model simulations of variability and change, although uncertainties remain, especially on local and regional scales, and inadequate progress has been made in using model predictions to support decision making. The best climate models encapsulate the current understanding of physical processes involved in the climate system, their interactions, and the performance of the system as a whole. They have been extensively tested and evaluated using observations and have become useful instruments for carrying out numerical climate experiments. For example, climate model simulations that account for changes in both natural and anthropogenic climate forcings have reliably shown that the observed warming of recent decades is a response to increased concentrations of greenhouse gases and sulfate aerosols in the atmosphere (IPCC, 2007). Attribution studies have also demonstrated that many of the observed changes in indicators of climate extremes consistent with warming (e.g., annual number of frost days, warm and cold days, warm and cold nights) have likely occurred as a result of increased anthropogenic forcing (e.g., Tebaldi et al., 2005).

Despite significant advances, climate models are not perfect, and some models are better than others. Uncertainties remain because of shortcomings in our understanding of climate processes operating in the atmosphere, ocean, land, and cryosphere and how to best represent those processes in models (e.g., Rodwell and Palmer, 2007). For example, parameterizations of vertical ocean mixing are unrealistic and most coupled ocean-atmosphere global circulation models mix heat into the ocean too efficiently (Forest et al., 2007). Moreover, the global coupled climate system exhibits a wide range of physical and dynamical phenomena with associated physical, biological, and chemical feedbacks that collectively result in a continuum of temporal and spatial variability. The accuracy of predictions on time scales from days or seasons to years, as well as long-standing systematic errors in climate models, is limited by our inadequate understanding and capability to simulate the complex, multiscale interactions intrinsic to atmospheric and oceanic fluid motions (e.g., Meehl et al., 2001) and to represent all other unresolved small-scale processes in the ocean and at the land surface. For example, decadal climate predictions may require the initialization of coupled models with estimates of the observed state of the climate system. This initialization requires an ongoing commitment and strengthening of the observing system (Trenberth et al., 2002, 2006; GCOS, 2003; NRC, 2007a). However, although some observations and data networks have improved (e.g., Gravity Recovery and Climate Experiment [GRACE], Argo ocean profiling floats[9]), others remain too sparse (e.g., atmospheric water vapor), poorly integrated with other essential observations (e.g., column ozone with temperature and water vapor), or in decline (e.g., Tropical Atmosphere Ocean [TAO] buoy array). Some observing systems suffer telemetry problems that have caused data to be lost (Trenberth et al., 2006). Ensembles of simulations that estimate the range of probable outcomes can be used to project climate change where uncertainty arises from limitations of the models and the emission scenarios used to represent the effects of human activity.

Finally, use of climate model output by resource managers, planners, and decision makers remains limited, although exceptions exist. For example, a model of Lyme disease transmission, which simulates the effects of climate and other factors on disease risk, is being used by public health officials to examine strategies for controlling tick populations (NRC, 2001c). However, the prediction value of such models is limited by uncertainties in the climate-disease relationship and the confounding influence of other factors. The California Department of Water Resources used a statistical analysis of VIC model outputs to obtain monthly average streamflows that could be used to estimate how reservoirs inflows would be affected by climate change (CDWR, 2006). In general, however, resource managers need research results to be translated into different forms of information. Apart from programs such as RISA that have facilitated sharing of seasonal-to-interannual capabilities with stakeholders, few research results have been used to support risk management and decision making.

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[9] The number of Argo floats has increased to 2,856 out of about 3,000 planned since 1999. See <http://wo.jcommops.org/>.

Q 4.3. What is the likelihood of abrupt changes in the climate system such as the collapse of the ocean thermohaline circulation, inception of a decades-long mega-drought, or rapid melting of the major ice sheets?

CCSP management has been effective in marshaling the necessary resources to help answer this question. Good progress has been made in documenting abrupt climate change, but predictive capability remains low and the impact on decision making has been minimal. Good progress has been made in documenting abrupt climate change (e.g., mega-droughts) from proxy records such as lake cores (Vershuren et al., 2000) ice cores (Thompson et al., 2000, 2006), and integrated tree ring and observational data (Herweijer et al., 2006). Longer and more comprehensive data sets have revealed evidence of past abrupt changes that have the potential to occur in the future (Trenberth et al., 2004; Kerr, 2005). A 300-year long drought similar to the one that gripped East Africa 4,000 years ago (Thomson et al., 2002) would have devastating consequences today. Of particular concern is that under warmer conditions, it is likely that heat waves and droughts will become both more severe and more frequent than those in the past (IPCC, 2007). Understanding and representing processes has improved significantly in some areas, but less so in others. For example, fair progress has been made in understanding mechanisms that force sustained drought (Trenberth et al., 2004; Kerr, 2005), but the likelihood of mega-droughts is unknown, despite the existence of efforts such as North American drought reconstructions. Both a collapse in the thermohaline circulation (Latif et al., 2000; Gregory et al., 2005) and a catastrophic release of methane hydrates (Schaefer et al., 2006) now seem unlikely. However, much more work (e.g., radar mapping of East Antarctica, dynamical modeling of the large ice sheets and their outlet glaciers) is needed to anticipate potentially large and abrupt changes in the climate system.

The mechanisms of past abrupt climate changes are not yet fully understood, and climate models typically underestimate the size, speed, and extent of those changes. Some processes (e.g., ice sheet sliding) represent major uncertainties in future climate projections (Vaughan and Arthern, 2007, and references therein). Abrupt changes are not predictable, although their past occurrence can be used to derive probabilistic estimates of future occurrence. However, such estimates depend on the assumption that the past was statistically similar to the present, which is unlikely given the unique climate we are currently experiencing. Given the state of knowledge, surprises are inevitable (Alley et al., 2003), and because of greenhouse warming and other human alterations of the Earth system, certain thresholds are likely to be crossed (IPCC, 2007). Despite wide media coverage, risks have not been quantified and the costs of undesirable surprises have not been factored into economic models (NRC, 2002a).

Q 4.4. How are extreme events, such as droughts, floods, wildfires, heat waves, and hurricanes, related to climate variability and change?

Fair progress has been made on producing (1) the longer histories, spanning centuries to a few millennia or more, needed to advance understanding and to increase prediction of extreme events and (2) risk assessments. For any change in mean temperature, there is likely to be an amplified change in extremes (Tebaldi et al., 2005). Extreme events, such as heat waves and droughts, are exceedingly important to both natural and human systems. Humans are adapted to a range of weather conditions, but extremes of weather and climate exceed these tolerances. Widespread changes in temperature extremes have been observed over the last 50 years (Easterling et al., 2000; Alexander et al., 2006) and are expected to increase in frequency if the Earth continues to warm (IPCC, 2007, Table SPM2). In particular, the number of heat waves has increased globally, and increases in the number of warm nights have been widespread (Alexander et al., 2006). Cold days, cold nights, and days with frost have become rarer (e.g., Tebaldi et al., 2005, and references therein). Freezing levels have risen in elevation (Diaz et al., 2003), and the spring maximum snowpack is expected to diminish as the climate warms (Snover et al., 2003), reducing the spring runoff that supplies much of the streamflow of the western United States. Drying has been pronounced throughout the subtropics of both hemispheres (e.g., Hoerling and Kumar, 2003; Seager et al., 2005), and the risk of more frequent and severe droughts has likely increased (Trenberth et al., 2004). Moreover, with global warming, warmer sea surface temperatures, sea level rise, and increased atmospheric moisture content mean that hurricanes will likely become more intense (e.g., Emanuel, 2005; Webster et al., 2005; Anthes et al., 2006). Modeling of many of these aspects has improved, but simulating small-scale extreme events remains a challenge.

Climate extremes of the past are recorded in high-resolution histories extracted from ice cores, tree rings, and other kinds of paleoclimate records. High-resolution paleotemperature histories from ice cores collected in Greenland (Masson-Delmotte et al., 2005; Mosley-Thompson et al., 2006) and Antarctica (Masson et al., 2000), as well as from tropical glaciers (Thompson et al., 2000, 2006) and extensive tree ring networks (Briffa et al., 2004; Osborn and Briffa, 2006) have revealed the differing temperature trends and variability among geographic regions. However, similarly high-resolution records that sample a wider range of regions and record other extreme events (e.g., severe storms, monsoon failure) are lacking. The reduction in the number of surface observing stations in recent decades (GCOS, 2003) will negatively affect documentation of extreme events. The delay of the Global Precipitation Measurement (GPM) mission will likely lead to a gap in critical regional records used to predict high-impact weather events such as floods, droughts, and landslides (NRC, 2007a).

CCSP synthesis and assessment product 3.3 (weather and climate extremes) is now in draft form. A National Research Council review found that the draft report provides a thorough assessment of the key issues, although the discussion of drought and ecological impacts should be strengthened (NRC, 2007b). In addition to this focused effort, the insurance industry has gained a better awareness of the links between climate change and hurricanes (e.g., see Schiermeier, 2006). Risk assessments for some extreme events (e.g., drought, heat waves) are under way and heat wave preparedness has improved (Goodrich and Ellis, 2006). Knowledge of wildfires associated with climate variability and change is also beginning to inform forest management (Morehouse et al., 2006).

Q 4.5. How can information on climate variability and change be most efficiently developed, integrated with non-climatic knowledge, and communicated in order to best serve societal needs?

This question was difficult to assess, but it is clear that progress has been inadequate. A different formulation (e.g., *How can information on climate variability and change best be communicated to intermediaries who provide tailored information to the public?*) might enhance its evaluation.

Opportunities and Threats

Rich data collections are currently available for use in understanding processes, reducing uncertainties, and constraining models. These data form the backbone upon which continued advances will be made. Studies of climate variability and change require long, continuous, high-fidelity records of key system variables. Consequently, maintenance of a suite of key observing systems is important. Unfortunately, many observing systems are put in place without a viable plan for follow-on support. In addition, new observing systems are required to meet new scientific needs. However, the number of satellite sensors is expected to decrease dramatically by the end of the decade (NRC, 2007a). The International Polar Year offers numerous opportunities for multinational collaborations (NRC, 2004d; Pennisi et al., 2007), but sustained funding for U.S. involvement is not assured (Leshner, 2007).

As our knowledge of the different components of the climate system and their interactions has increased, so has the complexity of climate models. Many of the most pressing scientific questions regarding the climate system and its response to natural and anthropogenic forcings cannot readily be addressed with traditional models of the physical climate. A key near-term climate change issue, for example, is the response of terrestrial ecosystems to increased concentrations of carbon dioxide. Will plants begin releasing carbon dioxide to the atmosphere in a warmer climate, thereby acting as a positive feedback, or will vegetation absorb more carbon dioxide and hence decelerate global warming? Related issues include the interactions among land use change, deforestation by biomass burning, emission of greenhouse gases and aerosols, weathering of rocks, carbon in soils, and marine biogeochemistry.

Exploration of these questions requires a more comprehensive treatment of the integrative Earth system. In order to address these emerging issues, physical models are being extended to include the interactions of climate with biogeochemistry, atmospheric chemistry, ecosystems, glaciers and ice sheets, and anthropogenic environmental change. These new Earth system models, however, will require large investments in computing infrastructure before they can be fully utilized. Similarly, inadequate resources for computing are limiting progress in several key modeling areas, including representation of extremes and feedbacks and paleoclimate simulations, which are critical for testing Earth system behavior on climate-relevant time scales (see Chapter 5, “Modeling”).

Finally, it is imperative that data archiving keep pace with data acquisition and advances in climate system understanding. Proper archiving of data to ensure their availability requires strong interagency cooperation, and the CCSP offers an excellent structure for such agreements and plans to be formulated.

WATER CYCLE

The water cycle encompasses the dynamics of water stored in the atmospheric (clouds and water vapor), the ground (soil moisture and groundwater), and at the surface (snow and ice, lakes, and oceans), as well as the fluxes (e.g., precipitation, evapotranspiration, runoff, recharge) between these stores. The water cycle plays a direct role in agriculture, ecosystems, industry, and transportation, and it is inherently linked to the climate system through its interaction with the energy cycle. Climatically significant amounts of energy are stored and transported as sensible heat in the ocean and latent heat in the atmosphere, and the distribution of water in the atmosphere and on the ground regulates radiative transmission and reflection and influences the energy balance of the land surface and boundary layer.

The CCSP water cycle research element focuses on (1) quantification of the water cycle through observed and modeled budgets at local to global scales; (2) process-based understanding of the physics, chemistry, and biology involved in the water cycle and their interaction with other parts of the climate system; and (3) development of economically and socially relevant predictive capabilities of seasonal-to-interannual anomalies and geographical shifts in the climate mean. The wide range of scales over which hydrologic processes act and can be measured and modeled, as well as the wide range of basic sciences involved require coordinated efforts from agencies with different research expertise and interests as well as different observational capabilities.

Progress Toward Answering the Research Questions

Progress in the water cycle research element has been uneven. Good progress has been made in understanding processes and improving models, built in part on data from satellites and field campaigns and strong leadership across participating agencies. Progress in bringing process understanding to bear on societal needs through improved predictive capabilities at longer time scales and smaller spatial (e.g., regional) scales has been mixed. Intertwined with these success stories are examples of missed opportunities to communicate with stakeholders (e.g., through a CCSP synthesis and assessment product) or to stave off deterioration of data collection networks (e.g., streamflow, snowpack) required to improve predictions. Water cycle research and data collection are spread across many agencies, and CCSP leadership is essential for creating the types of coordinated interagency field campaigns and joint funding opportunities (e.g., Global Energy and Water Cycle Experiment Continental-scale International Project, World Ocean Circulation Experiment) that so successfully united scientists around research priorities in the 1980s and 1990s.

Q 5.1. What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?

Progress has been mixed, with good advances in data collection, fair progress on predictability studies, and inadequate progress in understanding the impact of managed systems on the water cycle. Data from the Tropical Rainfall Measuring Mission (TRMM) have greatly improved global precipitation mapping, and multisensor and combined in situ and satellite precipitation data products (e.g., from the Global Precipitation Climatology Project and GRACE) have begun to be developed. The use of data from the U.S. Department of Agriculture (USDA) Snowpack Telemetry (SNOTEL) network has improved snowpack-snow water equivalent maps and led to a better understanding of cold season and mountainous region hydrologic process. Estimates of natural flow and unimpaired river flow are important, but some stations in the U.S. Geological Survey (USGS) stream gauging network have been shut down. Some of these station records spanned multiple decades and were valuable for understanding and assessing land use impacts on climate and water resources trends.

Understanding of the mechanisms that control water fluxes among the components of the Earth system has improved over the last several years. Such understanding provides a critical link between anthropogenic climate forcing and impacts on human systems. However, current Earth system models do not include the contribution of managed systems such as agriculture. The use of Earth system models for synthesis and assessment will also require inclusion of two-way coupling between such systems and the traditional components of climate models. Finally, a number of studies on predictability and limits of prediction, use of ensemble predictions (e.g., Hydrologic Ensemble Prediction Experiment), and analyses of uncertainty propagation have been initiated, but they are too new for progress to be evaluated.

Q 5.2. 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?

Progress toward answering this question has been fair. Satellite observations have made positive contributions to the consistent and continuous data record needed to understand how feedbacks work between different components of the Earth system. However, plans for replacing observing systems such as the A-Train and TRMM are in doubt. Progress on data assimilation (merging models and observations) has been good, especially on the atmosphere (e.g., National Centers for Environmental Prediction-National Center for Atmospheric Research reanalysis) and ocean (e.g., Estimating the Circulation and Climate of the Ocean, Global Ocean Ecosystems Dynamics) components of this question. However, data assimilation efforts do not yet include geochemistry, especially of carbon.

Good progress has also been made in understanding process such as cloud formation, air-sea interaction, and land-atmosphere interaction. However, additional work needs to be done on feedbacks that cut across physical processes, such as aerosol and moist processes and water and carbon fluxes. The strong leadership of program managers for multidisciplinary and large community programs has been a key factor in many of these gains, and this leadership must be maintained or progress will stall. Finally, few efforts have been made to synthesize and assess water cycle research results for the broader stakeholder community.

Q 5.3. 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?

Progress in predictability has been fair on seasonal-to-interannual time scales and inadequate on decadal and longer time scales. Less progress has been made on understanding long-term change and decadal variability than on interseasonal-to-interannual predictability because of the deficiency of sustained observing systems and robust models. The TAO array was started during the decade of the Tropical Ocean Global Atmosphere program (1985-1994) and has since been enhanced by the CCSP. These sustained observations have helped to produce modest advances in our understanding and ability to predict El Niño-Southern Oscillation (ENSO) in the tropical Pacific (NRC, 1996; Kondrashov et al., 2005). However, similar in situ networks have only begun to be deployed in the Atlantic or Indian Oceans, and seasonal-to-interannual predictability is poor in those regions.

Where ENSO signals exist, the seasonal water-related influence is well known. However, understanding remains poor in the inner continents. Because soil moisture is difficult to measure at regional scales, most inferred predictability is based on model experiments (e.g., Koster et al., 2004). Although these are valuable, they are an inherently poor substitute for data-based validations of predictions. NASA's Hydrosphere State (Hydros) mission has been cancelled. Snowpack information is being collected through the USDA SNOTEL network, but snowpack water equivalent remote sensing mapping remains a deficiency. The GRACE mission has yielded the first depth-integrated water storage measurements (Swenson et al., 2006). Such estimates have already provided valuable checks on climate and weather models (Hirschi et al., 2006; Niu and Yang, 2006). Numerous well-water heights have been measured by local, state, and federal agencies for groundwater management and water rights administration. Knowledge of groundwater fluctuations over large scales is critical to improving representation of groundwater processes in climate models. Groundwater storage and release to the surface are long-memory processes with potential to improve forecasting (Bierkens and van den Hurk, 2007). More systematic collection, standardization, and archiving of these data would help these advances to continue.

Contributions to interannual predictability, such as the Pacific Decadal Oscillation and the North Atlantic Oscillation, have received increased attention and the physical processes are becoming better understood. However, models to predict their future behavior have not yet been fully evaluated. Probabilistic seasonal climate forecasts can be used to make probabilistic forecasts of malaria incidence (Thomson et al., 2005, 2006), and seasonal models have been used in applications ranging from agriculture to public health (e.g., Solow et al., 1998; Changnon, 2004).

Q 5.4. What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?

Progress toward answering these questions has been inadequate. Fundamental data on water quality and sediment fluxes are not available outside of several experimental sites (e.g., Long-Term Ecological Research [LTER] sites). Other sources of information are geographically spotty (e.g., National Water-Quality Assessment Program), are useful for process studies but not monitoring, or have other limitations. For example, floodplain and coastal maps are not sufficiently precise to be used in process and assessment models. As a result, great uncertainty remains in understanding the dynamics of nutrient and sediment outflow (e.g., episodic or continuous). An increasing number of interdisciplinary research initiatives, such as integrated water and carbon cycle research, have been proposed, but diverse specialists are not yet working together routinely.

Q 5.5. How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?

Despite a few successes, overall progress has been inadequate in all aspects of the program, including data, predictive ability, and communication. A number of critical water cycle measurements (e.g., precipitation, soil moisture, small-scale sea level topography) are needed to construct and test models that are used to make projections on water resources.

However, three planned measurement systems (GPM, Hydros, Wide-Swath Altimetry) have been delayed or eliminated during the past few years. Accurate predictions of sea level rise, based on measurements from satellites and tide gauges, are especially important because of the impacts on coastal urban areas, wetlands, and sensitive ecosystems. Uncertainties about the timing and magnitude of sea level rise are being narrowed, and scientists now have greater confidence in projections (IPCC, 2007). Some water resource managers are using outputs from regional models, but they need more refined models (e.g., at the watershed level) with improved resolution.

The CCSP does not maintain an inventory of resources that might be useful to water resource managers and policy makers, nor does it communicate with these stakeholders through newsletters or liaisons. A few programs (e.g., RISA, Columbia International Research Institute for Climate and Society) have made fair progress in communicating the impacts and uncertainties of interannual variability and climate change on water resources. However, it seems likely that most water authorities and management offices have little knowledge of what the CCSP can offer.

Opportunities and Threats

Future progress in the water cycle research element would be fostered by stronger leadership and interagency coordination. For example, future sites of USDA's Soil Climate Analysis Network program, which measures soil moisture and soil temperature profiles, could be collocated with the Department of Energy's (DOE's) AmeriFlux stations, which measure carbon and water fluxes in the boundary layer. Measurements of these variables at the same locations would improve our understanding of processes and increase our ability to model mass and energy exchanges between the land surface and the atmosphere. Modeling of these exchanges has long been a weak and poorly constrained element in global climate models, due in large part to a scarcity of long-term data sets. This kind of budget-neutral coordination activity could increase the value of government investments in observing systems.

The cancellation of critical observing systems has the potential to greatly slow future progress. For example, the Hydros soil moisture mission, which is important for answering all five water cycle research questions, was recently cancelled. The GPM mission is now delayed, jeopardizing continued progress in global precipitation mapping. It is unclear whether international (e.g., Global Earth Observing System of Systems) or foreign initiatives can take the place of cancelled missions. At the same time, surface-based data collection systems are either deteriorating (e.g., USGS streamflow monitoring) or continually threatened with cutbacks (e.g., USDA SNOTEL observation system).

Finally, the CCSP has no synthesis and assessment product to focus efforts on the water cycle, although product 5.3 (seasonal to interannual forecasts) is aimed primarily at water resource managers. Such efforts are especially important with the retirement of program managers who provided strong leadership in multidisciplinary and large-community programs. A synthesis and assessment product could also provide a vehicle for communicating research results to water resource managers and policy makers.

LAND USE AND LAND COVER CHANGE

The land use and land cover change research element was created under the CCSP in 2002. Seventy percent of the funding for this research element is currently provided by NASA (CCSP, 2006b) and this is reflected in the research emphasis to date. NASA is the only agency on the Interagency Working Group (IWG) for Land Use and Land Cover Change with a formal land cover program. Program managers from other agencies on the IWG have little authority to commit resources to the research questions or to steer research directions.

Land use and land cover changes are the most proximate and visible forms of global environmental change. Land use change occurs locally but is also significant at regional and global scales. For example, extensive tropical deforestation affects the global carbon cycle and thus the climate. At regional and local scales, deforestation can affect water quality, biodiversity, and human livelihood. A variable and changing climate influences the distribution of land cover and the sustainability of land use practices, which in turn affect agricultural productivity, food supply, and human vulnerability in marginal lands. Urbanization and suburban extensification magnify these problems and create new ones for air and water quality, human health, and transportation systems. Fire at the wildland-suburban interface is a serious hazard to some ecosystems and a human health problem in areas with extensive prescribed biomass burning.

The impact of land use change on the resilience of human and social systems to climate change can be positive or negative. Land use management provides a means by which to adapt to the impacts of climate change (Pyke and Andelman, 2007). Consequently, predictions of land use and land cover change under a combination of climatic and economic scenarios are important for land use planning and policy at local, regional, and national scales. A close integration of natural and social science is required to advance this research element.

Progress Toward Answering the Research Questions

A strong intellectual and technological foundation has been developed for this research element. Good progress has been made in the quantification and characterization of land use and land cover change, based in large part on the use of satellite data and improvements in the analysis of geospatial data (Walsh and Crews-Meyer, 2002). Social and biophysical processes are beginning to be combined in models, and considerable potential for growth exists for modeling climate and land use interactions. Progress in developing synthesis and assessments and decision support has been inadequate, although a few research results have been synthesized, and some research has directly supported decision making (Rindfuss et al., 2004a).

Q 6.1. What tools or methods are needed to better characterize historic and current land use and land cover attributes and dynamics?

Good progress has been made on the characterization of land cover and its attributes and dynamics. The current need is to transition the methods developed in the research domain into the operational arena to obtain routine and consistent global monitoring of land cover change at high (30 m) spatial resolution. The availability of satellite data has given the program considerable momentum and has fostered good progress in the study of land cover change, global mapping of land cover types, and regional mapping of local changes. Time-series analysis approaches developed in the 1990s have been refined, and improved land cover products have been generated from MODIS to study changes in global phenology, length of growing season, fire distributions, and tree cover (Friedl et al., 2002; Hansen et al., 2002; Zhang et al., 2004; Giglio et al., 2006). These new moderate-resolution (250 m) satellite data provided the means to detect land cover changes around the world (Zhan et al., 2002). Techniques for mapping large areas of the Amazon using high-resolution (30 m) satellite data have been extended to other tropical regions, improving estimates of the rates of land cover change (Skole and Tucker, 1993; Curran et al., 2004).

The Landsat series of satellites has populated the national archive with unprecedented volumes of high-resolution data that facilitate continental- and regional-scale studies of land use (Arvidson et al., 2006). A national study of land cover change based on these data is currently under way.[10] Early results for the eastern U.S. show that land cover change is associated primarily with an increase in timber harvesting and urban growth and a decline in agricultural activity. Methods have been developed to map the extent and changes in impervious surfaces and to model future urban development (Jantz et al., 2003). Methods have also been developed to include pre-satellite land use change using a combination of census population, housing, and agricultural data (e.g., Aspinall, 2004; Brown et al., 2005). At both global and regional scales, efforts have been made to compile historical data on agricultural land use extent (e.g., Ramankutty and Foley, 1999). However, in general less emphasis has been given to the historical record than to recent changes.

Rapid land cover changes driven by major economic changes have been documented in a number of countries, including China and Paraguay (Seto and Kaufmann, 2003; Huang et al., 2007). Rates, causes, and consequences of urban land use change in the United States have been compiled by Acevedo et al. (2006). Studies are also assessing the nature, extent, and impact of land use change around areas of particular importance, such as conservation-protected areas, through, for example, shifting agriculture and selective logging (e.g., Curren et al., 2004; DeFries et al., 2005). Given the impact of land use change on biodiversity loss, particularly in the tropics, studying the causes, trends, and projected land use change around protected areas will become increasingly important.

Q 6.2. What are the primary drivers of land-use and land-cover change?

Fair progress has been made toward understanding the causes and process of land use and land cover change. Future progress will require greater emphasis on understanding the process of change in different physical and social environments, and the development of general rules that can be used in land use modeling studies. A few studies have provided insights on the causes of land use change in a limited number of environments (e.g., Geoghegan et al., 2001; Fox et al., 2003). Progress has been hampered in part by the difficulty of obtaining socioeconomic data at the local scale and site-specific census data. Mechanisms must be found that enable provision and analyses of the data without compromising the privacy of individuals. A number of synthetic reviews have been carried out to develop general rules from a series of case studies (Rindfuss et al., 2004b; Hansen and Brown, 2005). Finally, the Large-Scale Biosphere-Atmosphere Experiment in Amazonia project has provided an in-depth look at selected land use processes (e.g., land use trajectories, logging practices, pasture development) in

[10] See <http://eros.usgs.gov/LT/LCCEUS.html>.

the Amazon and their role in the carbon cycle (Bierregaard et al., 2001; Roberts et al., 2003; Asner et al., 2005).

Q 6.3. What will land use and land cover patterns and characteristics be 5 to 50 years into the future?

Fair progress is being made toward future projections of land use change, but methods for modeling land use change could benefit from the development of community standards and best practices. Improved understanding of the processes of change is enabling predictive modeling of land cover changes (e.g., Moran and Ostrom, 2005). It is now time to start integrating interactive land use change processes and models with dynamic vegetation and climate models at the regional and global scales to examine the feedbacks. Studies in tropical regions have combined satellite data with household surveys to project future changes at the regional scale (e.g., Geoghegan et al., 2001). Regional-scale projections of land use change provide scenarios of future changes intended to be useful for informing policy (Zhang et al., 2006). In this context, a model of future land cover changes in the Amazon developed by Laurance et al. (2001) initiated considerable debate on the causes of deforestation and on modeling approaches. Comparisons of the different modeling approaches has revealed methodological issues that have to be refined (Irwin and Geoghegan, 2001; Claggett et al., 2004).

Land use modeling is in its infancy but is gathering momentum and a number of approaches and techniques are available or under development (Verburg and Veldkamp, 2005). In general, model applications have lacked rigor, and more attention has to be paid to uncertainty in prediction and to model validation. Dynamic, process-driven models of land use have yet to be integrated in ecosystem and climate modeling studies and feedbacks between the coupled systems have not been well investigated. Finally, no standard modeling tools exist for stakeholders interested in developing projections of future land use change in the context of a changing climate.

Q 6.4. How do climate variability and change affect land use and land cover, and what are the potential feedbacks of changes in land use and land cover to climate?

Inadequate progress has been made on this question. The role of land use in the carbon cycle and its contribution to greenhouse gas emissions has been understood for some time (IPCC, 2000). The effect of climate variability on land use is an area of continuing research and development, particularly in the context of ENSO predictions (e.g., Reilly et al., 2003). Researchers are only now beginning to quantify the impacts of land use change on climate and to understand the impacts of regional climate change on land use (e.g., DeFries et al., 2002; Marshall et al., 2004; Pielke, 2005). Feedbacks between land use change and climate are being studied at the regional scale (e.g., in the Amazon; see Laurance and Williamson, 2001). Relatively little funding has been devoted to this research area to date in the context of adaptation, and there is considerable potential for growth. Questions on how land use practices can be used to mediate the impacts of climate change and to sustain human livelihoods warrant further investigation, not only in terms of mitigation but also of human vulnerability.

Q 6.5. What are the environmental, social, economic, and human health consequences of current and potential land use and land cover change over the next 5 to 50 years?

Although fair progress has been made toward answering this question, a wider range of impact studies focusing on human health and vulnerability is needed. Addressing this question requires significant interaction among CCSP research elements. Linkages between land use management and the environment are currently being explored by the CCSP. For example, land use in the context of the carbon and water cycles is part of the North American Carbon Program (NACP) (see "Carbon Cycle" below). A number of studies have examined the impacts of recent land use change, and the broader role of land use in the global carbon cycle continues to be refined (Houghton, 2003). Study of the impact of tropical land use on the carbon cycle and biodiversity continues to be hampered by the absence of continuous and systematic monitoring of land cover change in these ecosystems (DeFries et al., 2006). The global impact of land use change on the provision of ecosystem services is starting to be recognized (Foley et al., 2005). The impacts of land use practices on water quality are being examined in different ecosystems (e.g., Mustard and Fisher, 2004).

The effects of different aspects of land use on human health is being investigated (e.g., Patz et al., 2004; Kelly-Schwartz et al., 2004), but to date these studies have been supported almost entirely outside of the CCSP and have not benefited from interaction with the climate change community. The recent inclusion of the National Institutes of Health on the IWG for Land Use and Land Cover Change should help this integration. The paucity of CCSP research on impacts of climate change in general (see "Human Contributions and Responses to Environmental Change" below) has prevented significant progress on the societal impacts of land use change and human vulnerability.

Opportunities and Threats

Future progress in the land use and land cover research element is likely to be slow because of relatively low funding levels and the inability of the program to date to direct resources to strengthen the social science aspects of the research (e.g., process studies, research on societal adaptation). Increased support to collect and integrate socioeconomic and environmental data could advance understanding of the consequences of land use change on human health (NRC, 2006a). Similarly, research on the effect of different land use practices on the carbon budget (e.g., averted deforestation, agro-forestry, no-tillage practices) could inform carbon management strategies.

The groundwork has been laid for a community land use modeling initiative aimed at improving the representation of dynamic land use processes in climate and ecosystem models. The first step in developing such an initiative would be a review of current approaches to land use modeling and identification of best practices. The integration of ground-based measurements and high-temporal-frequency Landsat-class observations into regional-scale agriculture models would improve the accuracy of predictions (IGOL, 2006).

The results of research on land use and land cover change are being used to inform land management policy, but more could be done with a close and sustained working relationship with the land management community (Miles et al., 2006). A number of decision support tools created in the research domain might also be adapted for improved land management (e.g., verification of carbon sequestration projects). Finally, none of the planned CCSP synthesis and assessment products is focused on land use. An assessment of the impacts of predicted climate change on U.S. land use and strategies for adaptation could provide a useful tool to the policy community.

Progress in all of these areas depends on sustained observations from Landsat-class satellites. With the failure of the scan line corrector on the Landsat 7 instrument in 2003, a data gap is now inevitable. The Landsat program has been the primary source of data for much of the research on land use and land cover change, providing the basis for quantifying local changes and trends at the regional scale and initiating land use models. No replacement instrument is available, and the proposed Landsat Data Continuity Mission will not be launched before 2011. A fully functioning Landsat-class mission is a key part of a comprehensive land cover monitoring system needed, for example, to quantify the rates of tropical deforestation and the fate of deforested land in different regions (Skole et al., 1997; Aspinall and Justice, 2004). In the meantime, the CCSP could facilitate an international initiative in the context of the Global Earth Observing System of Systems on closing the gap with available foreign assets (Kintisch, 2007).

Finally, because land cover and land cover change are basic measurements for international conventions and assessments (e.g., United Nations Framework Convention on Climate Change, Biodiversity Convention), considerable benefit could be gained from maintaining and strengthening links between the CCSP and international land cover-related programs, both to bring the results of the U.S. research program to the international community and to provide a forum for international coordination (DeFries et al., 2006).

CARBON CYCLE

The carbon cycle research element seeks to quantify the exchanges of carbon among the atmosphere, biosphere, and ocean and learn how these flows change as a result of human activity. A key element of the program is to determine the sign and magnitude of feedbacks between the carbon cycle and climate, especially those expected to operate in the coming century. This research is important for predicting future levels of carbon dioxide and methane in the atmosphere and the potential impacts of different carbon management strategies. Carbon observation networks will become increasingly important if governments begin to regulate carbon dioxide emissions, and understanding processes that might enhance or reduce carbon sinks will be required to design management strategies and judge their effects.

The research strategy laid out in the CCSP strategic plan incorporates focused research and observation strategies developed by scientists to accelerate progress in U.S. carbon cycle research (Sarmiento and Wofsy, 1999). Implementation of the CCSP has resulted in new, multiagency science programs, including the North American Carbon Program (Wofsy and Harriss, 2002) and the Ocean Carbon and Climate Change Program (OCCP) (Doney et al., 2004), as well as enhanced efforts within agencies, such as the National Science Foundation's (NSF's) water and carbon in the Earth system competition, and a planned NASA satellite mission to monitor CO_2 concentration in the atmosphere (Crisp et al., 2004). The program is guided by an active IWG and scientific steering committee that provides advice on priorities and gaps in research plans.

Progress Toward Answering the Research Questions

As outlined below, good progress has been made toward answering CCSP research questions 7.1-7.4, although the overall objective of apportioning carbon dioxide emissions among atmospheric increases and land and ocean sinks has not been achieved. Research question 7.5 deals with understanding carbon cycle feedbacks for predicting future carbon dioxide and methane concentrations and is in an earlier stage of scientific enquiry. Although CO_2 increases from fossil fuel burning and land use change are the clear result of human activities, links still have to be forged between basic and social science, management, and policy to improve uncertainties in future carbon source scenarios (Dilling, 2007a, b). Question 7.6 addresses active carbon management strategies but is among the least developed of the carbon cycle efforts.

We cannot yet account for the fate of the carbon we emit to the atmosphere at the global or continental scale. Specific areas in which more research is needed to reduce uncertainties, such as carbon cycling in coastal oceans, have been identified through workshops (Doney and Glover, 2005) and in various carbon cycle planning documents (Wofsy and Harriss, 2002; Doney et al., 2004). *North American Carbon Budget and Implications for the Global Carbon Cycle* (synthesis and assessment product 2.2; CCSP, 2007b) is undergoing revision following its initial review and contains updated syntheses related to many of the carbon cycle research questions.

Q 7.1. What are the magnitudes and distributions of North American carbon sources and sinks on seasonal-to-centennial time scales, and what are the processes controlling their dynamics?

The North American carbon budget is being formally assessed in synthesis and assessment product 2.2 (state of the carbon cycle), but improvements in observations and modeling approaches are required to reduce uncertainties. The approach toward answering question 7.1 is outlined in the North American Carbon Program (Wofsy and Harriss, 2002) and its implementation plan (Denning et al., 2005). The approach for understanding land carbon sources and sinks is (1) to scale up information from surface observational networks using models and remote sensing, and (2) to compare the resulting picture of the spatial distributions of carbon sources and sinks with those inferred from inversion of atmospheric CO_2 anomalies using transport models.

A number of recent syntheses demonstrating the utility of continuous data from observational networks are now available. Examples include the estimation of carbon sequestered in regrowing forests from the USDA's Forest Inventory and Analysis Program (Goodale et al., 2002; Birdsey, 2006; Birdsey et al., 2006), and direct measurements of land-atmosphere carbon exchange from the AmeriFlux network (Law et al., 2002; Hollinger et al., 2004). Fair progress has also been made in assimilating surface flux data into models and regional assessment of the impact of changing weather (e.g., European drought; see Ciais et al., 2005). However, the existing AmeriFlux network is not currently able to operate as the "integrated, near-real time network" envisioned to support the goals of the NACP (Wofsy and Harriss, 2002). "Top-down" inversion approaches take advantage of monitoring of atmospheric CO_2 and methane mixing ratios (NOAA Earth System Research Laboratory, Global Monitoring Division; Dlugokencky et al., 2003) and have been tested at the regional scale using aircraft data (Lin et al., 2006). Tracers such as CH_4, CO, isotopes of carbon, and SF_6 (see Denning et al., 2005) and O_2-N_2 (Manning and Keeling, 2006), which emphasize the importance of specific sources or land cover types, provide additional observational constraints. Both approaches will be tested in the ongoing midcontinental intensive field campaign (Denning et al., 2005). However, planned expansion of tall towers and improved calibration at AmeriFlux towers to support experiment have not been fully realized as outlined in the NACP report or implementation plan.

Good progress has been made in understanding terrestrial ecosystem processes, including determining the complex reasons underlying interannual variation in storage of carbon by forest stands (e.g., Barford et al. 2001) and understanding the importance of disturbance in determining ecosystem-atmosphere CO_2 fluxes (Rapalee et al., 1998; Law et al., 2004; Saleska et al., 2003). Synthesis of several ongoing Free Air CO_2 Enrichment experiments (King et al., 2005; Norby et al., 2005) showed similarities in response of vegetation across a number of forested ecosystems. Other experiments have used experimental manipulations to elucidate effects of warming, tropospheric O_3, nitrogen deposition, and drought on ecosystem carbon storage and dynamics. While there is growing recognition of the importance of processes acting at decadal and longer time scales (e.g., disturbance, response to land management change), some key feedbacks that operate on those time scales are unquantified, including whether the decomposition of more stable forms of soil organic matter will accelerate with warming and feedbacks between warming, drought, and fire in the tropics (Cox et al., 2000).

Although fair progress has been made toward comparison of bottom-up and top-down prediction approaches (Pacala et al., 2001), major uncertainties remain because of the relatively sparse nature of stations in the observation network, uncertainties associated with the transport models (Baker et al., 2006), and problems with the resolution of meteorological data needed for inversions (Denning et al., 2005). A number of modeling advances have been made that use model data fusion or data assimilation approaches to improve parameterizations of predictive process models (Denning et al., 2005). Although progress has been good in improving predictions of the spatial distribution of fossil fuel sources (Denning et al., 2005), predictive understanding of how sources in urban and suburban areas will evolve over time is lacking (Pataki et al., 2006).

Good progress has been made in synthesizing and assessing existing data, as exemplified by CCSP synthesis and assessment product 2.2 (CCSP, 2007b). Risk management and decision support efforts are in their early stages (see question 7.6 below). Efforts related to the NACP include building partnerships and linking observational networks in Mexico, Canada, and the United States. A few studies have linked agricultural practice to carbon sequestration potential (Lal et al., 2003), and the USDA undertakes greenhouse gas assessments (USDA, 2004).

Q 7.2. What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?

Focused research efforts and the synthesis of decades of observations have reduced uncertainties about the size of the ocean carbon sink, but significant uncertainties on ocean carbon processes remain. A science plan for the Ocean Carbon and Climate Program (Doney et al., 2004) summarizes much of the recent progress and remaining uncertainties and suggests strategies for future research. The North American component of that research effort is also described in Denning et al. (2005).

The proposed OCCP global observation network involves repeat hydrographic surveys, remote sensing, and a new North American Coastal Observing system (Doney et al., 2004). Good progress has been made in narrowing uncertainty in the magnitude of the historical ocean carbon sink based on analyses of repeat hydrography measurements (Sabine et al., 2004) and in testing that estimate with observations of the atmospheric O_2-N_2 ratio (Manning and Keeling, 2006). However, a lack of observations still means that other estimates of air-sea CO_2 exchange based on surface CO_2 and gas exchange remain highly uncertain, especially with respect to interannual variations (Doney et al., 2004). Although satellite observations of ocean color (Sea-viewing Wide Field-of-view Sensor [SeaWiFS], MODIS) have enabled global mapping of ocean biota and assessment of interannual variations, problems with calibration and removal of instruments from NPOESS threaten the future continuity of ocean color records. Technology development (e.g., CO_2 sensors that can make continuous measurements on buoys) has made good progress, and further developments are envisioned as part of the OCCP program.

Good progress in understanding and representing processes has been made on several fronts. The potential importance of ocean acidification in terms of ecological effects on calcifying organisms and a potential feedback between reduced calcification and atmospheric CO_2 have been recognized (Feely et al., 2004). Programs such as the Joint Global Ocean Flux Study (Fasham, 2003) have yielded new insights into the functioning of ocean ecosystems and the efficiency of the "biological pump" that transports carbon from the surface to the deep ocean, although interannual variations in these processes (e.g., responding to ENSO variability) can be assessed at only a few stations (Doney et al., 2004). As is the case for terrestrial systems, slower, decadal-scale processes that operate in the oceans remain poorly understood. Important areas of uncertainty remain, including ocean-atmosphere gas exchange rates in the Southern Ocean (Ho et al., 2006) and quantification of the role of coastal oceans (Doney and Glover, 2005).

Progress toward coupled ocean-climate models has been good, but fundamental uncertainties limit their predictive capability. For example, models generally predict reduced uptake of anthropogenic CO_2 by the oceans based on decreased solubility and increased ocean stratification (Doney et al., 2004). However, the degree to which this might be offset by a reduction in export of carbon to the deep sea by marine biota is highly uncertain. Other major uncertainties include the degree to which ocean ecosystems will respond to altered dust inputs and the effects of warming on thermohaline circulation.

Inadequate progress has been made in risk management and decision support. A number of mitigation strategies involving the ocean have been proposed, including direct injection of CO_2 into the deep ocean and fertilization of the ocean biosphere with iron. Although fair progress has been made toward assessing the constraints of these two strategies, the scientific basis for fully assessing the processes involved and the potential consequences of such management activities is still in the developmental stages (Doney et al., 2004).

Q 7.3. What are the effects on carbon sources and sinks of past, present, and future land use change and resource management practices at local, regional, and global scales?

Good progress has been made in understanding the historical relationship between land use and the carbon balance, but great uncertainties in future land management scenarios limit predictive capability. Determining the extent to which land use change affects carbon sources and sinks requires two pieces of information: a record of land use change in the past, and an accounting of how different land use practices lead to carbon storage or loss. The first requires coordination with the land use and land cover research element (see "Land Use and Land Cover Change" above). The second requires observations and process studies to determine the relationship between carbon sources and sinks and the evolving state of land cover. A recent synthesis (Houghton, 2003) documented the sources of current uncertainties at the regional to global scale, which are a particular issue for estimates of the CO_2 emissions from tropical deforestation (Hirsch et al., 2004). Good progress has been made within agency programs, especially in reconstructing the effects of past land use change on the North American carbon balance (Goodale et al., 2002; Birdsey, 2006; Birdsey et al., 2006), conservation reserves (Follett et al., 2001), and agricultural lands (Johnson et al., 2005; Martens et al., 2005). However, efforts to measure the net radiative (net greenhouse gas balance plus surface energy balance change) effects of land cover change have not always been well coordinated with these efforts (Randerson et al., 2006). Answers to Q7.3 at the local scale are required to inform management strategies involving future land use, but little research has been translated to information that might be useful for management decisions, especially those potentially involving credits for carbon sequestration (IPCC, 2000).

Q 7.4. How do global terrestrial, oceanic, and atmospheric carbon sources and sinks change on seasonal-to-centennial time scales, and how can this knowledge be integrated to quantify and explain annual global carbon budgets?

Although fair progress has been made in linking changes in regional and global rates of CO_2 accumulation to climatic anomalies such as ENSO, understanding of the processes underlying some of these relationships is poor and limits our ability to predict factors that will dominate in the future. The same issues raised in questions 7.1 and 7.2—especially with respect to predictability, synthesis and assessment, and decision support—apply to this research question. Global-scale efforts rely on inversion of atmospheric observations using transport models and require coordination of the various trace gas monitoring networks. A planned satellite to map column CO_2 inventory globally (Orbiting Carbon Observatory) will require testing with in situ data, and perhaps augmentation of existing atmospheric sampling networks. The information added by observations of gases other than CO_2 (e.g., O_2, CO, CFCs, methane, isotopes of CO_2 and methane) aids in the attribution of sources and sinks globally (e.g., Bousquet et al., 2006; Manning and Keeling, 2006). Transport models and the sparse density of air sampling networks currently limit this approach (Baker et al., 2006). However, recent work combining remote sensing of fire and trace gas observations highlighted the importance of fire associated with tropical deforestation to interannual variation in land-atmosphere CO_2 exchange (van der Werf et al., 2006). A recent summary of ocean observations (Feely et al., 2006) focused on changes in ocean-atmosphere trace gas fluxes associated with interannual variations in tropical ocean upwelling and wind patterns (e.g., ENSO). Maintaining good progress on data will require strong international coordination among observation networks.

Q 7.5. What will be the future atmospheric concentrations of carbon dioxide, methane, and other carbon-containing greenhouse gases, and how will terrestrial and marine carbon sources and sinks change in the future?

Predictions of future fossil fuel CO_2 emissions as well as carbon sources and sinks associated with future changes in land management (the two largest uncertainties in the future carbon budget) are limited by the lack of involvement of stakeholder communities. Although good progress has been made in implementing coupled carbon-climate models, poor process understanding—especially of the magnitude (and sign) of feedbacks with

climate—severely limits prediction of the future carbon balance of unmanaged lands and the ocean carbon balance. Improving predictions of future carbon dioxide levels requires not only an understanding of land and ocean carbon feedbacks to climate as incorporated in coupled models, but also improved ability to predict carbon sources from fossil fuel and land cover change based on human behavior. A community effort to build models with predictive capability into the next century that specifically couple carbon cycle and climate models is under way and provided input to the recent IPCC report (Fung et al., 2005). These model experiments show that the land and oceans decrease their capacity to act as repositories of fossil fuel CO_2 in a future with higher global temperatures and fossil fuel emissions (Fung et al. 2005). Although these models are a major achievement, their predictive capability is limited in several areas. First, although records of the amount of past fossil fuel burning are updated regularly, and the spatial and temporal resolution of emissions has been improved (Marland et al., 2005), scenarios of future emissions require updating, especially in light of the sometimes very local scale of planning and carbon management strategies. Second, a number of uncertainties are associated with future land cover and land use changes and how they will influence whether the land is a net carbon source or sink. Human behaviors that will drive land use change (particularly the deforestation source), as well as improved understanding of how (and how fast) ecosystems can adjust to changing climate (e.g., lengthened growing season, melting of permafrost), have not yet been incorporated into predictive models.

Other sources of uncertainty are associated with our limited understanding of the processes that influence the magnitude and sign of ocean and land feedbacks between carbon and climate (Sarmiento and Gruber, 2002; Fung et al., 2005). For example, neither the feedback between temperature, organic matter decomposition rates, nor the sign of carbon exchange between land and atmosphere over the next century are well understood, and uncertainties remain about how temperature sensitivities scale from short (less than a season) to long (decades) time scales (Davidson and Janssens, 2006). Similarly, potential feedbacks between climate and ocean circulation may affect the net oceans CO_2 exchange, but these processes are not yet understood in sufficient detail to be included in models that predict the next century. Overall, the development of better models will require progress in answering questions 7.1-7.5 above.

Q 7.6. How will the Earth system, and its different components, respond to various options for managing carbon in the environment, and what scientific information is needed for evaluating these options?

Informing carbon management is a new area of emphasis for the carbon cycle research element, so inadequate progress has been made on this research question. Efforts to quantify carbon changes that might accompany a given management practice have only recently begun (Dilling, 2007a, b). One notable exception is in the area of agricultural (Johnson et al., 2005; Martens et al., 2005) and forest (Birdsey et al., 2006) management. A stakeholder workshop was held in November 2004 as input to CCSP synthesis and assessment product 2.2,[11] but potential stakeholders and the kinds of useful products that CCSP research could produce are still being identified (Dilling, 2007a, b). Future progress will depend on improvements in these areas, as well as coordination with the Climate Change Technology Program (e.g., alternative

[11] See <http://cdiac.ornl.gov/SOCCR/workshop1.html>.

energy implications for the atmosphere) and the ecosystems and land use and land cover research elements.

Opportunities and Threats

Although good progress has been made toward balancing the global carbon budget, the fate of a portion of the CO_2 added to the atmosphere by fossil fuel burning and deforestation remains unresolved. In part, this is because the strengths of ocean and land carbon sinks can change from one year to the next, making it difficult to patch together a coherent set of observations at the proper temporal and spatial scales for interpretation. Observations take place on short time scales of minutes to several years, whereas processes that operate on longer time scales (e.g., erosion, deposition, vegetation mortality and regrowth, ocean circulation changes) set the stage for these short-term fluxes. Understanding of the magnitude and even the sign of feedbacks to climate or land use of these longer-term processes is uncertain. For example, North America land carbon sinks reflect the dynamics of forest regrowth, fire suppression, or enhancement of plant growth by CO_2 fertilization (e.g., Pacala et al., 2001). Similarly, ocean carbon flux estimates in the future are limited by our understanding of how ocean thermohaline circulation and biology may change with climate (Sarmiento and Gruber, 2002).

The main factor limiting progress is not our understanding of where key uncertainties lie, but our ability to carry out the research needed to reduce those uncertainties under current budget constraints. For example, inversions of observations of gradients in atmospheric CO_2 (and other trace gases) can in theory provide measures of the locations of major carbon sources and sinks. However, making reliable estimates requires (1) investment in trace gas transport models, (2) expansion of networks to increase data density and to measure the free troposphere in addition to the boundary layer, and (3) expansion of a suite of trace gas and isotope measures.

ECOSYSTEMS

Ecosystems "supply food, fiber, fuel, clean air and water and many other goods to society" (CCSP, 2006a). By altering the structure and function of marine and terrestrial ecosystems, climate change potentially affects all aspects of society. The CCSP ecosystem research element aims to provide a scientific basis for the development of policies and procedures that will protect the goods and services derived from marine and terrestrial ecosystems.

Progress Toward Answering the Research Questions

Progress has been made in addressing aspects of all the overarching research questions that guide the ecosystem research element. For example, plans and strategies for managing some marine and terrestrial ecosystems affected by climate change have been developed (e.g., Dale et al., 2001; Murawski and Matlock, 2006). Efforts to couple climate and ecosystem models are established (e.g., Cramer et al., 2001; Schmittner, 2005). However, much remains to be done before the effects of climate change on marine and terrestrial ecosystems can be predicted (Burkett et al., 2005). Continued progress will require long-term support for data systems, development of integrated modeling frameworks with data assimilation and predictive capability, and continued refinement of our understanding of processes, feedbacks, and linkages within ecosystems and between ecosystems and the larger Earth system.

Q 8.1. What are the most important feedbacks between ecological systems and global change (especially climate), and what are their quantitative relationships?

Progress toward identifying feedbacks between ecological systems and global change and describing quantitative relationships for these linkages has been inadequate. Most of the research has been directed at understanding changes that will occur in ecosystems as a result of climate change (see question 8.2). Understanding feedbacks and quantitative relationships requires integrated modeling coupled with coordinated data collection programs that sample multiple temporal and spatial scales. However, progress on defining the types of measurements and models that are needed to address this research question for terrestrial (Hurtt et al., 1998) and marine (Doney et al., 2003) ecosystems has been inadequate. Progress will also depend on results of research being undertaken under the carbon cycle research element and on long-term in situ and satellite-based remote sensing capabilities. Current capabilities to study and monitor coastal ocean ecosystems are limited, and the planned high-resolution coastal water imager on the Geostationary Operational Environmental Satellite Series R (GOES-R) has been cancelled.

Q 8.2. What are the potential consequences of global change for ecological systems?

The bulk of research carried out within the ecosystems research element falls under this research question, and good progress has been made in answering it. The LTER program, which includes sites on both managed (e.g., farmland) and less managed landscapes (e.g., arctic tundra), has documented long-term (multidecadal) changes in terrestrial ecosystems in response to climate change and enabled process studies of the physical, chemical, and biological components of ecosystems.[12] The recent expansion of the LTER network to include more marine sites should enhance our ability to study the effects of climate change on a variety of ecosystems. The developing National Ecological Observatory Network is extending such studies to continental scales and advancing understanding of how ecosystems and organisms respond to variations in climate. The Global Ocean Ecosystems Dynamics Program (Fogarty and Powell, 2002) and the Throughfall Displacement Experiment (Hanson and Wullschleger, 2003) led to improved documentation of the response of marine and terrestrial ecosystems, respectively, to the effects of climate variability. These and other programs have led to increased understanding of the potential consequences of climate change for ecosystems, and attempts to use this information to guide ecosystem-based management of resources are beginning (e.g., see the June 2004 theme section of *Marine Ecology Progress Series*).[13]

Q 8.3. What are the options for sustaining and improving ecological systems and related goods and services, given projected global changes?

Progress on this research question has been good. Regulatory and management options and/or plans have been developed (and are under development), and the infrastructure is

[12] Contributions from individual LTER sites can be found at <http://www.lternet.edu>.
[13] See also materials on the Ecosystem-Based Management Tools Network, <http://www.embtools.org>.

now in place to guide management of changing terrestrial and marine ecosystems. The plans employ an adaptive approach to managing ecosystems, including agricultural and forest systems, that is intended to add resilience to the ecosystem (e.g., see USDA Northwest Forest Plan; Butler and Koontz, 2005; Bormann et al., 2007). Governance systems specific to ecosystems affected by climate change have also been developed. For example, the National Marine Fisheries Service uses plans that link fisheries management to climate variability (Murawski and Matlock, 2006). An important factor in the progress of this research question is identification of the relevant stakeholders and involvement of these individuals in ecosystem management.

Studies are under way to identify indices, bioindicators, and biocriteria that can be used to describe the current state of marine and terrestrial ecosystems and to project the consequences of climate change for these systems.[14] Much of the focus thus far has been on managed ecosystems, but unmanaged ecosystems are equally important in understanding responses to climate change and also deserve attention.

Opportunities and Threats

The temporal and spatial scales of ecosystem change that are important for management need to be better defined. Adaptive management structures are in place for managed ecosystems, but the consequences and feedbacks from the actions dictated by these structures have not been explored (e.g., Everglades example, Gunderson and Light, 2006). For unmanaged ecosystems, no clear stakeholder exists, but neglecting these large and possibly important ecosystems may result in unwanted surprises and unanticipated feedbacks. Understanding climate change effects in managed and unmanaged ecosystems is important to sequestration technologies that do not consider a priori potential effects on ecosystem structure and function. Improvements in understanding linkages between atmospheric, ecosystem, and water cycle processes are needed for terrestrial and marine ecosystems. However, current funding structures do not generally encourage research programs that span a wide range of potential interactions and inputs. Consequently, most research programs focus on one or two aspects of these interactions, which provides only limited insights into possible effects of climate change.

Areas in which future investments in ecosystem research can result in significant advances in understanding are (1) improving atmospheric transport models to better take advantage of existing and planned observational capabilities and coupling these models to marine and/or terrestrial ecosystem models; (2) supporting development of ecosystem models that include inputs of reanalysis products, forward models, and data assimilative models that are at the cutting edge of model development; (3) supporting the development of ecosystem models and coupled models (e.g., atmosphere-ecosystem, ocean circulation-ecosystem) that include the effects of disturbances and long-term changes; and (4) developing monitoring and observations systems that can document the impacts of changing ecosystems on humans and feedbacks to climate. Ecosystems are already beginning to respond to climate change, and it is imperative to develop the modeling and research infrastructure to predict the possible outcomes and consequences.

Continued progress in the characterization and understanding of ecosystem change and its consequences depends on the availability of long-term observations of atmospheric, terrestrial, and marine systems. Existing observational networks, such as the TAO array in the

[14] Projects and publications appear at <http://www.epa.gov/bioindicators/coral/index.html>.

tropical Pacific Ocean, continue to be important and to need ongoing maintenance, and new remote sensing (e.g., GOES-R satellite) and in situ observing capabilities would improve understanding of ecosystems in the coastal ocean. Also, intercalibration of legacy and operational observing systems (e.g., MODIS, SeaWiFS, Coastal Zone Color Scanner) would provide a basis for assessing long-term (multidecadal) effects of climate change.

Finally, ecosystems and the carbon cycle are closely linked; there are many different and possibly overlapping feedbacks (e.g., changes in methane). Yet most current research programs in the agencies and the CCSP as a whole consider them separately. Progress in both research elements could be fostered by a more coordinated approach.

HUMAN CONTRIBUTIONS AND RESPONSES TO ENVIRONMENTAL CHANGE

The CCSP currently manages research on human dimensions, decision support tools, and human health effects of climate change together. These areas are interconnected, but distinct. Human dimensions research involves a very broad set of research questions and disciplines. The topics are some of the most fundamental in the arena of climate change as an environmental problem (as distinct from an interesting scientific puzzle), including how humans affect climate processes; how societies' and people's well-being is affected (positively and negatively) by changes in climate and by actions taken to mitigate or abate the effects of climate change; and how societies respond, cope, and adapt to climate-related impacts. The disciplines involved in the human contributions and responses research element include demography, psychology, geography and regional sciences, economics, anthropology, political science, and sociology (CCSP, 2003).

Decision support includes research on ways to get climate information used in decision making, the development of tools, and other activities similar to those traditionally associated with extension functions. It also includes research on and application of a systems engineering approach to decision making as exemplified by NASA's program focusing on the use of data generated by its Earth Observation System in decision making. Although decision support activities often draw on results from human dimensions research, the latter is broader in scope and includes basic social sciences to understand and explain both anthropogenic causes of climate change and potential consequences of climate change for societies, cultures, political systems, and individuals. For example, research on how individuals make decisions under great uncertainty will clearly have payoffs in the decision support arena. NSF's program on Decision Making Under Uncertainty (DMUU), which has established five university centers, is a promising example of how human dimensions resources can be used to produce both basic and decision-driven science of great relevance (CCSP, 2007a; McNie et al., 2007; Sarewitz and Pielke, 2007).

Finally, health effects research, as defined in the CCSP strategic plan, includes data collection, studies to understand potential effects of global environmental change on health, and assessment of the cumulative risk of negative effects of climate and environmental change on human health.

A single interagency working group handles all three topics, and progress and future plans for the three are reported together in *Our Changing Planet*. Combining management of human dimensions research and decision support tools deemphasizes the need for basic research in the social sciences throughout all the CCSP overarching goals. Moreover, the inclusion of research on the effects of ozone on health and systems engineering aspects of decision support resources in the budget makes it harder to determine the amount of resources being invested in human dimensions research. Consequently, to evaluate progress in the human contributions and responses research element, the committee had to obtain separate programmatic and budget information from the CCSP (see Appendix B).

Research questions for the CCSP human contributions and responses research element encompass the main areas of inquiry, including determining the causes and consequences of human drivers of global climate change; understanding impacts and differential levels of vulnerability and adaptive capacity; and developing methods and capacities to improve societal decision making under conditions of uncertainty and complexity. One of the questions also concerns understanding the human health effects of global climate change.

Progress Toward Answering the Research Questions

Important research in human dimensions has been has been carried out by a committed, if small, research community, despite the modest investment research thus far (about $25 million to $30 million per year; Appendix B). Significant findings have been published on both the human causes of global climate change and its impacts on societal well-being in the United States and other countries. In addition, a substantial portion of this research has been stakeholder driven and has resulted in positive interactions across the science-society divide, which not only created opportunities for decision-relevant research but also enhanced our understanding of opportunities and constraints for CCSP science-generated knowledge to affect decision making. The research on human dimensions appears to be of high quality, particularly work undertaken as part of NSF programs (e.g., DMUU centers, Harvard knowledge systems for sustainable development project; see Cash, 2001; Cash et al., 2006; Clark and Holliday, 2006; van Kerkhoff and Lebel, 2006) and DOE's program on integrated assessment modeling. The DOE program has coupled long-term support for major research programs at the Massachusetts Institute of Technology (MIT) and the Joint Global Change Research Institute (Pacific Northwest National Laboratory) with a diverse portfolio of smaller-scale research programs that focus on how natural science, economics, and other social science are integrated into policy models for climate change. However, many research gaps remain, and both the size of the human dimensions community and the level of available funding seem inadequate to carry out the research necessary to answer all of the research questions.

Q 9.1. What are the magnitudes, interrelationships, and significance of primary human drivers of and their potential impact on global environmental change?

Progress in answering this research question has been inadequate. *Our Changing Planet* reports two projects that focus on the dynamics of human drivers of climate change (CCSP, 2005b). One study examined the relationship between income and the use of traditional fuels (e.g., firewood) versus commercial fuels for home heating and cooking in rural China, and the other study examined the role of household demography in decisions on land use, especially deforestation. Some research on human drivers has also been conducted outside the CCSP. However, synthesis and integration of results across human dimensions disciplines has been limited. For example, greenhouse gas emission scenarios continue to be based on simple models involving a few drivers (e.g., population, affluence, technological change). Recent studies are beginning to explore how these drivers affect each other and how they interact with other major social changes (e.g., urbanization, industrialization) and with environmental factors (e.g., tropical or temperate location) (York et al., 2003a, b; Rosa et al., 2004).

Current understanding of the effects of human drivers on ecosystem change and, in turn, the effects of changes in ecosystem services on human well being is meager (Millennium Ecosystem Assessment, 2006). Changes in ecosystem services, including those caused by climate variability, are almost always due to multiple, interacting drivers that work over time. These changes operate over multiple temporal, spatial, and governance scales and can also feed back to drivers. No existing conceptual framework captures the broad array of findings from the large bank of case studies presented in the Millennium Ecosystem Assessment.

Q 9.2. 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?

A few lines of research have shown promise, but considerably more effort and resources have to be expended to begin to answer this question. Although RISAs focus on climate variability and change, these regionally based programs have (1) produced valuable insights on institutional opportunities and constraints on the use of climate knowledge by decision makers in different application sectors (e.g., water resources, fire and risk management, agriculture); (2) assessed vulnerabilities of a few groups of stakeholders; and (3) developed innovative methodologies to understand and manage the interaction between scientists and stakeholders (McNie et al., 2007). In addition, NOAA-sponsored research on the economics and human dimensions of climate variability and change has identified potential impacts of climate-related phenomena on different sectors (e.g., water, agriculture, coastal areas). The same program has also sponsored a few projects focusing on vulnerability assessment and adaptation.[15] Although a substantial portion of this research focused on climate variability, its findings have relevance to the transfer and diffusion of climate information to decision makers in different sectors working at smaller scales. A significant part of this research is being reported in synthesis and assessment product 5.3 (see Appendix A). Finally, a few assessments of vulnerability have been sponsored by DOE (Moss et al., 2001) and NSF (e.g., vulnerability of coastal communities; see Appendix B). However, these projects are minuscule relative to the magnitude of the question. Much more research is needed, especially in understanding the impacts of and adaptation to climate change across different sectors and geographical regions, mapping differential vulnerabilities, and designing interventions to build resilience. Similarly, progress on the economics of climate change has generally been inadequate, although a recent U.K. report was an important contribution to the field (Stern, 2007).

Q 9.3. How can the methods and capabilities for societal decision making under conditions of complexity and uncertainty about global environmental variability and change be enhanced?

Overall, progress in advancing capabilities for decision making has been inadequate, but some significant research has been carried out to characterize uncertainty

[15] See project descriptions and a list of publications at <http://www.climate.noaa.gov/index.jsp?pg=./cpo_pa/cpo_pa_index.jsp&pa=sarp&sub=3>.

and complexity in the context of global climate change, to understand their impact on decision making and management, and to understand the links between producers and users of climate science. Four programs stand out as successes: DMUU centers, RISAs, DOE's Integrated Assessment Program, and the Harvard knowledge systems project. Within the RISA programs, for example, some original data on potential impacts and governance responses (from both the public and the private sector) have been generated (e.g., Callahan et al., 1999; Hartmann et al., 2002; Pagano et al., 2002; Carbone and Dow, 2005; Jacobs et al., 2005; Lemos and Morehouse, 2005; O'Connor et al., 2005; CCSP, 2007a). However, RISA-generated data are mostly at the regional level and limited to sectors relevant at this scale, such as water in California or fisheries in the Pacific Northwest.

Each of these four programs has made fair progress in understanding and characterizing uncertainties related to both physical and institutional processes affecting and being affected by global climate change. Some studies have addressed the need to incorporate information from climate science into decision making and how to evaluate predictability and predictive capabilities of different physical and socioeconomic models, but this work is at an early stage. Finally, they have assessed and synthesized knowledge in their focus areas (e.g., Cash et al., 2003; CCSP, 2007a; McNie et al., 2007). In addition, DOE's long-standing support of major integrated assessment projects has led to increased capabilities to conduct these assessments; major modeling teams at the Joint Global Change Research Institute and MIT, as well as a number of other researchers, are now working in this area. Some of this work is related to decision support and some to human dimensions research. However, the total output from these efforts has been low for the complexity and high levels of uncertainty that still characterize the physical processes causing global climate change and the magnitude of the potential impacts on socioeconomic and ecosystems (e.g., Millennium Environmental Assessment, 2006; Stern, 2007).

Q 9.4. What are the potential human health effects of global environmental change, and what climate, socioeconomic, and environmental information is needed to assess the cumulative risk to health from these effects?

The vast bulk of this research program involves either health effects of ultraviolet radiation or satellite measurement of particulate matter concentrations for health-related analysis. A few research projects focusing on the intersection of climate, health, and human dimensions have been carried out under the auspices of the Environmental Protection Agency and the Centers for Disease Control and Prevention (see Appendix B; CCSP, 2005b, pp. 131-132). For example, a health impacts assessment (Patz et al., 2000) examined the interactions between health and climate variability and change, and identified adaptation strategies.

Opportunities and Threats

A review of the CCSP strategic plan recommended accelerating efforts in human dimensions, economics, adaptation, and mitigation by strengthening science plans and institutional support (NRC, 2004c). The inadequate progress of the human contributions and responses research element may reflect organizational problems within the agencies and the CCSP. Of particular concern are the absence of social science leadership to guide the program and sufficient resources (dollars and people) to carry it out (see Table 2.1). Few agencies have programs dedicated to human contributions and responses, and CCSP funding devoted especially to human dimensions is significantly less than funding devoted to most of the other research elements (Table 1.1). Human capacity may also be insufficient to carry out this work. The natural sciences may offer a successful model for building human dimensions capacity, especially programs to move young investigators into the arena and to support postdocs.

The program could benefit from improved linkages to other programs, such as NSF's biocomplexity program. Integration and enhanced support for human dimensions are especially critical given the potential for such research to inform decision making and the management of climate impacts on human, sociopolitical, and ecological systems. If the quality and "usability" of the few projects already funded are any indication, investment in human dimensions not only is necessary, but may be highly cost effective.

Improvement of existing data sets and the collection of new data at suitable resolution would also speed progress in human dimensions. A major need is for data sets on both climate-related human activities and environmental data at the same spatial and temporal coverage and resolution. Many relevant social data sets exist at useful levels of aggregation, but they have not been geocoded or are not available in spatial forms that are readily linked to environmental data (e.g., they are coded by political jurisdictions rather than spatial coordinates). For example, DOE has collected energy consumption data on residential, commercial, and industrial users since the 1970s, but most available data are aggregated at only the state or regional level and cannot be used to model the drivers of greenhouse gas emissions at higher resolutions. Data on property values are collected by jurisdictions around the country and they appear on maps, but not in forms that facilitate linkage to climate models and thus estimates of the economic consequences of possible future floods or storms on particular places. The use of such data sets in models would enable projections of greenhouse gas emissions that are based on analyses of the driving forces and their interactions, rather than on simplified assumptions about a few driving forces. It would also provide an empirical base for disaggregated analyses of the human consequences of climate variability and change and of the potential benefits of various adaptive and mitigative responses.

Finally, future evaluations of progress would be greatly facilitated if the CCSP reports accomplishments on human dimensions research separately from accomplishments on decision support activities and health effects research.

PRELIMINARY ASSESSMENT OF THE OVERARCHING GOALS: AN EXAMPLE

As noted in Chapter 2, it should be possible to use results of the preliminary evaluation of research questions to assess the overarching goals. An example of how the evaluation could be conducted for focus area 1.4 of overarching goal 1 is given below. The committee first mapped the research questions and relevant cross-cutting issues to the focus areas (Box 4.1). The mapping proved challenging because the connections are not all laid out in the CCSP strategic plan, and each focus area is connected to several research questions and often to one or more cross-cutting issues. The scores and comments on the relevant questions were then combined to make an overall evaluation.

BOX 4.1 Links Between Overarching Goal 1 Focus Areas, Research Questions, and Cross-Cutting Issues

Overarching Goal 1: Extend knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change

Focus 1.1. Better understand natural long-term cycles in climate (e.g., Pacific Decadal Variability, North Atlantic Oscillation)
Associated research questions: 4.2, 5.1, 8.2, and 9.2
Focus 1.2. Improve and harness the capability to forecast El Niño-La Niña and other seasonal-to-interannual cycles of variability
Associated research questions: 4.2, 5.2, and 9.2
Focus 1.3. Sharpen understanding of climate extremes through improved observations, analysis, and modeling, and determine whether any changes in their frequency or intensity lie outside the range of natural variability
Associated research questions: 4.3, 4.4, and 8.2
Focus 1.4. Increase confidence in the understanding of how and why climate has changed
Associated research questions: 3.1, 3.2, 3.3, 4.4, 5.1, 5.2, 6.1, 6.2, 6.4, 7.1, 7.4, 8.1, and 9.1
Associated cross-cutting issues: 10.1, 10.2, and 10.3 (modeling)
Focus 1.5. Expand observations and data and information system capabilities
Associated research questions: 3.1, 3.2, 3.3, 3.5, 4.1, 4.5, 5.2, 5.4, 6.1, 6.2, 6.4, 7.1, 7.4, 8.1, and 8.2
Associated cross-cutting issues: 12 (observing) and 13 (data management) subgoals

Focus Area 1.4

The twentieth century has witnessed major changes in both climate forcing terms (greenhouse gases, aerosols, land use and land cover, volcanic emissions of SO_2) and climate (e.g., surface temperatures, atmospheric temperatures, ice and snow cover, mountain glaciers). Understanding how and why these changes occur is important for evaluating the human impact on climate and predicting future changes. Thus, focus area 1.4 is a key component of the CCSP and involves several research questions. Focus area 1.4 is addressed by five research elements—including atmospheric composition, climate variability and change, water cycle, land use and land cover change, and human contributions and responses—and the modeling cross-cutting issue. It has two parts, which are evaluated separately below.

How Has Climate Changed?

Good progress has been made in this area. For example, the IPCC (2007) concludes that "warming of the climate system is unequivocal". Research conducted under the CCSP, including the synthesis and assessment report on atmospheric temperature trends, played an important role in the IPCC's finding. However, continued progress is seriously threatened by the loss of climate instruments on NPOESS and other satellites. The research part of this topic is covered under questions 4.2 and 4.4 of the climate variability and change research element. Sustained investments in observing systems and models have led to advances in understanding ocean processes and several natural forcing terms (e.g., solar insulation, volcanic emissions), as well as the relationship between climate variability and change, droughts, and wildfires. A limited number of paleoclimate records needed to advance understanding and improve predictions are also available.

In addition, three synthesis and assessment products (1.1, 1.2, and 1.3) are relevant to this focus area. Synthesis and assessment product 1.1 (temperature trends) largely resolved the discrepancy between surface observations of surface warming and satellite observations of atmospheric warming (CCSP, 2006b). The two other products have not yet been published (see Appendix A).

Why Has Climate Changed?

Major improvements have been made in quantifying the anthropogenic forcing terms (i.e., radiative forcing due to greenhouse gases, aerosol forcing, land use albedo forcing). For example, the IPCC (2007) concludes that the " globally averaged net effect of human activities since 1750 has been one of warming with a radiative forcing of +1.6 [+0.6 to +2.4] Wm^{-2}." However, large uncertainties remain in the magnitude of emissions of aerosols, aerosol-cloud interactions, and the importance of tropospheric ozone forcing. Internal variability in the coupled land-ocean-atmosphere system, changes in natural climate forcing terms (solar insolation and volcanic emissions), and anthropogenic influences (changes in greenhouse gas emissions, aerosols, and land use and land cover) contribute to climate changes. Our understanding of these processes has improved significantly over the last few decades, fueled by the synthesis of different types of observations (satellite, aircraft, ship, buoy, land surface) and the integration of observations and laboratory experiments. In addition, models (e.g., coupled ocean-atmosphere-land climate models, chemical transport models, carbon cycle models) have played a fundamental role in sorting out the various forcing factors that influenced the observed changes. Changes in climate forcing are covered in research questions 3.1, 3.2, 3.3, 6.1, 6.2, 7.1, 7.4, and 9.1. The effects of climate change feedbacks on forcing are covered in questions 5.2, 6.4, and 8.1. Fundamental weaknesses still exist in the following areas:

- *Regional climate changes*. Concerted efforts to quantify the impact of human activities on North American climate change and its subsequent consequences for agriculture, the water budget, and health have been limited since the last major assessment of climate change impacts in the late 1990s (National Assessment Synthesis Team, 2000).
- *Role of cloud feedback in climate change*. Changes in water vapor, clouds, and precipitation in response to changes in climate forcing and climate change can have major feedback effects. Aerosol-cloud-precipitation feedbacks are also part of this issue. The effect of aerosols in inhibiting cloud formation has been measured, but large uncertainties remain about the emission sources of elemental and organic carbon, the indirect effect of aerosols on climate, and the importance of aerosol solar heating of the atmosphere on climate.
- *Feedback processes between the physical, chemical, and biological parts of the climate system*. Progress in understanding these feedback processes, which may also have influenced the observed changes, has been inadequate.
- *Climate-societal interactions*. Progress has been inadequate in the development of a quantitative understanding of how societal behavior and choices affect the environment and how societies in turn are affected by the environment.

Good progress has been made in mapping land cover change, but these studies have been limited by difficulty in obtaining relevant socioeconomic data. With the exception of advances in land use change and decision making under uncertainty, inadequate progress has been made on understanding the human drivers of climate change. Ecosystems influence atmospheric composition of greenhouse gases, aerosol precursors, and absorption and reflection of solar radiation at the surface. However, research efforts to date have focused on understanding changes that will occur in ecosystems as a result of climate change.

Scientific questions regarding the response of the climate system to natural and anthropogenic forcing cannot be addressed with traditional physical climate models (e.g., those that do not include interactive chemistry, the carbon cycle, or interactive aerosol models). Consequently, significant efforts have been made to extend physical models to include the interactions of climate with biogeochemistry, atmospheric chemistry, ecosystems, glaciers and ice sheets, and anthropogenic environmental change. The types of measurements and models needed to obtain a more comprehensive understanding of feedbacks for terrestrial and marine ecosystems are still being defined. Finally, U.S. underinvestment in computing power has limited progress in accurately representing key climate processes and feedbacks.

Overall, the committee found that a fair amount of progress has been made on focus area 1.4. Slightly greater advances have been made in understanding how climate has changed than why it has changed. These advances have been driven largely by the availability of a wide range of data from satellite and in situ networks, which have significantly improved our ability to represent physical quantities. Understanding of the forcing factors that affect climate—and vice versa—has progressed steadily, with the greatest gains in atmospheric composition and, to a lesser extent, the water cycle. Inadequate progress has been made in understanding ecosystem or human feedbacks and developing coupled models capable of addressing natural and anthropogenic forcing.

5
Progress Toward the Cross-Cutting Issues

A critical role of the Climate Change Science Program (CCSP) is to coordinate activities "to achieve results that no single agency, or small group of agencies, could attain" (CCSP, 2003, p. 3). Six cross-cutting issues—observations and monitoring, data management, modeling, decision support resources, communications, and international cooperation—lay the foundation for achieving this integration. Each of these cross-cuts is guided by an interagency working group (IWG), although some working groups handle two areas (Figure 1.2): decision support resources is combined with human contributions and responses, modeling is combined with climate variability and change, and data management is a subgroup of observations and monitoring.

This chapter describes the committee's preliminary assessment of progress in the 22 goals of the CCSP cross-cutting issues. The assessment was based on analysis of the columns of the matrix used to evaluate the research questions (Chapter 4), as well as presentations by CCSP interagency working groups, CCSP publications and web sites, and the scientific literature. Given the breadth and generality of these cross-cutting goals, it was difficult to assign meaningful scores. Thus, in most cases, only the commentary appears below.

OBSERVATIONS, MONITORING, AND DATA MANAGEMENT

One of the four core approaches of the CCSP is "to enhance observations and data management systems to generate a comprehensive set of variables needed for climate related research" (CCSP, 2003). The overarching challenge is that the existing global observation system is an incomplete and distributed set of remote and in situ components, managed and operated by different agencies and international partners with different objectives (e.g., research, weather forecasting, resource management). Data derived from these observing systems are distributed and archived by multiple agencies, each with different information management systems. The need to collect social, economic, and health data to address the human dimensions aspects of the program adds an additional level of complexity because these data are outside the purview of agencies traditionally associated with climate measurements. Moreover, concerns about privacy bring unique challenges to the collection and dissemination of social science data. Finally, a global observing system enables the collection of long-term (century or longer) climate records while remaining sufficiently flexible to respond to changing observation needs as the science evolves.

Several U.S. agencies are responsible for climate observations and data management. Total expenditures on observations and data management are unknown because climate observing programs of agencies other than the National Aeronautics and Space Administration (NASA) are counted as research in the CCSP budget tables, and some of the operational systems which are also used for climate science are not counted at all. Nevertheless, it is clear that observations account for a significant fraction of the total CCSP budget. The NASA space-based observations portion alone was one-third of the total CCSP budget in Fiscal Year 2006 (CCSP, 2006a) and more than half of the research element budget (Table 1.1). The program's emphasis on satellite observations is proportional to this investment.

The IWG on observations and monitoring provides both a forum to develop a consensus on the priority requirements for climate observations and a platform to advocate for resources to enable those climate observations to be made. Individual federal agencies have their own advisory process for addressing observation and data management. External studies of these programs, especially NASA and National Oceanic and Atmospheric Administration (NOAA) programs, are common (e.g., NRC, 1998, 2000a-d, 2001a, 2003d, 2004b, e, 2005a, 2006c, 2007a). As a result, there has been no shortage of strategic thinking about climate observations and data management.

Progress Toward the Observations and Monitoring Goals

Investment in NASA's Earth Observing System (EOS) in the 1990s has paid off during the tenure of the CCSP. Some recent highlights include the creation of science quality time-series data for the ocean, land, and atmosphere from the Moderate Resolution Imaging Spectroradiometer (MODIS); estimates of trends in the Earth radiation budget from Clouds and the Earth's Radiant Energy System (CERES); new cryosphere and freshwater assessments from IceSat and the Gravity Recovery and Climate Experiment (GRACE); the first observations of variations across the full solar spectrum from the Solar Radiation and Climate Experiment (SORCE); new results on ozone, aerosols, and greenhouse gases from Aura; and the first global cloud and aerosol profile data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), which enabled new studies of aerosol sources and transport and aerosol-cloud interactions. New instruments on satellites flown by other agencies have also opened horizons, such as obtaining temperature profiles from radio occultation on the Global Positioning System (e.g., Leroy, 1999).

In situ measurements are essential for all of the research elements, partly for studying processes or areas that cannot be studied from space (most notably in the oceans), and partly to provide ground truth for the satellite observations. Networks of in situ observations have been deployed to monitor conditions at the Earth's surface and the rates of ocean-atmosphere and land-atmosphere energy exchanges. These networks are linked to international efforts to determine the budget of trace gas emissions and the role of oceans and terrestrial ecosystems in climate. Such activities often contribute to more than one observations and monitoring goal, such as deploying observation components, integrating modeling activities, and fostering international cooperation.

12.1. Design, develop, deploy, integrate, and sustain observation components into a comprehensive system.

A wide variety of satellite and in situ instruments have been deployed, but they are operated individually without the framework of a comprehensive system. Operational satellite systems have been designed primarily to meet the needs of the National Weather Service and do not carry instruments capable of producing climate quality data records. In addition, cancellations of instruments that were to make new climate measurements as part of the National Polar-orbiting Environmental Satellite System (NPOESS) or to continue an unbroken time series (e.g., Landsat) threaten to reduce the overall observing capability of the United States and present a serious setback to CCSP science objectives (see Chapter 4).

12.2. Accelerate the development and deployment of observing and monitoring elements needed for decision support.

Data from operational satellite systems are routinely used to produce information useful to decision makers, for example by the National Weather Service. NOAA, through its Regional Integrated Sciences and Assessment (RISA) projects, is developing procedures for improving the use of climate information in the decision-making process for a number of sectors. NASA's Applied Sciences program is aimed at generating new information products from research satellite systems to meet the needs of decision makers. However, NASA's satellite sensors were designed primarily to meet scientific and technology demonstration objectives, and if observations and monitoring goal 12.2 is to be achieved, decision support requirements will have to be factored into the design of future satellite systems. CCSP plans envision observation networks that support priorities of decision makers, but the design and implementation of such networks requires coordination with non-scientist stakeholders who have yet to be identified. Finally, there is often no pathway to transition observation or information extraction and dissemination capabilities developed in the research domain into the operational domain (NRC, 2003d). A broader community of operational users will have to be involved in the specification of future observation and data delivery systems.

12.3. Provide stewardship of the observing system.

This observation and monitoring goal concerns the use of climate monitoring principles and scientific oversight of algorithm development, instrument calibration, data processing, product validation, archiving, and distribution. Although general guidelines for stewardship have been developed (NRC, 2004b), responsibility for following them is distributed among the agencies and no one body is charged with oversight of climate data. The success of individual agency efforts with respect to climate data stewardship has been reviewed in a number of National Research Council (NRC) studies (e.g., NRC, 2001b, 2005c, 2006b). Stewardship of the observing system is discussed in Chapter 4, which notes (1) that some in situ observing systems are degrading and others have not been expanded as proposed in science implementation plans, and (2) that some proposed satellite systems needed to extend the climate data record have been cancelled or delayed.

12.4. Integrate modeling activities with the observing system.

Integration of modeling with observation systems involves technological tools such as those that have been developed by the National Weather Service community. This integration has generated weather-related climate data as reanalysis products. Observations and monitoring goal 12.4 will be further advanced as progress is made in the development of algorithms for modeling other forms of time-varying climate parameters and relating them to corresponding observational data.

12.5. Foster international cooperation to develop a complete global observing system.

A considerable amount of deliberation and coordination on climate observations has taken place at the international level. Coordinating bodies exist on different aspects of the climate observing system, including the Global Climate Observing System (GCOS), the Global Ocean Observing System, and the Global Terrestrial Observing System. These groups have established principles for climate observation, developed observation requirements, and assessed the adequacy of available climate observations. All three groups have identified the essential climate variables needed to support the United Nations Framework Convention on Climate Change (GCOS, 1997, 2003, 2006), and the Committee on Earth Observation Satellites is assessing current capabilities to provide the satellite-derived essential climate variables. On a broader scale, the international Group on Earth Observations was established to develop a comprehensive framework to integrate a wide array of space and in situ observations. Steps are now being taken to develop the international Global Earth Observing System of Systems (GEOSS) through a series of tasks organized around nine areas of societal benefit, including understanding, assessing, predicting, mitigating, and adapting to climate variability and change.[16]

Although individual agencies participate in the international global observing systems, CCSP coordination with these international observing efforts has thus far been weak. The CCSP observations IWG is, however, developing metrics to evaluate and prioritize the contribution of U.S. satellite and in situ observations to GCOS, based on results of a workshop held in June 2006. Several CCSP managers also sit on committees and working groups to plan the U.S. contribution to GEOSS, but CCSP influence on international programs, and vice versa, remains limited. With increasing demands for Earth observations, delays in launching U.S. satellites, and the removal of a number of climate sensors from NPOESS, increasing attention will have to be paid to international cooperation. The role of the CCSP in this coordination has yet to be determined.

12.6. Manage the observing system with an effective interagency structure.

Of all the observations and monitoring goals the least progress has been made in developing an effective interagency structure for climate observations. The CCSP's inability to influence the observing programs of its participating agencies is related partly to the absence to date of a clear articulation and prioritization of CCSP observation requirements (NRC, 2004c) and partly to the absence of funding authority. CCSP goals are clearly a consideration for the participating agencies, but they are largely secondary to agency goals.

Progress Toward the Data Management Goals

Good progress is being made on three of the four data management goals.

13.1. Collect and manage data in multiple locations.

A host of NOAA, Department of Energy (DOE), and U.S. Geological Survey (USGS) environmental data centers have existed around the country for decades (see list in NRC, 2003a), providing access to a wide range of satellite and in situ data to a wide range of users. As part of its Earth Observing System, NASA made a significant investment in data systems and

[16] See <http://www.earthobservations.org/index.html>.

technologies. The resulting Distributed Active Archive Centers, Science Computing Facilities, and specialized data projects are now providing access to unprecedented volumes of Earth science data, and peer-reviewed data products are being generated routinely for NASA's systematic observations (NRC, 2002b). These data are being reprocessed as improvements to calibration and algorithms are made, and data products are being systematically validated and the associated validation data made available.

13.2. Enable users to discover and access data and information via the Internet.

The Internet has revolutionized the way users find and obtain data. On-line access to data has increased dramatically, and a variety of tools are now available for manipulating and visualizing data (NRC, 2003a). Increases in computational capacity have enabled scientists to download and manage terabytes of data routinely in their own laboratories. Grid computing approaches are also being developed to share computing resources and enable distributed data processing. The Global Change Master Directory provides a summary of data holdings, including climate indicators, which helps users find distributed data holdings. Information on the CCSP is available through the Internet, although the CCSP web site is sparsely populated with information and difficult to navigate (see "Communications" below).

13.3. Develop integrated information data products for scientists and decision makers.

The emphasis to date has been on meeting the needs of the science community (e.g., NRC, 2002b, 2003c). Both NASA and NOAA are currently supporting research and development to provide data products and services suited to the needs of operational users. Although most efforts have focused on preparing and delivering information suitable for use by scientists and agency managers, systems such as the National Integrated Drought Information System are beginning to be established for decision makers (NSTC, 2006).

13.4. Preserve data.

It is within the mission of both NOAA and USGS, but not NASA, to preserve data over the long term. In addition to its other archival systems, NOAA is developing the Comprehensive Large-array Stewardship System, which will provide access to data from satellite programs, including the Polar Operational Environmental Satellite and the Geostationary Operations Environmental Satellite systems, the NPOESS Preparatory Project, and EOS. The CCSP has had little involvement in ensuring the long-term archive of climate-related data collected by participating agencies.

Opportunities and Threats

CCSP progress in prioritizing the climate observation requirements and developing and implementing an interagency strategy for securing the necessary long-term (century or longer) climate observations will be the ultimate measure of success of this part of the program. As long as multiple agencies are responsible for climate observations, interagency coordination will continue to be critical. The CCSP provides a structure for building consensus among the agencies, and it could be used more effectively to determine what should be done to secure the necessary climate observations and to resolve other observation and data issues. With a decreasing budget for Earth observation in the United States, international cooperation and data exchange will become increasingly important. For example, the upcoming International Polar Year provides an opportunity for increased international coordination on polar observations.

Different agency missions create obstacles to CCSP progress in securing climate observations. In particular, NOAA's primary mission with respect to satellite observations is to meet the needs of the National Weather Service, which does not require climate observations. NASA does not undertake operational measurements, although some "systematic" measurements (e.g., from MODIS, Landsat, Tropical Rainfall Measuring Mission) are made in support of climate change research. Now that NASA's priorities are directed toward exploration, its climate budget is shrinking and the case for long-term measurements has to be weighed against new instruments and technologies. The absence of a pathway and funding for transitioning observations from NASA research to NOAA operations raises serious concerns about the continuity of climate quality observations.

Consistent long-term (multidecadal to century) observations are crucial, and long-term measurements from the polar-orbiting systems are of particular importance for the CCSP. It is unclear how effective the transition of climate quality observations will be from MODIS, with its rigorous calibration and validation programs, to the NPOESS Preparatory Project (NPP) Visible Infrared Imager/Radiometer Suite (VIIRS) instrument. In this respect, it is important that the MODIS instruments not be decommissioned until after NPP VIIRS is launched and inter-comparison and calibration can be made. A number of other critical observations will not be extended. The cancelled NPOESS climate instruments would have continued measurements of top-of-atmosphere energy sources and sinks. No means have been proposed for extending current observations from SORCE and CERES. Finally, a break in data continuity also appears inevitable in the Landsat series (see Chapter 4). The CCSP is starting to bring these issues to the fore, highlighting the need for a mechanism to fill these critical data gaps. The CCSP could perform a similar role in clarifying the issues and supporting the necessary agency programs in the EOS-to-NPOESS transition and extensions of other current observations.

Upcoming validation experiments for Aura, Cloudsat, and CALIPSO provide opportunities for securing new climate quality measurements. NASA is also giving emphasis to the development of a suite of Earth science data records for climate and global change studies (NRC, 2004b). Similarly, NOAA is developing plans for generating climate data records from NPP and NPOESS VIIRS. It is important that the VIIRS instrument be calibrated to enable science quality products to be generated from the system designed to meet the needs of operational users, and that these products continue the climate data record developed from MODIS (NRC, 2000b). The CCSP could help ensure that the climate principles and priority observations are met by these initiatives and that there is effective coordination.

Concerns also exist for the continuity of data from ground-based observation networks, which are required to test conclusions based on remote observations. For example, data from atmospheric sampling networks are used to test the validity of results from the Orbiting Carbon Observatory satellite. However, research funds are not available to support the expansion of existing networks planned under several of the CCSP research elements, and priorities for which networks receive other limited resources will likely be set at the agency level.

Challenges in data management include securing and managing the long-term data archive (NRC, 2006b), coordinating development and distribution of climate data records, establishing consistent long-term data records across instruments (NRC, 2000b, c), and international data coordination. The latter could be undertaken in the framework of the emerging international GEOSS. Finally, data systems currently designed primarily to meet the needs of the science community will have to be augmented with systems that can provide climate-related information to decision makers.

MODELING

The CCSP strategic plan describes two complementary streams of climate modeling activities. The first is fundamental research on climate processes operating in the atmosphere, ocean, land, and cryosphere required for model development through improved representation of climate processes. Climate process research also provides a framework for climate model experiments and for deciding which observations to analyze. Included, for instance, is basic research on the research elements described in Chapter 4, including chemistry and climate; aerosols; clouds and convection; the global carbon, nitrogen, water and energy cycles; ocean and atmospheric eddies; snow and ice; dynamic vegetation; and land cover and land use change. The second stream of work is the sustained and timely delivery of predictive model products that are required to support assessments and decision making. The intent of the CCSP is to maintain a productive partnership between product-driven modeling activities and the discovery-driven modeling research program that will underpin its credibility and future success. Other types of models (e.g., economics, integrated assessments) are not included in this cross-cutting issue.

Several of the most pressing scientific questions regarding the climate system and its response to natural and anthropogenic forcing cannot readily be addressed with traditional models of the physical climate. One of the open issues for near-term climate change, for example, is the response of terrestrial ecosystems to increased concentrations of carbon dioxide. Will soils release stored carbon dioxide to the atmosphere in a warmer climate, thereby acting as a positive feedback, or will vegetation absorb more carbon dioxide and hence decelerate global warming? Exploration of this and other questions requires a more comprehensive treatment of the integrative Earth system as well as improved understanding of feedbacks derived from manipulations and long-term (decades to a century or longer) observations. Physical models, in particular, are being extended to include the interactions of climate with biogeochemistry, atmospheric chemistry, ecosystems, glaciers and ice sheets, and anthropogenic environmental change.

Progress Toward the Modeling Goals

Over the past few years, the CCSP has supported and initiated several activities that have significantly improved models for investigating and understanding how the Earth system works and how it is affected by human actions. Yet many challenges remain, ranging from scientific uncertainties and questions on climate processes articulated in many of the CCSP research questions to the extensive computational demands required to build more comprehensive models. While the ultimate objective is a comprehensive Earth system model, constrained by observations, the complexity of Earth's climate system will require the CCSP to focus on models that will aid in understanding the processes that maintain and regulate climate. The information produced by these models will be of limited use to the stakeholder community, however, until a research and applications infrastructure is developed that better involves stakeholders in developing new approaches for projecting impacts on society and ecosystems and in designing and implementing response options. As noted in NRC (2004c), such efforts are still in their formative stages.

10.l. Improve the scientific basis of climate and climate impacts models.

Several notable CCSP-initiated successes have occurred in the arena of climate modeling. Significantly improved representations of physical processes, as well as increased resolution, characterize the latest generation of U.S. climate models (e.g., Collins et al., 2006; Delworth et al., 2006). New simulations of climate change during the twentieth and twenty-first centuries have been carried out using these models, and this output is a centerpiece of the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC). These simulations have increased the credibility of scientific conclusions on the causes of global surface warming witnessed over the past several decades. Various high-end modeling centers sponsored by DOE, NASA, NOAA, and the National Science Foundation (NSF) developed and tested the new U.S. models. All show significant improvements in the simulation of the physical climate system compared to their predecessors a decade ago (IPCC, 2007), although there is still a need to reduce systematic biases that plague coupled models, such as the biases associated with the double Inter-tropical Convergence Zone, errors in the simulated intraseasonal and interannual variability of the tropics, and various regional biases in simulated rainfall and surface temperature. The reduction of such biases becomes even more important as the complexity of the models increases, for example, through the introduction of dynamic vegetation parameters.

Despite recent model improvements, however, significant uncertainties associated with various aspects of climate models remain. One of these is the representation of clouds, which continues to be one of the weakest links in modeling the physical climate system (IPCC, 2007). A climate process team (CPT) on cloud feedbacks has been formed to address this challenge by incorporating high-resolution satellite data, field observations, and small-scale cloud models. In addition, the Climate Change Prediction Program-Atmospheric Radiation Program Parameterization Testbed project is addressing the cloud modeling problem by first analyzing the ability of a climate model to accurately simulate weather events, diagnosing the errors, and subsequently improving the model. Other improvements are being made in understanding and modeling different components of the Earth system, including atmospheric chemistry, ecosystems, and carbon cycling, although many challenges remain, including integrating these capabilities into increasingly comprehensive Earth system models.

10.2. Provide the infrastructure and capacity necessary to support a scientifically rigorous and responsive U.S. climate modeling activity.

U.S. climate modeling capability has advanced significantly in the last several years, fueled by improvements in software and understanding of physics. Resources for supercomputing are provided by NSF, NASA, DOE, and NOAA, and scientific requirements for, and the availability of, petascale computing were analyzed in UCAR (2005). An extensive database of model output is archived and made accessible to interested climate researchers through an enabling technology (the Earth System Grid) and the Program for Climate Model

Diagnosis and Intercomparison (PCMDI). With CCSP support, the U.S. element of the Climate Variability and Predictability (CLIVAR) initiated the Climate Model Evaluation Project (CMEP) to increase community-wide diagnostic research into the quality of model simulations, leading to more robust evaluations of model predictions and a better quantification of uncertainty in projections of future climate. More than 400 CMEP analysis projects are currently registered at PCMDI, and more than 200 papers have resulted and been submitted to peer review journals (Meehl et al., 2007).

Another success, again via the U.S. CLIVAR program, has been the development of CPTs, which gather observationalists, process modelers, and coupled climate modelers around specific issues or key uncertainties. They aim to link process-oriented research to modeling for the purpose of addressing key uncertainties in coupled climate models. A CPT effort on low-latitude cloud feedbacks was funded, and CPTs on gravity current entrainment and eddy mixed layer interaction are working to improve major ocean models.

10.3. Coordinate and accelerate climate modeling activities and provide relevant decision support information on a timely basis.

Output from the major U.S. climate models is available for the CCSP synthesis and assessment products and individual assessment research studies. It also provided much of the modeling results on which the IPCC synthesis was based. However, the CCSP has not made any progress in facilitating communication between modelers and the applications community about what statistics would best serve the applications communities. Although there is considerable overlap in the requirements of these two communities, the provided output has been driven largely or entirely by research needs, rather than by support of assessments and decision making.

Opportunities and Threats

An overarching concern is that inadequate resources for computing power is limiting progress in several key modeling areas, including representation of extremes and accurate representations of key climate processes and feedbacks (NRC, 2005b; UCAR, 2005). Continued progress on climate science and decision support will require large amounts of high-performance computer time, petabyte mass storage capabilities, and appropriately balanced high-speed communications networks. Based on the IPCC fourth assessment modeling contributions, the U.S. will need at least a thirtyfold increase in high-performance computing resources within the next five years. Managing and sharing data and models pose significant technical challenges.

Another concern is the lack of a national strategy for seasonal-to-interannual climate prediction, given the importance of predictions on these time scales to support climate services needed by a variety of stakeholders (NRC, 2005b). Routine, if not operational, seasonal-to-interannual climate forecasts have been issued by a number of numerical weather prediction centers around the world since the close of the Tropical Ocean Global Atmosphere program in 1994. However, these have focused on the response to El Niño Southern Oscillation (ENSO)-induced signals emanating from the tropical Pacific basin (NRC, 1996; see also June 1998 special issue of *Journal of Geophysical Research-Oceans*). A rigorous assessment of the present capability of seasonal-to-interannual climate forecasts in the United States has not been undertaken. The delivery of climate services also requires an enhanced regional climate modeling capability, and perhaps initialized climate forecasts out to decadal time scales (e.g., Hibbard et al., 2007) to improve understanding of climate change and impacts at spatial scales relevant to many stakeholders (NRC, 2005b).

Some of these issues are beginning to be addressed through the concept of the "seamless prediction paradigm," which recognizes that the traditional boundaries between weather and climate are somewhat artificial and that fundamental barriers to advancing weather and climate prediction on time scales of days to years, as well as long-standing systematic errors in weather and climate models, are partly attributable to our limited understanding of and capability to simulate the complex, multiscale interactions intrinsic to atmospheric and oceanic fluid motions (WCRP, 2005). Several seamless prediction activities are under way, although all are still in their infancy. These efforts typically fall into one of the three categories: (1) using the IPCC class models for days-to-decades prediction; (2) using numerical weather prediction class models for seasons-to-decades prediction; or (3) developing very high resolution models with mesoscale processes explicitly resolved, either globally or by nesting high-resolution regional models within global climate models. Other approaches that attempt to blur the distinction between weather and climate are also emerging, such as beginning integrations with higher resolution to satisfy weather forecast requirements, then cascading down to lower-resolution versions of the model with consistent physical parameterization schemes. The potential benefits of a stronger research focus on the seamless paradigm include skill improvement in both weather and climate forecasts; stronger collaboration and shared knowledge among the weather and climate communities working on physical parameterization schemes, data assimilation schemes, and initialization methods; and shared infrastructure and technical capabilities.

DECISION SUPPORT RESOURCES

The CCSP strategic plan identifies three types of decision making that require decision support resources: (1) public discussion and planning based on state-of-science syntheses and assessments; (2) operational adaptive management decisions undertaken by managers of natural resources and built infrastructure (i.e., climate services applications); and (3) support for policy formulation. These cover the kinds of knowledge necessary to both mitigate and adapt to climate change, although they do not explicitly account for the role of the private sector, especially business.

Progress Toward the Decision Support Goals

The overall objectives of the decision support resources cross-cutting issue appear to be sound. However, most of the reported activities follow a knowledge-driven model of interactions between science and society. This model focuses on identifying potential uses for existing observations, data, and research products, rather than defining a research agenda to support the three types of decision making. As a result, most efforts to date have been skewed toward products that the CCSP research elements were already developing. An exception is research programs in which stakeholder interaction is part of the research design, such as the RISAs and DMUU centers. Although increasing the usefulness of research products is important, it should neither replace nor eclipse the need to engage in stakeholder-driven research, an expressed but not demonstrated priority of the CCSP.

A 2004 NRC report recommended that the CCSP accelerate efforts in eight previously underemphasized areas, many of which concern meeting the needs of decision makers (e.g., human dimensions, economics, impacts, adaptation, mitigation). The report also calls for further development of decision support activities to meet the needs of local, regional, national, and international stakeholders (NRC, 2004c). However, progress toward achieving the CCSP decision support goals has been inadequate. Indeed, a bill introduced in Congress in February 2007 (HR 907) notes that the U.S. Global Change Research Program "has not produced sufficient information to meet the expressed needs of decision makers."

11.1. Prepare scientific syntheses and assessments to support informed discussion of climate variability and change and associated issues by decision makers, stakeholders, the media, and the general public.

Progress has been inadequate on the 21 CCSP synthesis and assessment products, and at the time of writing only two have been completed (see Appendix A). However, the content of these reports (CCSP, 2006b, 2007c) and the scientific effort required to carry them out provided a fundamental contribution to current national and international assessment of what is being observed as climate change. Three of the synthesis and assessment products will be aimed at decision support. The focus of products 5.1 and 5.3 is primarily to understand how currently available knowledge and information, such as seasonal climate forecasts or NASA observational data, can be made available and useful to managers and other stakeholders. These products also report early findings of application projects. Product 5.2 focuses on decision making under uncertainty. .A National Research Council review of the latter found that the draft report contains useful information for researchers, but does not address the needs of all the specified audiences, including policy and decision makers, and misses some best practice approaches for characterizing, incorporating, and communicating uncertainty (NRC, 2007c). The review recommends that CCSP assessment product 5.2 be substantially revised to address these and other issues.

Scientific syntheses of specific topics have also been developed by some of the CCSP research elements. These range from data compilations (e.g., forest management and carbon fluxes) to model predictions (e.g., predictions of seasonal-to-interannual climate variability or subdecadal climate variability, such as ENSO) (see Chapter 4). However, the research elements are targeted primarily toward answering science questions rather than informing policy and management. As a result, the potential stakeholders are largely unknown and only a few groups are using research results for decision support. The CCSP held a stakeholder workshop in November 2005 (CCSP, 2005a), but it is not clear how information and feedback obtained from that workshop helped refine the decision support research agenda.

11.2. Develop resources to support adaptive management and planning for responding to climate variability and climate change, and transition these resources from research to operational application.

Adaptive management is a governance mechanism used to shape mitigation and adaptation to climate change. However, adaptive management is not carefully defined in the

CCSP strategic plan, and the activities reported in *Our Changing Planet* seem not to consider the scholarly literature on its many facets, strengths, and limitations (e.g., Holling, 1978; Gunderson and Holling, 2002; Arvai et al., 2006). Understanding how adaptive management works is as important as producing tools to support it. Moreover, although the dynamic and integrative (i.e., across disciplines and across the science-policy divide) dimensions of adaptive management are covered in the CCSP strategic plan, in practice these dimensions are not being fully realized. Judging from the highlighted accomplishments reported in *Our Changing Planet*, the emphasis is more on the design of decision support systems based on currently available research and less on understanding their transfer and use in adaptive management. Examples include a model to forecast mosquito abundance and estimate the risk of encephalitis infection, a tool for visualizing carbon sinks and CO_2 fluctuations in U.S. ecosystems, and improvements in observation, monitoring, and prediction capabilities of the National Integrated Drought Information System (CCSP, 2006a). Although the RISA program and DMUU centers have explored interactions between knowledge producers and users in the context of managing natural resources and response to climate variability and change (Chapter 4), these programs correspond to a very small fraction of the decision support budget (Appendix B).

Ecosystems is the only research element that has made progress on adaptive management (Chapter 4). For example, climate variability is an explicit factor in decisions about fisheries management, and adaptive management strategies are also beginning to be put in place for forestry and are supported by an infrastructure that includes scientific inputs on climate variability. Greenhouse gas emissions from various agricultural or forestry practices have been investigated, but these are not yet widely considered in land management decisions. Some activities, such as nascent carbon markets, are emerging without CCSP involvement or input.

The largest activity in the transition from research to operational applications is NASA's Applied Sciences program, which has an annual budget of about $90 million (Appendix B). NASA, along with partner federal agencies, is working to integrate its spacecraft observations and model outputs into decision-making tools in 12 application areas: agricultural efficiency, air quality, aviation, carbon management, coastal management, disaster management, ecological forecasting, energy management, homeland security, invasive species, public health, and water management. An NRC review of the program's approach and results is expected in 2007. Other agencies also have programs intended to make practical use of research results (e.g., NOAA's Climate Test Bed), but they are generally not tied to the CCSP research questions.

11.3. Develop and evaluate methods (scenario evaluations, integrated analyses, and alternative analytical approaches) to support climate change policy making and demonstrate these methods with case studies.

Our Changing Planet lists several examples of efforts to develop methods and tools to support policy making, such as alternative incentive designs for practices to increase soil carbon levels (CCSP, 2005b) and if/then analyses of the potential effects of cap-and-trade policies (CCSP, 2006a). Especially promising is the development of integrated models that explore the feedbacks between coupled human-environment systems (e.g., research funded under NSF's Biocomplexity and Human and Social Dynamics programs). However, the total effort reported appears small compared to the potential demand among policy makers and stakeholders in the private sector (e.g., Western Governors' Association, 2006).

Opportunities and Threats

The CCSP's emphasis on the development of decision support tools is an important step toward supporting policy and management decisions in both the public and the private sectors. However, the research community focusing on decision support is small. To achieve the potential of this cross-cutting issue, the community will have to be built and sustained so that decision support activities can be expanded across the social sciences. Without adequate support, the field not only will stagnate but actually could regress at a time when the need for its input will be the highest.

The human contributions and responses research element has the potential to inform the decision support resources cross-cutting issue (1) by fostering social science to substantiate the creation of decision support tools and (2) by transferring knowledge that can support decision making. However, the combined management of the human contributions and responses research element and the decision support cross-cutting issue has made it more difficult to assess whether the decision support goals are being met and where critical gaps lay (see Chapter 4). A separation of the two, as envisioned in the CCSP strategic plan, would help ensure that each receives appropriate attention from the program.

COMMUNICATIONS

The Global Change Research Act of 1990 calls for the production of "information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change."[17] The communications chapter of the CCSP strategic plan focuses on transparent development of research plans and reports and two-way communication with a broad spectrum of stakeholders (CCSP, 2003). The plan recognizes that research findings are generally well reported in the scientific literature, but that relevant aspects of the findings have to be reported in formats suitable for use by diverse audiences. A comprehensive communications plan was to be developed by the end of 2003.

The CCSP communicates with stakeholders through peer-reviewed scientific literature, the CCSP web sites,[18] the news media, and outreach materials. The latter three are aimed at audiences with varying levels of understanding about climate change. In addition, the CCSP produces an annual report for Congress (*Our Changing Planet*), which is intended to be "the authoritative guide to ongoing climate science research by federal agencies" (CCSP, 2003, p. 154).

Progress Toward Communications Goals

Well-thought-out intentions expressed in the CCSP strategic plan have not yet been translated into implementation. The CCSP has neither prepared a comprehensive communications plan nor developed processes for effective delivery of relevant information and

[17] 104 Stat. 3096-3104.
[18] The family of CCSP web sites includes sites for the CCSP, the U.S. Global Change Research Program, and the U.S. Global Change Research Information office, all of which can be accessed through <http://www.climatescience.gov/>.

engagement of stakeholders. As a result, inadequate progress has been made toward achieving the two closely related communications goals:

1. *Disseminate the results of CCSP activities credibly and effectively.*
2. *Make CCSP science findings and products easily available to a diverse set of audiences.*

Communications activities to date have focused on publishing *Our Changing Planet*, maintaining and preparing content (e.g., fact sheets) for the CCSP web sites, and facilitating a 2005 workshop on decision support (CCSP, 2006a). The CCSP program office has also prepared one internal annual implementation plan and is working on another, and it is assisting CCSP agencies with their public comment processes for pending synthesis and assessment reports (Nick Sundt, personal communication, January 9, 2007).

The CCSP has not prepared a comprehensive communications plan with "specific benchmarks and time tables to allow tracking of the plan's progress." (CCSP, 2003, p. 155). Also missing is any substantive effort to implement basic communications protocols commonly used by industry and by government agencies that would accompany a comprehensive plan—such as identifying key audiences (stakeholders in relevant sectors), the information needed by those audiences, and appropriate information delivery methodologies—as well as social science research that would inform development of a robust communications strategy. Identification of key audiences is not trivial, as experience from the U.S. national assessment and RISA programs showed, but it provides the foundation for framing many aspects of decision support (NRC, 2004c).

Examples of federal agency communications strategies are widely available (e.g., Griffith and McCullough, 1990; Pedigo et al., 2005), as are best practices in scientific communication (e.g., Borchelt, 2001). The CCSP also received substantial input on communications via comments on its draft strategic plan (NRC, 2003b) and its 2005 stakeholder workshop (CCSP, 2005a). The NRC (2004c) review of the CCSP strategic plan noted that the program's increased emphasis on decision support and stakeholder communication would require increased staffing in the CCSP office to support this workload.

Some CCSP programs have succeeded in engaging stakeholders on climate issues. For example, NOAA's RISA program has done a commendable job serving as a bridge between scientists and end users, such as water or wildfire managers (see "Human Contributions and Responses to Environmental Change" in Chapter 4; Western States Water Council, 2007). However, even some CCSP agencies with strong involvement from stakeholders have not always succeeded in communicating information on climate. For example, the U.S. Department of Agriculture (USDA) conducted an extensive, well-organized outreach program pertaining to reauthorization of the 2007 Farm Bill, an omnibus act that funds most USDA activities, including the agency's role in CCSP, and is of high importance to stakeholders. Review of the public comments received by USDA in its outreach program reveals a dearth of stakeholder engagement on CCSP.[19] The program as a whole is failing to reach stakeholders in a comprehensive way at a time when stakeholder participation in natural resources and environmental planning processes is becoming commonplace in programs of other federal agencies (Pahl-Wostl, 2002; NRC, 2004a).

[19] See <http://www.usda.gov/wps/portal/!ut/p/_s.7_0_A/7_0_1UH?navid=FARM_BILL_READING&parentnav=FARM_BILL_FORUMS&navtype=RT>.

Opportunities and Threats

Many aspects of CCSP research would be useful to diverse stakeholders if they were made aware of the information or of the program itself. However, the program as a whole lacks resources and a process for communicating with the broader set of stakeholders. Two-way dialogue is important for ensuring that CCSP products are relevant to end users (NRC, 1999; 2004c) and is a requirement of the federal climate program's enabling legislation. The absence of two-way dialogue is a shortcoming of current federal climate services (Miles et al., 2006). The current agency culture of developing products that it hopes stakeholders will use (the "loading dock" model; see Dilling, 2007b, and references therein) illustrates the need for strong program leadership to manage external communications and engage stakeholders.

The CCSP's web site displays a level of development that might be expected from a newly established program, not one that has been in existence for several years. Content is sparse relative to the breadth of the program, often organized randomly, and spread across three separate web sites. A reorganization of the information into a single web site would significantly ease searches for program information. Posting additional content (e.g., abstracts of papers published with CCSP support) would also make the web site a more useful resource. Federal agency guidelines for using the web as a communications tool (e.g., HHS, 2003) could provide a useful resource for improving the CCSP web site.

The planned synthesis and assessment products should improve CCSP communications by providing content for dissemination. However, although the CCSP web site provides both the status of synthesis and assessment products and a mechanism for providing public comment, few stakeholders have been engaged in reviewing the draft prospectuses or reports (Nick Sundt, personal communication, January 9, 2007). Substantial effort will be required to raise stakeholder awareness of and participation in these products.

Only two staff are responsible for communications at the program level (Nick Sundt, personal communication, January 9, 2007). With this allocation, the program office cannot be expected to handle daily housekeeping tasks—maintaining web sites, responding to press inquiries, and coordinating public review of synthesis and assessment products—and develop and implement meaningful outreach strategies for diverse audiences.

INTERNATIONAL COOPERATION

Global climate change science is advanced through contributions from many countries. With only U.S. agency and CCSP programs, our understanding and characterization of climate change would not be nearly as advanced as it is. It would be virtually impossible to observe with adequate detail the changing climate without an important web of international collaborations. Furthermore, the United States by itself would not be able to control the growth of greenhouse gases by as much as will likely be necessary. Fortunately, many other countries support climate research, and international coordination with these countries can avoid considerable duplication of effort. The CCSP goals on international cooperation are the following:

- *Actively promote and encourage cooperation between U.S. scientists and scientific institutions and agencies and their counterparts around the globe so that they can aggregate the* *scientific and financial resources necessary to undertake research on change at all relevant scales, including both the regional and the global.*

- *Expand observing systems in order to provide global observational coverage of change in the atmosphere and oceans and on land, especially as needed to underpin the research effort.*
- *Ensure that the data collected are of the highest quality possible and suitable for both research and forecasting, and that these data are exchanged and archived on a timely and effective basis among all interested scientists and end users.*
- *Support development of scientific capabilities and the application of results in developing countries in order to promote the fullest possible participation by scientists and scientific institutions in these countries in the above research, observational, and data management efforts.*

It is difficult to review progress in scientific coordination. Nevertheless, it is clear that some of the most effective coordination is done by international programs, such as the World Climate Research Programme, the International Human Dimensions Programme, and the International Geosphere-Biosphere Programme. These programs have sponsored a host of international conferences and published numerous strategic and implementation plans. The most effective coordination of international assessment activities has been that of the IPCC, which has had strong contributions from U.S. scientists and agencies through the CCSP.

Agencies participating in the CCSP contribute much to international collaborative activities, through the participation of individual scientists and, in some cases, through provision of funding to support international program offices. The CCSP's international IWG is tasked to coordinate between the CCSP and international activities, but the committee did not see much visible impact of this coordination. For example, the IWG coordinated a large number of bilateral arrangements (e.g., the United States and Japan have approximately 100 ongoing bilateral projects),[20] but it is not clear how these arrangements facilitated advancement of the CCSP international cooperation goals. A fully effective CCSP would be expected to have a major facilitating role in connecting U.S. climate research to that of the rest of the world beyond what has already been achieved by its participating agencies.

[20] Presentation from Jonathan Padgham, U.S. Agency for International Development and international IWG, on March 20, 2007.

Part II References

Acevedo, W., J.L. Taylor, D.J. Hester, C.S. Mladinich, and S. Glavac, 2006, *Rates, Trends, Causes, and Consequences of Urban Land-Use Change in the United States*, USGS Professional Paper 1726, Reston, Vir., 206 pp.

Alexander, L.V., and 23 coauthors, 2006, Global observed changes in daily climate extremes of temperature and precipitation, *Journal of Geophysical Research*, **111**, D05109.

Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Pielke Jr., R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley, and J.M. Wallace, 2003, Abrupt climate change, *Science*, **299**, 2005-2010.

Alverson, K., and D.J. Baker, 2006, Taking the pulse of the oceans, *Science*, **314**:1657.

Anthes, R.A., R.W. Corell, G. Holland, J.W. Hurrell, M.C. MacCracken, and K.E. Trenberth, 2006, Hurricanes and global warming—Potential linkages and consequences, *Bulletin of the American Meteorological Society*, **87**, 623-628.

Arvai, J., G. Bridge, N. Dolsak, R. Franzese, T. Koontz, A. Luginbuhl, P. Robbins, K. Richards, K. Korfmacher, B. Sohngen, J. Tansey, and A. Thompson, 2006, Adaptive management of the global climate problem: Bridging the gap between climate research and climate policy, *Climatic Change*, **78**, 217-225.

Arvidson, T., S. Goward, J. Gasch, and D. Williams, 2006, Landsat-7 long-term acquisition plan: Development and validation, *Photogrammetric Engineering and Remote Sensing*, **72**, 1137-1146.

Asner, G.P., D.E. Knapp, E.N. Broadbent, P.J.C. Oliveira, M. Keller, and J.N. Silva, 2005, Selective logging in the Brazilian Amazon, *Science*, **310**, 480-482.

Aspinall, R., 2004, Modeling land use change with generalized linear models—A multi-model analysis of change between 1860-2000 in Gallatin Valley, Montana, *Journal of Environmental Management*, **72**, 91-103.

Aspinall, R., and C. Justice, eds., 2004, *A Land Use and Land Cover Change Science Strategy*, Summary of a workshop held at the Smithsonian Institution, November 19-21, 2003; available at <http://www.usgcrp.gov/usgcrp/Library/land/LULCCworkshop19-21nov2003.pdf>.

Aydin, M., W.J. DeBruyn, and E.S. Saltzman, 2002, Preindustrial atmospheric carbonyl sulfide (OCS) from an Antarctic ice core, *Geophysical Research Letters*, **29**, doi:10.1029/2002GL014796.

Baker, D.F., and 19 coauthors, 2006, TransCom 3 inversion intercomparison: Impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988-2003, *Global Biogeochemical Cycles*, **20**, GB1002.

Barford, C.C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S.P. Urbanski, L. Hutyra, S.R. Saleska, D. Fitzjarrald, and K. Moore, 2001, Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest, *Science*, **294**, 1688-1691.

Bierkens, M.F.P., and B.J.J.M. van den Hurk, 2007, Groundwater convergence as a possible mechanism for multi-year persistence in rainfall, *Geophysical Research Letters*, **34**, L02402.

Bierregaard, R.O., C. Gascon, T.E. Lovejoy, and R. Mesquita, eds., 2001, *Lessons from Amazonia: Ecology and Conservation of a Fragmented Forest*, Yale University Press, New Haven, Conn., 478 pp.

Birdsey, R.A., 2006, Carbon accounting rules and guidelines for the United States forest sector, *Journal of Environmental Quality*, **35**, 1518-1524.

Birdsey, R., K. Pregitzer, and A. Lucier, 2006, Forest carbon management in the United States: 1600-2100, *Journal of Environmental Quality*, **35**, 1461-1469.

Borchelt, R.E., 2001, Communicating the future, *Science Communication*, **23**, 194-211.

Bormann, B.T., R.W. Haynes, and J.R. Martin, 2007, Adaptive management of forest ecosystems: Did some rubber hit the road?, *BioScience*, **57**, 186-191.

Bousquet, P., and 17 coauthors, 2006, Contribution of anthropogenic and natural sources to atmospheric methane variability, *Nature*, **443**, 439-443.

Briffa, K.R., T.J. Osborn, and F.H. Schweingruber, 2004, Large-scale temperature inferences from tree rings: A review, *Global and Planetary Change*, **40**, 11-26.

Brown, D.G., K.M. Johnson, T.R. Loveland, and D.M. Theobald, 2005, Rural land use change in the conterminous U.S. 1950-2000, *Ecological Applications*, **15**, 1851-1863.

Burkett, V.R., D.A. Wilcox, R. Stottlemer, W. Barrow, D. Fagre, J. Baron, J. Price, J.L. Nielsen, C.D. Allen, D.L. Peterson, G. Ruggerone, and T. Doyle. 2005, Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications, *Ecological Complexity*, **2**, 357-394.

Butler, K.F., and T.M. Koontz, 2005, Theory into practice: Implementing ecosystem management objectives in the USDA Forest Service, *Journal Environmental Management*, **35**, 138-150.

California Department of Water Resources (CDWR), 2006, *Progress on Incorporating Climate Change into Management of California's Water Resources*, Technical Memorandum Report, Sacramento, Calif., 291 pp.

Callahan, B., E. Miles, and D. Fluharty, 1999, Policy implications of climate forecasts for water resources management in the Pacific Northwest, *Policy Sciences*, **32**, 269-293.

Carbone, G.J., and K. Dow, 2005, Water resources and drought forecasts in South Carolina, *Journal of the American Water Resources Association*, **February**, 145-155.

Cash, D.W., 2001, In order to aid in diffusing useful and practical information: Agricultural extension and boundary organizations, *Science, Technology and Human Values*, **26**:431-453.

Cash, D.W., J.C. Borck, and A.G. Patt, 2006, Countering the loading-dock approach to linking science and decision making: Comparative analysis of El Niño/Southern Oscillation (ENSO) forecasting systems, *Science, Technology and Human Values*, **31**, 465-494.

Cash, D.W., W.C. Clark, F. Alcock, N.M. Dickson, N. Eckley, D. Guston, J. Jäger, and R. Mitchell, 2003, Knowledge systems for sustainable development, *Proceedings of the National Academy of Sciences*, **100**, 8086-8091.

Changnon, S.A., 2004, Changing uses of climate predictions in agriculture: Implication for prediction research, providers, and users, *Weather and Forecasting*, **19**, 606-613.

Chase, T.N., R.A. Pielke, T.G.F. Kittel, R.R. Nemani, and S.W. Running, 2000, Simulated impacts of historical land cover changes on global climate in northern winter, *Climate Dynamics*, **16**, 93-105.

Chung, C.E., V. Ramanathan, D. Kim, and I.A. Podgomy, 2005, Global anthropogenic aerosol direct forcing derived from satellite and ground-based observations, *Journal of Geophysical Research*, **110**, D24207, doi:10.1029/2005JD006356.

Ciais, Ph., and 32 coauthors, 2005, Europe-wide reduction in primary productivity caused by the heat and drought in 2003, *Nature*, **437**, 529-533.

Claggett, P.R., C.A. Jantz, S.J. Goetz, and C. Bisland, 2004, Assessing development pressure in the Chesapeake Bay watershed: An evaluation of two land-use change models, *Earth and Environmental Science*, **94**, 129-146.

Clark, W., and L. Holliday, 2006, *Linking Knowledge with Action for Sustainable Development: The Role of Program Management - Summary of a Workshop*, Roundtable on Science and Technology for Sustainability, National Academies Press, Washington, D.C., 134 pp.

Climate Change Science Program (CCSP) and Subcommittee on Global Change Research, 2003, *Strategic Plan for the U.S. Climate Change Science Program*, Washington, D.C., 202 pp.

Climate Change Science Program, 2005a, *Climate Science in Support of Decisionmaking: Workshop Report*, November 14-16, 2005, Available at <http://www.climatescience.gov/workshop2005/finalreport/default.htm>.

Climate Change Science Program and Subcommittee on Global Change Research, 2005b, *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2006*, Washington, D.C., 215 pp.

Climate Change Science Program and Subcommittee on Global Change Research, 2006a, *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2007*, Washington, D.C., 264 pp.

Climate Change Science Program and Subcommittee on Global Change Research, 2006b, *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*, Synthesis and Assessment Product 1.1, T.R. Karl, S.J. Hassol, C.D. Miller, and W.L. Murray, eds., Washington, D.C., 164 pp.

Climate Change Science Program and Subcommittee on Global Change Research, 2007a, *Best Practice Approaches for Characterizing, Communicating and Incorporating Scientific Uncertainty in Climate Decision Making*, G. Morgan, ed., CCSP Synthesis Report 5.2 Draft Report, in review.

Climate Change Science Program and Subcommittee on Global Change Research, 2007b, *North American Carbon Budget and Implications for the Global Carbon Cycle*, Synthesis and Assessment Product 2.2, draft.

Climate Change Science Program and Subcommittee on Global Change Research, 2007c, *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations; and Review of Integrated Scenario Development and Application*, Synthesis and Assessment Product 2.1, L.E. Clarke, J.A. Edmonds, H.D. Jacoby, H.M. Pitcher, J.M. Reilly, R.G. Richels, E.A. Parson, V.R. Burkett, K. Fisher-Vanden, D.W. Keith, L.O. Mearns, H.M. Pitcher, C.E. Rosenzweig, and M.D. Webster, authors, Department of Energy, Washington, D.C., 260 pp.

Collins, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. Mckenna, B.D. Santer, and R.D. Smith, 2006, The Community Climate System Model Version 3 (CCSM3), *Journal of Climate*, **19**, 2122-2143.

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, 2000, Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature*, **408**, 184-187.

Cramer, W., and 16 coauthors, 2001, Global response of terrestrial ecosystem structure and function to CO_2 and climate change: Results from six dynamic global vegetation models, *Global Change Biology*, **7**, 357-373.

Crisp, D., and 30 coauthors, 2004, The orbiting carbon observatory (OCO) mission, *Trace Constituents in the Troposphere and Lower Stratosphere*, **34**, 700-709.

Curran, L.M., S. Trigg, A. McDonald, D. Astiani, Y.M. Hardiono, P. Siregar, I. Caniago, and E. Kasischke, 2004, Lowland forest loss in protected areas of Indonesian Borneo, *Science*, **303**, 1000-1003.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, and B.M. Wotton, 2001, Climate change and forest disturbances, *Bioscience*, **51**, 723-734.

Danabasoglu, G., R. Ferrari, and J.C. McWilliams, 2007, Sensitivity of an ocean general circulation model to a parameterization of near-surface eddy fluxes. *Journal of Climate*, in press.

Davidson, E.A., and I.A. Janssens, 2006, Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, *Nature*, **440**, 165-173.

DeFries, R.S., L. Bounoua, and G.J. Collatz, 2002, Human modification of the landscape and surface climate in the next fifty years, *Global Change Biology*, **8**, 438-458.

DeFries, R., A.J. Hansen, A. Newton, and M.C. Hansen, 2005, Isolation of protected areas in tropical forests over the last twenty years, *Ecological Applications*, **15**, 19-26.

DeFries, R., G. Asner, F. Achard, C. Justice, N. Laporte, K. Price, C. Small, and J. Townshend, 2006, Monitoring tropical deforestation for carbon credits, in *Reduction of Tropical Deforestation and Climate Change Mitigation*, P. Mountinho and S. Schwartzman, eds., Instituto de Pesquisa Ambientalda Amazonia, pp. 35-46.

Delworth, T.L., and 41 coauthors, 2006, GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics, *Journal of Climate*, Special Section, **19**, 643-674.

Denning, A.S., ed., and 40 coauthors, 2005, *Science Implementation Strategy for the North American Carbon Program*, Report of the NACP Implementation Strategy Group for the U.S. Carbon Cycle Scientific Steering Group and Interagency Working Group, University Corporation for Atmospheric Research, Boulder, Colo., 68 pp.

Diaz, H.F., J.K. Eischeid, C. Duncan, and R.S. Bradley, 2003, Variability of freezing levels, melting season indicators, and snow cover for selected high-elevation and continental regions in the last 50 years, *Climatic Change*, **59**, 33-52.

Dilling, L., 2007a, The opportunities and responsibility for carbon cycle science in the U.S., *Environmental Science and Policy*, **10**, 1-4.

Dilling, L., 2007b, Towards science in support of decision making: Characterizing the supply of carbon cycle science, *Environmental Science and Policy*, **10**, 48-61.

Dlugokencky, E.J., S. Houweling, L. Bruhwiler, K.A. Masarie, P.M. Lang, J.B. Miller, and P.P. Tans, 2003, Atmospheric methane levels off: Temporary pause or a new steady state? *Geophysical Research Letters*, **30**, doi:10.1029/2003/GL018126.

Doney, S.C., and D.M. Glover, 2005, Recent advances in the ocean carbon system, *EOS, Transactions of the American Geophysical Society*, **86**, 399-400.

Doney, S.C., ed., and 18 coauthors, 2004, *Ocean Carbon and Climate Change (OCCC): An Implementation Strategy for U.S. Ocean Carbon Research*, Report of the Carbon Cycle Science Ocean Interim Implementation Group for the U.S. Carbon Cycle Scientific Steering Group and Interagency Working Group, University Corporation for Atmospheric Research, Boulder, Colo., 108 pp.

Doney, S.C., K. Lindsay, and J.K. Moore, 2003, Global ocean carbon cycle modeling, in *Ocean Biogeochemistry: The Role of the Ocean Carbon Cycle in Global Change*, M.J.R. Fashm, ed., IGBP Global Changes Series, Springer, Berlin, pp. 217-238.

Drewnick, F., J. Schwab, J. Jayne, M. Canagaratna, D. Worsnop, and K. Demerjian, 2004, Measurement of ambient aerosol composition during the PMTACS-NY 2001 using an aerosol mass spectrometer. Part I: Mass concentrations, *Aerosol Science and Technology*, **38**, 92-103.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, and L.O. Mearns, 2000, Climate extremes: Observations, modeling and impacts, *Science*, **289**, 2068-2074.

Emanuel, K., 2005, Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, **436**, 686-688.

Fasham, M.J.R., ed., 2003, *Ocean Biogeochemistry: The Role of the Ocean Carbon Cycle in Global Change*, International Geosphere-Biosphere Programme Book Series, Springer-Verlag, New York, 297 pp.

Feddema, J.J., K.W. Oleson, G.B. Bonan, L.O. Mearns, L.E. Buja, G.A. Meehl, and W.M. Washington, 2005, The importance of land-cover change in simulating future climates, *Science*, **310**, 1674-1678.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Millero, 2004, Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans, *Science*, **305**, 362-366.

Feely, R.A., T. Takahashi, R. Wanninkhof, M.J. McPhaden, C.E. Cosca, S.C. Sutherland, and M.E. Carr, 2006, Decadal variability of the air-sea CO_2 fluxes in the equatorial Pacific Ocean, *Journal of Geophysical Research-Oceans*, **111**, C08S90.

Fogarty, M.J., and T.M. Powell, 2002, An overview of the U.S. GLOBEC Program, *Oceanography, Special Issue: U.S. GLOBEC*, **15**, 4-12.

Foley, J.A., and 18 coauthors, 2005, Global consequences of land use, *Science*, **309**, 570-574.

Follett, R.F., S.E. Samson-Liebig, J.M. Kimble, E.G. Preussner, and S.W. Waltman, 2001, Carbon sequestration under the CRP in the historic grassland soils of the USA, in *Soil Management for Enhancing Carbon Sequestration*, R. Lal and K. McSweeney, eds., Special SSSA Publication 57, Madison, Wisc., pp. 27-49.

Forest, C.E., P.H. Stone, and A.P. Sokolov, 2007, Estimated PDF of climate system properties including natural and anthropogenic forcings, *Geophysical Research Letters*, in press.

Fox, J., R.R. Rindfuss, S.J. Walsh, and V. Mishra, eds., 2003, *People and the Environment: Approaches for Linking Household and Community Surveys to Remote Sensing and GIS*, Environmental Studies Series, Kluwer Academic Publishers, Boston, Mass., 319 pp.

Friedl, M.A., D.K. McIver, J.C.F. Hodges, X.Y. Zhang, D. Muchoney, A.H. Strahler, C.E. Woodcock, S. Gopal, A. Schneider, A. Cooper, A. Baccini, F. Gao, and C. Schaaf, 2002, Global land cover mapping from MODIS: Algorithms and early results, *Remote Sensing of Environment*, **83**, 287-302.

Fung, I.Y., S.C. Doney, K. Lindsay, and J. John, 2005, Evolution of carbon sinks in a changing climate, *Proceedings of the National Academy of Sciences*, **102**, 11201-11206.

Geoghegan, J., S.C. Villar, P. Klepeis, P.M. Mendoza, Y. Ogneva-Himmelberger, R.R. Chowdhury, B.L. Turner II, and C. Vance, 2001, Modeling tropical deforestation in the Southern Yucatán peninsular region: Comparing survey and satellite data, *Agriculture, Ecosystems and Environment*, **85**, 25-46.

Giglio, L., I. Csiszar, and C.O. Justice, 2006, Global distribution and seasonality of active fires as observed with the Terra and Aqua MODIS sensors, *Journal of Geophysical Research—Biogeosciences*, **111**, G02016, doi:10.1029/.

Global Climate Observing System (GCOS), 1997, *GCOS/GTOS Plan for Terrestrial Climate-Related Observations*, Version 2.0. GCOS Report 32, World Meteorological Organization, Geneva, 103 pp.

Global Climate Observing System, 2003, *Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC*, GCOS Report 82, World Meteorological Organization, Geneva, 85 pp.

Global Climate Observing System, 2006, *Systematic Observation Requirements for Satellite-Based Products for Climate—Supplemental Details to the Satellite-Based Component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC*, GCOS Report 107, World Meteorological Organization, Geneva, 103 pp.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.H. Kohlmaier, W. Kurz, S.R. Liu, G.J. Nabuurs, S. Nilsson, and A.Z. Shvidenko, 2002, Forest carbon sinks in the Northern Hemisphere, *Ecological Applications*, **12**, 891-899.

Goodrich, G.B., and A.W. Ellis, 2006, Climatological drought in Arizona: An analysis of indicators for guiding the Governor's Drought Task Force, *The Professional Geographer*, **58**, 460-469.

Grant, R.H., and J.R. Slusser, 2004, Estimation of photosynthetic photon flux density from 368-nm spectral irradiance, *Journal of Atmospheric and Oceanic Technology*, **21**, 481-487.

Gregory, J.M., and 17 coauthors, 2005, A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration, *Geophysical Research Letters*, **32**, L12703, doi:10.1029/2005GL023209.

Griffith, S.K., and J.M. McCullough, 1990, *Strategic Communications and Training Program*, Strategic Highway Research Program, National Research Council; available at <http://pubsindex.trb.org/document/view/default.asp?lbid=363898>.

Gunderson, L., and C.S. Holling, 2002, *Panarchy: Understanding Transformations In Human And Natural Systems*, Island Press, Washington, D.C., 450 pp.

Gunderson, L., and S. Light, 2006, Adaptive management and adaptive governance in the everglades ecosystem, *Policy Science*, **39**, 323-334.

Guttikunda, S.K., Y. Tang, G.R. Carmichael, G. Kurata, L. Pan, D.G. Streets, J.-H. Woo, N. Thongboonchoo, and A. Fried, 2005, Impacts of Asian megacity emissions on regional air quality during spring 2001, *Journal of Geophysical Research*, **110**, D20301, doi:10.1029/2004JD004921.

Hansen, A.J., and D.G. Brown, eds., 2005, Land-use change in rural America: Rates, drivers, and consequences, *Ecological Applications*, **15**, 1849-1914.

Hansen, M.C., R.S. DeFries, J.R.G. Townshend, R. Sohlberg, C. Dimiceli, and M. Carroll, 2002, Towards an operational MODIS continuous field of percent tree cover algorithm: Examples using AVHRR and MODIS data, *Remote Sensing of Environment*, **83**, 303-319.

Hanson, P.J., and S.D. Wullschleger, eds., 2003, *North American Temperate Deciduous Forest Responses to Changing Precipitation Regimes*, Ecological Studies 166, Springer, New York, 472 pp.

Hartmann, H.C., T.C. Pagano, S. Sorooshian, and R. Bales, 2002, Confidence builders: Evaluating seasonal climate forecasts from user perspectives, *Bulletin of the American Meteorological Society*, **8**, 683-698.

Heald, C.L., D.J. Jacob, S. Turquety, R.C. Hudman, R.J. Weber, A.P. Sullivan, R.E. Peltier, E.L. Atlas, J.A. deGouw, C. Warneke, J.S. Holloway, J.A. Neuman, F.M. Flocke, and J.H. Seinfeld, 2006a, Concentrations and sources of organic carbon aerosols in the free troposphere over North America, *Journal of Geophysical Research*, **111**, D23S47, doi:10.1029/2006JD007705.

Heald, C.L., D.J. Jacob, R.J. Park, B. Alexander, T.D. Fairlie, R.M. Yantosca, and D.A. Chu, 2006b, Transpacific transport of Asian anthropogenic aerosols and its impact on surface air quality in the United States, *Journal of Geophysical Research*, **111**, D14310, doi:10.1029/2005JD006847.

Health and Human Services (HHS), 2003, *Research-Based Web Designs and Usability Guidelines*, U.S. Government Printing Office, Washington, D.C., 267 pp.

Hibbard, K.A., G. Meehl, P. Cox, and P. Friedlingstein, 2007, A strategy for climate change stabilization experiments, *EOS*, **88**, 217, 219, 221.

Herweijer, C., R. Seager, and E. Cook, 2006, North American droughts of the mid to late nineteenth century: A history, simulation and implication for Mediaeval drought, *The Holocene*, **16**, 159-171.

Hirsch, A.I., W.S. Little, R.A. Houghton, N.A. Scott, and J.D. White, 2004, The net carbon flux due to deforestation and forest re-growth in the Brazilian Amazon: Analysis using a process-based model, *Global Change Biology*, **10**, 908-924.

Hirschi, M., P. Viterbo, and S.I. Seneviratne, 2006, Basin-scale water-balance estimates of terrestrial water storage variations from ECMWF operational forecast analysis, *Geophysical Research Letters*, **33**, L21401.

Ho, D.T., C.S. Law, M.J. Smith, P. Schlosser, M. Harvey, and P. Hill, 2006, Measurements of air-sea gas exchange at high wind speeds in the Southern Ocean: Implications for global parameterizations, *Geophysical Research Letters*, **33**, L16611.

Hoerling, M., and A. Kumar, 2003, The perfect ocean for drought, *Science*, **299**, 691-694.

Holland, M.M., C.M. Bitz, and B. Tremblay, 2006, Future abrupt reductions in the summer Arctic sea ice, *Geophysical Research Letters*, **33**, L23503, doi:10.1029/2006GL028024.

Holling, C.S., ed., 1978, *Adaptive Environmental Assessment and Management*, John Wiley & Sons, New York, 377 pp.

Hollinger, D.Y., J. Aber, B. Dail, E.A. Davidson, S.M. Goltz, H. Hughes, M.Y. Leclerc, J.T. Lee, A.D. Richardson, C. Rodrigues, N.A. Scott, D. Achuatavarier, and J. Walsh, 2004, Spatial and temporal variability in forest-atmosphere CO_2 exchange, *Global Change Biology*, **10**, 1689-1706.

Houghton, R.A., 2003, Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000, *Tellus Series B-Chemical and Physical Meteorology*, **55**, 378-390.

Howat, I.M., I. Joughin, and T.A. Scambos, 2007, Rapid changes in ice discharge from Greenland outlet glaciers, *Science*, **315**, 1559-1561.

Huang, C., S. Kim, A. Alstatt, J.R.G. Townshend, P. Davis, K. Song, C.J. Tucker, O. Rodas, A. Yanosky, R. Clay, and J. Musinsky, 2007, Rapid loss of Paraguay's Atlantic forest and status of protected areas—A Landsat assessment, *Remote Sensing of Environment*, **106**, 460-466.

Hurtt, G.C., P.R. Moorcroft, S.W. Pacala, and S.A. Levin, 1998, Terrestrial models and global change: Challenges for the future, *Global Change Biology*, **4**, 581-590.

Integrated Global Observations of Land (IGOL) Theme Team, 2006, *Agricultural Monitoring*, Report of a workshop, Rome, Italy, March 8-11, 39 pp.; available at <http://www.fao.org/gtos/igol/docs/meeting-reports/ag-IGOL-meeting-report_v10.pdf>.

Intergovernmental Panel on Climate Change (IPCC), 2000, *Land Use, Land Use Change and Forestry*, IPCC Special Report, Cambridge University Press, Cambridge, 377 pp.

Intergovernmental Panel on Climate Change, 2007, Summary for Policymakers, in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds., Cambridge University Press, Cambridge, 18 pp.

Irwin, E.G., and J. Geoghegan, 2001, Theory, data, methods: Developing spatially explicit economic models of land use change, *Agriculture, Ecosystems and Environment*, **85**, 7-23.

Jacobs, K.L., G.M. Garfin, and M. Lenart, 2005, More than just talk: Connecting science and decision making, *Environment*, **47**, 6-22.

Jantz, C.A., S.J. Goetz, and M.K. Shelley, 2003, Using the SLEUTH urban growth model to simulate the impacts of future policy scenarios on urban land use in the Baltimore-Washington Metropolitan Area, *Environment and Planning B*, **31**, 251-271.

Johnson, J.M.F., D.C. Reicosky, R.R. Allmaras, T.J. Sauer, R.T. Venterea, and C.J. Dell, 2005, Greenhouse gas contributions and mitigation potential of agriculture in the central USA, *Soil & Tillage Research*, **83**, 73-94.

Kaufman, Y.J., O. Boucher, D. Tanré, M. Chin, L.A. Remer, and T. Takemura, 2005a, Aerosol anthropogenic component estimated from satellite data, *Geophysical Research Letters*, **32**, L17804, doi:10.1029/2005GL023125.

Kaufman, Y.J., I. Koren, L. Remer, D. Rosenfeld, and Y. Rudich, 2005b, The effect of smoke, dust and pollution aerosol on shallow cloud development over the Atlantic Ocean, *Proceedings of the National Academy of Sciences*, **102**, 11207-11212.

Kelly-Schwartz, A.C., J. Stockard, S. Doyle, and M. Schlossberg, 2004, Is sprawl unhealthy?, *Journal of Planning, Education and Research*, **24**, 184-196.

Kerr, R.A., 2005, Confronting the bogeyman of the climate system, *Science*, **310**:432-433.

King, J.S., P.J. Hanson, E. Bernhardt, P. DeAngelis, R.J. Norby, and K.S. Pregitzer, 2004, A multiyear synthesis of soil respiration responses to elevated atmospheric CO_2 from four forest FACE experiments, *Global Change Biology*, **10**, 1027-1042.

Kintisch, E., 2007, Improved monitoring of rainforests pierce haze of deforestation, *Science*, **316**, 536-537.

Kondrashov, D., S. Kravtsov, A.W. Robertson, and M.S. Ghil, 2005, A hierarchy of data-based ENSO models, *Journal of Climate*, **18**, 4425-4444.

Koster, R.D., and 24 coauthors, 2004, Regions of strong coupling between soil moisture and precipitation, *Science*, **305**, 1138-1140.

Lal, R., R.F. Follett, and J.M. Kimble, 2003, Achieving soil carbon sequestration in the United States: A challenge to the policy makers, *Soil Science*, **168**, 827-845.

Lamarque, J.-F., P. Hess, L. Emmons, L. Buja, W. Washington, and C. Granier, 2005, Tropospheric ozone evolution between 1890 and 1990, *Journal of Geophysical Research*, **110**, doi:10.1029/2004JD005537.

Latif, M., E. Roeckner, U. Mikolajewicz, and R. Voss, 2000, Tropical stabilization of the thermohaline circulation in a greenhouse warming simulation, *Journal of Climate*, **13**, 1809-1813.

Laurance, W.F., and G.B. Williamson, 2001, Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon, *Conservation Biology*, **15**, 1529-1535.

Laurance, W.F., M.A. Cochrane, S. Bergen, P.M. Fearnside, P. Delamônica, C. Barber, S. D'Angelo, and T. Fernandes, 2001, The future of the Brazilian Amazon, *Science*, **291**, 438-439.

Law, B.E., and 32 coauthors, 2002, Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, *Agricultural and Forest Meteorology*, **113**, 97-120.

Law, B.E., D. Turner, J. Campbell, O.J. Sun, S. Van Tuyl, W.D. Ritts, and W.B. Cohen, 2004, Disturbance and climate effects on carbon stocks and fluxes across western Oregon USA, *Global Change Biology*, **10**, 1429-1444.

Lemos, M.C., and B. Morehouse, 2005, The co-production of science and policy in integrated climate assessments, *Global Environmental Change*, **15**, 57-68.

Leroy, S.S., 1999, Optimal detection of global warming using temperature profiles: A methodology, *Journal of Climate*, **12**, 1185-1198.

Leshner, A.I., 2007, Celebrating polar science, *Science*, **315**, 1465.

Lin, J.C., C. Gerbig, S.C. Wofsy, B.C. Daube, D.M. Matross, V.Y. Chow, E. Gottlieb, A.E. Andrews, M. Pathmathevan, and J.W. Munger, 2006, What have we learned from intensive atmospheric sampling field programmes of CO_2? *Tellus Series B—Chemical and Physical Meteorology*, **58**, 331-343.

Madronich, S., 2006, Chemical evolution of gaseous air pollutants down-wind of tropical megacities: Mexico City case study, *Atmospheric Environment*, **40**, 6012-6018.

Manning, A.C., and R.F. Keeling, 2006, Global oceanic and land biotic carbon sinks from the Scripps atmospheric oxygen flask sampling network, *Tellus Series B—Chemical and Physical Meteorology,* **58**, 95-116.

Marland, G., T.A. Boden, and R.J. Andres, 2005, Global, regional, and national CO_2 emissions, in *Trends: A Compendium of Data on Global Change,* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn.; available at <http://cdiac.ornl.gov/trends/emis/em_cont.htm>.

Marshall, C.H., R.A. Pielke, L.T. Steyaert, and D.A. Willard, 2004, The impact of anthropogenic land cover change on Florida peninsula sea breezes and warm season sensible weather, *Monthly Weather Review*, **132**, 28-52.

Martens, D.A., W. Emmerich, J.E.T. McLain, and T.N. Johnsen, 2005, Atmospheric carbon mitigation potential of agricultural management in the southwestern USA, *Soil & Tillage Research*, **83**, 95-119.

Masson, V., F. Vimeux, J. Jouzel, V. Morgan, M. Delmotte, P. Ciais, C. Hammer, S. Johnsen, V.Y. Lipenkov, E. Mosley-Thompson, J.-R. Petit, E.J. Steig, M. Stievenard, and R. Vaikmae, 2000, Holocene climate variability in Antarctica based on 11 ice-core isotopic records, *Quaternary Research*, **54**, 348-358.

Masson-Delmotte, V., J. Jouzel, A. Landais, M. Stievenard, S.J. Johnsen, J.W.C. White, M. Werner, A. Sveinbjornsdottir, and K. Fuhrer, 2005, GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin, *Science*, **309**, 118-121.

McNie, E., R. Pielke Jr., and D. Sarewitz, 2007, Climate science policy: Lesson from the RISAs, Workshop Report, August 15-17, 2005, SPARC, Boulder, Colo., 110 pp.; available at <http://sciencepolicy.colorado.edu/sparc/research/projects/risa/risa_workshop_report.pdf>.

Meehl, G.A., R. Lukas, G.N. Kiladis, K.M. Weickmann, A. Matthews, and M. Wheeler, 2001, A conceptual framework for time and space scale interactions in the climate system, *Climate Dynamics*, **17**, 753-775.

Meehl, G.A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor, 2007, The global coupled climate multi-model dataset: A new era in climate change research, *Bulletin of the American Meteorological Society*, in press.

Miles, E.L., A.K. Snover, L.C. Whitely Binder, E.S. Sarachik, P.W. Mote, and N. Mantua, 2006, An approach to designing a national climate service, *Proceedings of the National Academy of Sciences*, **103**, 19616-19623.

Millennium Ecosystem Assessment, 2006, *Ecosystems and Human Well-Being*, Condition and Trends Working Group, Vol. I, Island Press, Washington, D.C., 76 pp.

Morehouse, B., G. Christopherson, M. Crimmins, B. Orr, J. Overpeck, T. Swetnam, and S. Yool, 2006, Modeling interactions among wildland fire, climate and society in the context of climatic variability and change in the Southwest US, in *Regional Climate Change and Variability, Impacts and Responses,* M. Ruth, K. Donaghy, P. Kirshen, eds., Edward Elgar, Cheltenham, UK, pp. 58-78.

Moran, E., and E. Ostrom, eds., 2005, *Seeing the Forest and the Trees: Human-Environment Interactions in Forest Ecosystems*, MIT Press, Cambridge, Mass, 504 pp.

Mosley-Thompson, E., L.G. Thompson, and P.-N. Lin, 2006, A multi-century perspective on 20th century climate change with new contributions from high Arctic and Greenland (PARCA) cores, *Annals of Glaciology*, **43**, 42-48.

Moss, R., E. Malone, and A. Brenkert, 2001, *Vulnerability to Climate Change: A Quantitative Approach*, PNNL-SA-33642, Pacific Northwest National Laboratory, National Technical Information Service, Springfield, Vir., 70 pp.

Murawski, S.A., and G.C. Matlock, eds., 2006, Ecosystem Science Capabilities Required to Support NOAA's Mission in the Year 2020, NOAA Technical Memorandum NMFS-F/SPO-74, Department of Commerce, Silver Spring, Md., 97 pp.

Mustard, J.F., and T.R. Fisher, 2004, Land use and hydrology, in *Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface*, G. Gutman, A.C. Janetos, C.O. Justice, E.F. Moran, J.F. Mustard, R.R. Rindfuss, D. Skole, B.L. Turner II, and M.A. Cochrane, eds., Remote Sensing and Digital Image Processing series **6**, Kluwer Academic Publishers, Boston, Mass., pp. 257-267.

National Assessment Synthesis Team, 2000, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, U.S. Global Change Research Program, Washington, D.C., 154 pp.

National Research Council (NRC), 1990, *Research Strategies for the U.S. Global Change Research Program*, National Academy Press, Washington, D.C., 291 pp.

National Research Council, 1996, *Learning to Predict Climate Variations Associated with El Niño and the Southern Oscillation: Accomplishments and Legacies of the TOGA Program*, National Academy Press, Washington, D.C., 192 pp.

National Research Council, 1998, *Adequacy of Climate Observing Systems*, National Academy Press, Washington, D.C., 50 pp.

National Research Council, 1999, *Making Climate Forecasts Matter*, National Academy Press, Washington, D.C., 192 pp.

National Research Council, 2000a, *Improving Atmospheric Temperature Monitoring Capabilities: Letter Report*, National Academy Press, Washington, D.C., 18 pp.

National Research Council, 2000b, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design*, National Academy Press, Washington, D.C., 152 pp.

National Research Council, 2000c, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part II. Implementation*, National Academy Press, Washington, D.C., 98 pp.

National Research Council, 2000d, *Reconciling Observations of Global Temperature Change*, National Academy Press, Washington, D.C., 104 pp.
National Research Council, 2001a, *A Climate Services Vision: First Steps Towards the Future*, National Academy Press, Washington, D.C., 96 pp.
National Research Council, 2001b, *Enhancing NASA's Contributions to Polar Science: A Review of Polar Geophysical Data Sets*, National Academy Press, Washington, D.C., 138 pp.
National Research Council, 2001c, *Under the Weather: Climate, Ecosystems, and Infectious Disease*, National Academy Press, Washington, D.C., 160 pp.
National Research Council, 2002a, *Abrupt Climate Change: Inevitable Surprises*, National Academy Press, Washington, D.C., 244 pp.
National Research Council, 2002b, *Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data*, National Academy Press, Washington, D.C., 100 pp.
National Research Council, 2003a, *Government Data Centers: Meeting Increasing Demands*, National Academies Press, Washington, D.C., 70 pp.
National Research Council, 2003b, *Planning Climate and Global Change Research: A Review of the Draft U.S. Climate Change Science Program Strategic Plan*, National Academies Press, Washington, D.C., 85 pp.
National Research Council, 2003c, *Review of NOAA's National Geophysical Data Center*, National Academies Press, Washington, D.C., 106 pp.
National Research Council, 2003d, *Satellite Observations of the Earth's Environment: Accelerating the Transition from Research to Operations*, National Academies Press, Washington, D.C., 182 pp.
National Research Council, 2004a, *Analytical Methods and Approaches for Water Resources Project Planning*, National Academies Press, Washington, D.C., 165 pp.
National Research Council, 2004b, *Climate Data Records from Environmental Satellites: Interim Report*, National Academies Press, Washington, D.C., 136 pp.
National Research Council, 2004c, *Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan*, National Academies Press, Washington, D.C., 96 pp.
National Research Council, 2004d, *Planning for the International Polar Year 2007-2008: Report of the Implementation Workshop*, National Academies Press, Washington, D.C., 65 pp.
National Research Council, 2004e, *Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond*, National Academies Press, Washington, D.C., 186 pp.
National Research Council, 2005a, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*, National Academies Press, Washington, D.C., 45 pp.
National Research Council, 2005b, *Improving the Scientific Foundation for Atmosphere-Land-Ocean Simulations. Report of a Workshop*, National Academies Press, Washington, D.C., 72 pp.
National Research Council, 2005c, *Review of NOAA's Plan for the Scientific Stewardship Program*, National Academies Press, Washington, D.C., 38 pp.
National Research Council, 2005d, *Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program*, National Academies Press, Washington, D.C., 150 pp.
National Research Council, 2006a, *Contributions of Land Remote Sensing for Decisions about Food Security and Human Health*, National Academies Press, Washington, D.C., 126 pp.

National Research Council, 2006b, *Preliminary Principles and Guidelines for Archiving Environmental and Geospatial Data at NOAA: Interim Report*, National Academies Press, Washington, D.C., 37 pp.

National Research Council, 2006c, *Review of Goals and Plans for NASA's Space and Earth Sciences*, National Academies Press, Washington, D.C., 74 pp.

National Research Council, 2006d, *Surface Temperature Reconstructions for the Last 2,000 Years*, National Academies Press, Washington, D.C., 160 pp.

National Research Council, 2007a, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, National Academies Press, Washington, D.C., in press.

National Research Council, 2007b, *Review of the U.S. Climate Change Science Program's Synthesis and Assessment Product 3.3, "Weather and Climate Extremes in a Changing Climate*," National Academies Press, Washington, D.C., 60 pp.

National Research Council, 2007c, *Review of the U.S. Climate Change Science Program's Synthesis and Assessment Product 5.2, "Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Climate Decision Making*," National Academies Press, Washington, D.C., 64 pp.

National Science and Technology Council (NSTC), 2006, *National Integrated Drought Information System (NIDIS) Near-Term Opportunity Plan*, Washington, D.C., 20 pp.; available at <http://usgeo.gov/docs/nto/NIDIS_NTO_2006-0925.pdf>.

Niu, G.Y., and Z.L. Yang, 2006, Assessing a land surface model's improvements with GRACE estimates, *Geophysical Research Letters*, **33**, L07401.

Norby, R.J., and 18 coauthors, 2005, Forest response to elevated CO_2 is conserved across a broad range of productivity, *Proceedings of the National Academy of Sciences*, **102**, 18052-18056.

O'Connor, R.E., B. Yarnal, K. Dow, C.L. Jocoy, and G.J. Carbonne, 2005, Feeling at risk matters: Water managers and the decision to use forecasts, *Risk Analysis*, **25**, 1265-1275.

Osborn, T.J., and K.R. Briffa, 2006, The spatial extent of 20th-century warmth in the context of the past 1200 years, *Science*, **311**, 841-844.

Pacala, S.W., and 22 coauthors, 2001, Consistent land- and atmosphere-based US carbon sink estimates, *Science*, **292**, 2316-2320.

Pagano, T.C., H.C. Hartmann, and S. Sorooshian, 2002, Factors affecting seasonal forecast use in Arizona water management: A case study of the 1997-98 El Nino, *Climate Research*, **21**, 259-269.

Pahl-Wostl, C., 2002, Participative and stakeholder-based policy design, evaluation, and modeling processes, *Integrated Assessment*, **3**, 3-14.

Pataki, D.E., R.J. Alig, A.S. Fung, N.E. Golubiewski, C.A. Kennedy, E.G. McPherson, D.J. Nowak, R.V. Pouyat, and P. Romero Lankao, 2006, Urban ecosystems and the North American carbon cycle, *Global Change Biology*, **12**, 2092-2102.

Patz, J.A., M.A. McGeehin, S.M. Bernard, K.L. Ebi, P.R. Epstein, A. Grambsch, D.J. Gubler, P. Reiter, I. Romieu, J.B. Rose, J.M. Samet, and J. Trtanj, 2000, The potential health impacts of climate variability and change for the United States, Executive Summary of the Report of the Health Sector of the U.S. National Assessment, *Environmental Health Perspectives*, **108**, 367-376.

Patz J., P. Daszak, G.M. Tabor, A. Alonso Aguirre, M. Pearl, J. Epstein, N.D. Wolfe, A. Marm Kilpatrick, J. Foufopoulos, D. Molyneux, D.J. Bradley, and members of the Working Group on Land Use Change Disease Emergence, 2004, Unhealthy landscapes: Policy recommendations on land use change and infectious disease emergence, *Environmental Health Perspectives*, **112**, 1092-1098.

Pedigo, S., R. Nahan, S. Moon, D. Gwinner, C. Brooks, and W. Butler Burt, 2005, Planning strategic communications and outreach for the solar program, in *2004 DOE Solar Energy Technologies Program Review Meeting*, Denver, Colo., October 25-28, 2004, Conference paper NREL/CP-520-37094; available at <http://www.nrel.gov/docs/fy05osti/37094.pdf>.

Pennisi, E., J. Smith, and R. Stone, 2007, Momentous changes at the poles, *Science*, **315**, 1513.

Pfister, G.G., L.K. Emmons, P.G. Hess, R. Honrath, J.-F. Lamarque, M. Val Martin, R.C. Owen, M.A. Avery, E.V. Browell, J.S. Holloway, P. Nedelec, R. Purvis, T.B. Ryerson, G.W. Sachse, and H. Schlager, 2006, Ozone production from the 2004 North American boreal fires, *Journal of Geophysical Research*, **111**, D24S07, doi:10.1029/2006JD007695.

Pielke, R.A., 2005, Land use and climate change, *Science*, **310**, 1625-1626.

Pyke, C.R., and S.J. Andelman, 2007, Land use and land cover tools for climate adaptation, *Climatic Change*, **80**, 239-251.

Ramankutty, N., and J. Foley, 1999, Estimating historical changes in land cover: North American croplands from 1850–1992, *Global Ecology and Biogeography*, **8**, 381-396.

Rapalee, G., S.E. Trumbore, E.A. Davidson, J.W. Harden, and H. Veldhuis, 1998, Soil carbon stocks and their rates of accumulation and loss in a boreal forest landscape, *Global Biogeochemical Cycles*, **12**, 687-701.

Randerson, J.T., and 16 coauthors, 2006, The impact of boreal forest fire on climate warming, *Science*, **314**, 1130-1132.

Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg, and C. Rosenzweig, 2003, U.S. agriculture and climate change: New results, *Climate Change*, **57**, 43-67.

Ren, X., H. Harder, M. Martinez, R.L. Lesher, A. Oliger, J.B. Simpas, W.H. Brune, J.J. Schwab, K.L. Demerjian, Y. He, X. Zhou, and H. Gao, 2003, OH and HO2 chemistry in the urban atmosphere of New York City, *Atmospheric Environment*, **27**, 3639-3651.

Rindfuss, R.R., S.J. Walsh, B.L. Turner II, J. Fox, and V. Mishra, 2004a, Developing a science of land change: Challenges and methodological issues, *Proceedings of the National Academy of Sciences*, **101**, 13976-13981.

Rindfuss, R.R., S.J. Walsh, B.L. Turner II, E.F. Moran, and B. Entwisle, 2004b, Linking pixels and people, in *Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface*, G. Gutman, A.C. Janetos, C.O. Justice, E.F. Moran, J.F. Mustard, R.R. Rindfuss, D. Skole, B.L. Turner II, and M.A. Cochrane, eds., Remote Sensing and Digital Image Processing Series **6**, Kluwer Academic Publishers, Boston, Mass., pp. 379-394.

Roberts, D.A., M. Keller, and J.V. Soares, 2003, Studies of land-cover, land-use, and biophysical properties of vegetation in the large scale biosphere atmosphere experiment in Amazonia (LBA), *Remote Sensing of Environment*, **87**, 377-388.

Rodwell, M.J., and T.N. Palmer, 2007, Using numerical weather prediction to assess climate models, *Quarterly Journal of the Royal Meteorological Society*, **133**, 129-146.

Rosa, E.A., R.F. York, and T. Dietz, 2004, Tracking the anthropogenic drivers of ecological footprints, *Ambio: A Journal of the Human Environment*, **33**, 509-512.

Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W.R. Wallace, B. Tilbrook, F.J. Millero, T.H. Peng, A. Kozyr, T. Ono, and A.F. Rios, 2004, The oceanic sink for anthropogenic CO_2, *Science*, **305**, 367-371.

Saleska, S.R., and 17 coauthors, 2003, Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance-induced losses, *Science*, **302**, 1554-1557.

Sarewitz, D., and R. Pielke Jr., 2007, The neglected heart of science policy: Reconciling supply of and demand for science, *Environmental Science and Policy*, **10**, 5-16.

Sarmiento, J.L., and N. Gruber, 2002, Sinks for anthropogenic carbon, *Physics Today*, **55**:30-36.

Sarmiento, J., and S. Wofsy, 1999, *A U.S. Carbon Cycle Science Plan*, Report of the Carbon and Climate Working Group for the U.S. Global Change Research Program, University Corporation for Atmospheric Research, Boulder, Colo., 69 pp.

Schaefer, H., M.J. Whiticar, E.J. Brook, V.V. Petrenko, D.F. Ferretti, and J.P. Severinghaus, 2006, Ice record of d13C for atmospheric CH_4 across the Younger Dryas-Preboreal Transition, *Science*, **313**, 1109-1112.

Schiermeier, Q., 2006, Insurers' disaster files suggest climate is culprit, *Nature*, **441**, 674-675.

Schmittner, A., 2005, Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation, *Nature*, **434**, 628-633.

Schmittner, A., M. Latif, and B. Schneider, 2005, Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations, *Geophysical Research Letters*, **32**, L23710, doi:10.1029/2005GL024368.

Seager, R., Y. Kushnir, C. Herweijer, N. Naik, and J. Velez, 2005, Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856-2000, *Journal of Climate*, **18**, 4065-4088.

Seto, K.C., and R.K. Kaufmann, 2003, Modeling the drivers of urban land use change in the Pearl River Delta, China: Integrating remote sensing with socioeconomic data, *Land Economics*, **79**, 106-121.

Shepherd, A., and D. Wingham, 2007, Recent sea-level contributions of the Antarctic and Greenland ice sheets, *Science*, **315**, 1529-1532.

Sillman, S., M.A. Carroll, T. Thornberry, B.K. Lamb, H. Westberg, W.H. Brune, I. Faloona, D. Tan, P.B. Shepson, A.L. Sumner, D.R. Hastie, C.M. Mihele, E.C. Apel, D.D. Riemer, and R.G. Zika, 2002, Loss of isoprene and sources of nighttime OH radicals at a rural site in the United States: Results from photochemical models, *Journal of Geophysical Research*, **107**, doi:10.1029/2001JD000449.

Singh, H.B., W.H. Brune, J.H. Crawford, D.J. Jacob, and P.B. Russell, 2006, Overview of the summer 2004 intercontinental chemical transport experiment—North America (INTEX-A), *Journal of Geophysical Research*, **111**, D24S01, doi:10.1029/2006JD007905.

Skole, D., and C.J. Tucker, 1993, Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Science*, **260**, 1905-1910.

Skole, D.S., C.O. Justice, A. Janetos, and J.R.G. Townshend, 1997, A land cover change monitoring program: A strategy for international effort, *Mitigation and Adaptation Strategies for Global Change*, **2**, 157-175.

Snover, A.K., A.F. Hamlet, and D.P. Lettenmaier, 2003, Climate-change scenarios for water planning studies: Pilot applications in the Pacific Northwest, *Bulletin of the American Meteorological Society*, **84**, 1513-1518.

Solow, A.R., R.F. Adams, K.J. Bryant, D.L. Legler, J.J. O'Brien, B.A. McCarl, W. Nayda, and R. Weiher, 1998, The value of improved ENSO forecasting to US agriculture, *Climatic Change*, **39**, 47-60.

Stern, N., 2007, *Stern Review: The Economics of Climate Change*, Cambridge University Press, Cambridge, UK, 579 pp.

Streets, D.G., T.C. Bond, G.R. Carmichael, S.D. Fernandes, Q. Fu, D. He, Z. Klimont, S.M. Nelson, N.Y. Tsai, M.Q. Wang, J.-H. Woo, and K.F. Yarber, 2003, An inventory of gaseous and primary aerosol emissions in Asia in the year 2000, *Journal of Geophysical Research*, **108**, doi:10.1029/2002JD003093.

Swenson, S., P.J.-F. Yeh, J. Wahr, and J. Famiglietti, 2006, A comparison of terrestrial water storage variations from GRACE with in situ measurements from Illinois, *Geophysical Research Letters*, **33**, L16401.

Tebaldi, C., R.L. Smith, D. Nychka, and L.O. Mearns, 2005, Quantifying uncertainty in projections of regional climate change: A Bayesian approach to the analysis of multimodel ensembles, *Journal of Climate*, **18**, 1524-1540.

Thompson, L.G., T. Yao, E. Mosley-Thompson, M.E. Davis, K.A. Henderson, and P.-N. Lin, 2000, A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores, *Science*, **289**, 1916-1919.

Thompson, L.G., E. Mosley-Thompson, H. Brecher, M.E. Davis, B. Leon, D. Les, T.A. Mashiotta, P.-N. Lin, and K. Mountain, 2006, Evidence of abrupt tropical climate change: Past and present, *Proceedings of the National Academy of Sciences*, **103**, 10536-10543.

Thomson, M.C., S.J. Mason, T. Phindela, and S.J. Connor, 2005, Use of rainfall and sea surface temperature monitoring for malaria early warning in Botswana, *American Journal of Tropical Medicine and Hygiene*, **73**, 214-221.

Thomson, M.C., F.J. Dobles-Reyes, S.J. Mason, R. Hagedorn, S.J. Connor, T. Phindela, A.P. Morse, and T.N. Palmer, 2006, Malaria early warning based on seasonal climate forecasts from multi-model ensembles, *Nature*, **439**, 576-579.

Trenberth, K.E., 2005, Trends and variability in column-integrated atmospheric water vapor, *Journal of Climate Dynamics*, **24**, doi:10.1007/s00382-005-0017-4.

Trenberth, K.E., T.R. Karl, and T.W. Spence, 2002, The need for a systems approach to climate observations, *Bulletin of the American Meteorological Society*, **83**, 1593-1602.

Trenberth, K.E., J.T. Overpeck, and S. Solomon, 2004, Exploring drought and its implications for the future, *EOS Transactions of the American Geophysical Union*, **85**, 27.

Trenberth, K.E., B. Moore, T.R. Karl, and C. Nobre, 2006, Monitoring and prediction of the Earth's climate: A future perspective, *Journal of Climate* (CLIVAR special issue), **19**, 5001-5008.

Truffer, M., and M. Fahnestock, 2007, Climate change: Rethinking ice sheet time scales, *Science*, **315**, 1508-1510.

University Corporation for Atmospheric Research (UCAR), 2005, *Establishing a Petascale Collaboratory for the Geosciences: Scientific Frontiers,* Report of the Ad Hoc Committee and Technical Working Group for a Petascale Collaboratory for the Geosciences, 80 pp., available at <http://www.isse.ucar.edu/HP_rick/NSA/petascale_science.pdf>.

U.S. Department of Agriculture (USDA), 2004, *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1999-2001*, Technical Bulletin No. 1907, Global Change Program Office, Office of the Chief Economist, 164 pp.; available at <http://www.usda.gov/oce/global_change/gg_inventory.htm>.

van der Werf, G.R., J.T. Randerson, L. Giglio, G.J. Collatz, P.S. Kasibhatla, and A.F. Arellano Jr., 2006, Interannual variability in global biomass burning emissions from 1997 to 2004, *Atmospheric Chemistry and Physics Discussions*, **6**, 3175-3226.

van Kerkhoff, L., and L. Lebel, 2006, Linking knowledge and action for sustainable development, *Annual Review of Environment and Resources*, **31**, 1-33.

Vaughan, D.G., and R. Arthern, 2007, Climate change: Why is it hard to predict the future of ice sheets? *Science*, **315**, 1503-1504.

Velicogna, I., and J. Wahr, 2006, Acceleration of Greenland ice mass loss in spring 2004, *Nature*, **443**, 329-331.

Verburg, P.H., and A. Veldkamp, 2005, Introduction to the special issue on spatial modeling to explore land use dynamics, *International Journal of Geographic Information Science*, **19**, 99-102.

Verschuren, D., K.R. Laird, and B.F. Cumming, 2000, Rainfall and drought in equatorial east Africa during the past 1,100 years, *Nature*, **403**, 410-414.

Walsh, S.J., and K.A. Crews-Meyer, eds., 2002, *Linking People, Place, and Policy: A GIScience Approach*, Kluwer Academic Publishers, Boston, Mass., 360 pp.

Wang, X., D.L. Mauzerall, Y. Hu, A.G. Russell, E.D. Larson, J.-H. Woo, D.G. Streets, and A. Guenther, 2005, A high-resolution emission inventory for eastern China in 2000 and three scenarios for 2020, *Atmospheric Environment*, **39**, 5917-5933.

Webster, P.J., G.J. Holland, J.A. Curry, and H.-R. Chang, 2005, Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, **309**, 1844-1846.

Western Governors' Association, 2006, *Water Needs and Strategies for a Sustainable Future*, Denver, Colo., p. 23.

Western States Water Council, 2007, Resolution urging congress and administration to support funding for federal programs to study the water resources-related impacts of climate variability and change and our ability to adapt, Position 285, Sioux Falls, SD, May 4, 2007.

Wofsy, S.C., and R.C. Harriss, 2002, *The North American Carbon Program (NACP)*, Report of the NACP Committee of the U.S. Interagency Carbon Cycle Science Program, U.S. Global Change Research Program, Washington, D.C., 56 pp.

World Climate Research Programme (WCRP), 2005, *The World Climate Research Programme Strategic Framework 2005-2015: Coordinated Observation and Prediction of the Earth System (COPES)*, WCRP-123, WMO/TD-No.1291, Geneva, Switzerland, 59 pp.

World Meteorological Organization (WMO), 2003, *Scientific Assessment of Ozone Depletion: 2002*, Global Ozone Research and Monitoring Project, Report No. 47, Geneva, 498 pp.

Wunsch, C., and R. Ferrari, 2004, Vertical mixing, energy and the general circulation of the ocean, *Annual Review of Fluid Mechanics*, **26**, 281-314.

York, R., E.A. Rosa, and T. Dietz, 2003a, Footprints on the Earth: The environmental consequences of modernity, *American Sociological Review*, **68**, 279-300.

York, R., E.A. Rosa, and T. Dietz, 2003b, STIRPAT, IPAT, and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts, *Ecological Economics*, **46**, 351-365.

Yu, H., and 17 coauthors, 2006, A review of measurement-based assessments of the aerosol direct radiative effect and forcing, *Atmospheric Chemistry and Physics*, **6**, 613-666.

Zhan, X., R. Sohlberg, J.R.G. Townshend, C. DiMiceli, M. Carroll, J.C. Eastman, M. Hansen, and R.S. DeFries, 2002, Detection of land cover changes using MODIS 250 m data, *Remote Sensing of Environment*, **83**, 336-350.

Zhang, Q.F., C.O. Justice, M.X. Jing, J. Bruner, and D.S. Wilkie, 2006, A GIS-based assessment on the vulnerability and future extent of the tropical forests of the Congo Basin, *Environmental Monitoring and Assessment*, **114**, 107-121.

Zhang, X., M.A. Friedl, C.B. Schaaf, and A.H. Strahler, 2004, Climate controls on vegetation phenological patterns in northern mid- and high latitudes inferred from MODIS data, *Global Change Biology*, **10**, 1133-1145.

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Appendixes

Appendix A
Status of CCSP Synthesis and Assessment Products

Topic	Prospectus	Final Draft	Publication
1.1 Temperature trends in the lower atmosphere—Steps for understanding and reconciling differences	2/05	3/06	5/06
1.2 Past climate variability and change in the Arctic and at high latitudes	1/07		6/08
1.3 Re-analyses of historical climate data for key atmospheric features. Implications for attribution of causes of observed change	10/06		6/08
2.1 Scenarios of greenhouse gas emissions and concentrations and review of integrated scenario development and application	12/05	12/06	7/07
2.2 North American carbon budget and implications for the global carbon cycle	2/06	3/07	7/07
2.3. Aerosol properties and their impacts on climate	7/07		9/07
2.4 Trends in emissions of ozone-depleting substances, ozone layer recovery, and implications for ultraviolet radiation exposure	2/07		6/08
3.1 Climate models: An assessment of strengths and limitations for user applications	2/06	9/07	10/07
3.2 Climate projections for research and assessment based on emissions scenarios developed through the Climate Change Technology Program	10/06		12/07
3.3 Weather and climate extremes in a changing climate. Regions of focus: North America, Hawaii, Caribbean, and U.S. Pacific islands	7/06		6/08
3.4 Abrupt climate change	1/07		6/08
4.1 Coastal elevation and sensitivity to sea level rise	12/06		12/07
4.2 Thresholds of change in ecosystems	6/07		12/07
4.3 The effects of climate change on agriculture, biodiversity, land, and water resources	12/06		12/07
4.4 Preliminary review of adaptation options for climate-sensitive ecosystems and resources	7/06		12/07
4.5 Effects of climate change on energy production and use in the United States	4/06	6/07	7/07
4.6 Analyses of the effects of global change on human health and welfare and human systems	7/06		12/07
4.7 Impacts of climate change and vulnerability on transportation systems and infrastructure: Gulf Coast study	5/06		12/07

5.1 Uses and limitations of observations, data, forecasts, and other projections in decision support for selected sectors and regions	2/06	12/07
5.2 Best practice approaches for characterizing, communicating, and incorporating scientific uncertainty in decision making	10/06	9/07
5.3 Decision support experiments and evaluations using seasonal-to-interannual forecasts and observational data	4/06	12/07

NOTE: All dates beyond 7/15/2007 are anticipated.
Source: <http://www.climatescience.gov/Library/sap/>.

Appendix B
Supplemental Information on Human Contributions and Responses

The National Research Council's (NRC's) Committee on Human Dimensions of Global Change (CHDGC) asked the nine Climate Change Science Program (CCSP) agencies with programs in the human contributions and responses research element to provide a list of relevant activities and their annual cost. Estimating their annual funding levels for human dimensions work proved difficult for every agency for two reasons:

1. Considerable ambiguity exists in what constitutes "human dimensions" work.
2. Current agency accounting systems are inadequate to make detailed cost estimates.

The boundaries of what is variously labeled "human dimensions," "human contributions and responses," and "decision support and related research on human contributions and responses" are not well defined in CCSP documents, and differences in agencies' interpretations of these terms substantially influenced their budget estimates. For the agency questionnaire, the CHDGC defined the field as covering human systems as driving forces for climate change, impacts of climate change on human systems, responses by human systems to climate change and its observed or anticipated impacts, and decision support frameworks to inform and facilitate appropriate responses.

Decision support can include any effort to provide information to inform decision making. However, the CCSP appears to have adopted a narrower definition, which restricts decision support efforts to those aimed at producing information in forms and from sources that decision makers find useful (i.e., the development of decision support tools and information must begin with a consideration of users' needs). A related but separate question is whether operational decision support—primarily a communications function—qualifies as human dimensions work. Agencies generally agreed that their budget estimates for human dimensions work would increase substantially if they included funding for decision support under its broadest definition.

Agency	Annual Budget	Example Programs
CDC	$1 K to $1 M[a]	Agency priorities include understanding the human health consequences of extreme temperature, extreme weather, climate-induced changes in vectors of human disease, and climate-induced changes in food- and water-borne infectious disease *Example program*: Developing an "Extreme Heat Events Guidebook" with the EPA and National Weather Service
USDA Forest Service	$1 K to $1 M[b]	The Resource Planning Act Assessment requires the Forest Service to address climate change in its analysis of resource status and trends across all U.S. forests and grasslands *Example program*: Incorporating climate change science into management, mitigation, and adaptation strategies for natural resources
DOE	$3 M	The Integrated Assessment Program integrates greenhouse gas emissions and actions that would affect emissions into simplified representations of the global

		climate system. The program connects the underlying Earth and climate sciences to the human dimensions and socioeconomics of future options and choices. *Example programs*: • Creation of two major integrated assessment modeling teams, at the Massachusetts Institute of Technology and the Pacific Northwest National Laboratory • Determination of the model parameter values that produce simulations with a range consistent with historical variability in economic growth and energy efficiency improvements • Development of a small number of multi-gas emissions scenarios for further research and decision support • Efforts to incorporate purchasing power parity (PPP) specifications for regional output and behavioral relationships into integrated economic and geophysical models of the economics of climate change, and to test the difference between PPP and market exchange rates specifications • Development of a spatially explicit emissions data set that would include developing countries
EPA	$1 M to $10 M[c]	Priorities include improving characterizations of the potential impacts of global change on air quality, water quality, and aquatic ecosystems to inform managers responsible for implementing Title I of the Clean Air Act and Title III (Standards and Enforcement) of the Clean Water Act. *Example programs*: • An assessment of how technology alters pollution from mobile sources • A study of the impacts of climate change on surface water users of the Roaring Fork Watershed in Colorado • A study on the impact of climate change and variability on human health • A preliminary review of adaptation options for climate-sensitive ecosystems and resources • A project on decision support systems involving climate change and public health • The development and compilation of socioeconomic scenarios • Potential costs associated with climate impacts on publicly owned treatment works • Analyses of the effects of global change on human systems and human health and welfare • Development of integrated climate and land use change scenarios for the lower 48 states
NASA	$0[d]	All programs appear to be focused on decision support *Example programs* (decision support): • The NASA-CDC Health and Environment Linked for Information Exchange, Atlanta (HELIX-Atlanta) demonstration project uses satellite observations of ozone, aerosols, and other environmental factors that can affect public health to create enhanced air quality products for emergency care providers • The SERVIR Regional Visualization and Monitoring System for Mesoamerica provides support for environmental management and disaster response by providing access to satellite and other data sets as well as a range of decision support tools
NOAA	$6.6 M	The Regional Integrated Sciences and Assessments (RISA) program funds multidisciplinary research on how climate affects resources and how climate information could assist decision makers in the region. The Sectoral Applications Research Program funds improved decision support for climate-related issues in key socioeconomic sectors.

		Example programs: • The Alaska Center for Climate Assessment and Policy seeks to quantify actual and potential impacts of changes in the seasonality of weather and climate on Alaskan people and ecosystems • The California Applications Program studies the impacts of climate variability and change in California and the surrounding area, with an eye toward improving the climate information available to decision makers in key sectors such as water, human health, and wildfire • The Carolinas Integrated Sciences and Assessments project investigates ways to present climate research that is relevant to water resource policy and to increase decision-makers' understanding of climate variability, forecast uncertainty, and risks associated with forecast failure • The Climate Impacts Group works to increase the resilience of the region to climate change through research and working with planners and policy makers to apply climate information to regional decision-making processes, particularly in the areas of water resources, aquatic ecosystems, forests, and coastal systems • The Climate Assessment for the Southwest project investigates climate variability in rural and urban areas, climate impacts on water resources, water policy, and wildland fire, and how to improve climate inputs for drought planning • The Pacific Islands RISA works in close collaboration with stakeholders in water and natural resources, agriculture, tourism, and public health to reduce vulnerability to climate-related events such as drought, floods, and tropical cyclones • The Southeast Climate Consortium is working to develop methods that can translate regional climate forecasts into local forecasts linked with crop and hydrology models in an attempt to reduce the vulnerability of agriculture, forestry, and water resources to climate variability • The Western Water Assessment provides vulnerability assessments, climate forecasts, and paleoclimate studies to water resource managers to aid in addressing issues relating to climate change and variability • An analysis of how increased or improved use of climate information can lead to better, more cost-effective water resource management • An attempt to demonstrate that climate-based hydrologic forecasts will improve water resource management • Identification of the constraints and opportunities at institutional and community levels for improving surface water management by using seasonal climate forecasts • A multidisciplinary assessment of the hydrologic and agricultural vulnerabilities of the Missouri River Basin and their economic consequences • Integration of NOAA climate forecast information into short- and long-term water resource decisions • Assessment of the impacts of drought on the economies of Colorado, Nebraska, and New Mexico • Evaluation of mechanisms for incorporating climate information into humanitarian relief and reconstruction programs • Application of a suite of satellite observation and forecast products to develop and evaluate coral bleaching forecast tools • Identification of current and future thermal stress risks of coral reefs in Southeast Asia to help develop conservation programs • Development of tools that will allow managers to strengthen the resiliency of the coral reef system
NSF	$8 M[e]	Research support is focused different aspects of decision making under uncertainty associated with climate change, as well as basic science on how people interact with natural systems in general

		Example programs under Decision Making Under Uncertainty centers: • Decision Center for a Desert City: use of models of decision science, studies of the cognitive processes by which individuals and water managers make decisions, and development of decision support tools and models to improve water management decisions in central Arizona • Climate Decision Making Center: development of methods to characterize irreducible uncertainties about climate and the future of the energy system, to evaluate decision strategies incorporating these uncertainties, and to evaluate the social consequences of management decisions • Improving Decisions in a Complex and Changing World: studies of ways to represent uncertainty for decision makers, including the best tools and methods for making these representations • Center for Research on Environmental Decisions: studies of decision processes that underlie human adaptation to uncertainty and change, particularly with relation to climate • Science Policy Assessment and Research on Climate: exploration of how climate change research agendas are developed with respect to the informational needs of decision makers, and studies of how the U.S. climate science portfolio relates to the magnitude of various sources of global change *Example basic research programs* (individual investigators): • Understanding linkages among human and biogeochemical processes in agricultural landscapes • Feedbacks between complex ecological and social models: urban landscape structure, nitrogen flux, vegetation management, and adoption of design scenarios • The dynamics of human-sea ice relationships: comparing changing environments in Alaska, Nunavut, and Greenland • Understanding and modeling the scope for adaptive management in agroecosystems in the Pampas: response to interannual and decadal climate variability and other risk factors • The role of experience in climate change detection, risk perception, and behavior • Doctoral dissertation research: multilevel modeling of household and accessibility-zone drivers of land change in the northeastern Peruvian Amazon • Disaster, resilience, and the built environment on the Gulf Coast • Improving citizen participation in deliberative decisions: understanding and evaluating different sources of knowledge • Collaborative research: globalization, deforestation, and the cattle sector of the Brazilian Amazon
USGS	$1.6 M	There are no focused programmatic efforts for human dimensions or socioeconomic research relating to climate change. However, socioeconomic research has been identified as a gap in the new USGS strategic science plan for global change activities *Example programs*: • The Land Cover Trends project documents the rates, causes, and consequences of land use and land cover change within a geographic framework for the conterminous United States between 1972 and 2000 • The Impacts of Climate Variability and Change on Transportation Systems and Infrastructure—Gulf Coast Study will identify the potential effects of climate variability and change on transportation infrastructure and systems in the central U.S. Gulf Coast. The project will develop decision support tools to assist transportation decision makers.

NOTES: CDC = Centers for Disease Control and Prevention; DOE = Department of Energy; EPA = Environmental Protection Agency; NASA = National Aeronautics and Space Administration; NOAA = National Oceanic and Atmospheric Administration; USDA = U.S. Department of Agriculture; USGS = U.S. Geological Survey.

[a]It is unclear how much of the estimate represents funding of research related to stratospheric ozone depletion, which is not an element of climate change per se. The CDC has *no* funding specifically allocated to climate change.

[b]Funding reported is limited to the Forest Service. EPA has funded additional Forest Service work on models to predict land use change and assess policy options for climate change; that work has been reported by the Forest Service land use subgroup.

[c]The distinctions in the NRC's categories for human dimensions research were difficult to apply to EPA's activities.

[d]$89.5 million was appropriated for NASA's Applied Sciences Program, which supports NASA's efforts to make the results of Earth science flight missions and research projects available to external users with specific operational requirements.

[e]An additional $9 million is estimated to support research that may not focus specifically on climate change but deals with broader aspects of human-natural system interaction.

Appendix C
Matrix to Evaluate CCSP Progress

Question	A. Data and Physical Quantities	B. Understand and Represent Processes	C. Uncertainty, Predictability, or Predictive Capabilities	D. Synthesis and Assessment	E. Risk Management and Decision Support
Atmospheric Composition					
Q 3.1. What are the climate-relevant chemical, microphysical, and optical properties, and spatial and temporal distributions, of human-caused and naturally occurring aerosols?					
Q 3.2. What are the atmospheric sources and sinks of the greenhouse gases other than CO_2 and the implications for the Earth's energy balance?					
Q 3.3. 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?					
Q 3.4. What are the characteristics of the recovery of the stratospheric ozone layer in response to declining abundances of ozone-depleting gases and increasing abundances of greenhouse gases?					
Q 3.5. What are the couplings and feedback mechanisms among climate change, air pollution, and ozone layer depletion, and their relationship to the health of humans and ecosystems?					
Climate Variability and Change					
Q 4.1. To what extent can uncertainties in model projections due to climate system feedbacks be reduced?					
Q 4.2. How can predictions of climate variability and projections of climate change be improved, and what are the limits of their predictability?					

Q 4.3. What is the likelihood of abrupt changes in the climate system such as the collapse of the ocean thermohaline circulation, inception of a decades-long mega-drought, or rapid melting of the major ice sheets?					
Q 4.4. How are extreme events, such as droughts, floods, wildfires, heat waves, and hurricanes, related to climate variability and change?					
Q 4.5. How can information on climate variability and change be most efficiently developed, integrated with non-climatic knowledge, and communicated in order to best serve societal needs?					
Water Cycle					
Q 5.1. What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?					
Q 5.2. 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?					
Q 5.3. 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?					
Q 5.4. What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?					
Q 5.5. How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?					

Land Use/Land Cover Change					
Q 6.1. What tools or methods are needed to better characterize historic and current land use and land cover attributes and dynamics?					
Q 6.2. What are the primary drivers of land-use and land-cover change?					
Q 6.3. What will land use and land cover patterns and characteristics be 5 to 50 years into the future?					
Q 6.4. How do climate variability and change affect land use and land cover, and what are the potential feedbacks of changes in land use and land cover to climate?					
Q 6.5. What are the environmental, social, economic, and human health consequences of current and potential land use and land cover change over the next 5 to 50 years?					
Carbon Cycle					
Q 7.1. What are the magnitudes and distributions of North American carbon sources and sinks on seasonal-to-centennial time scales, and what are the processes controlling their dynamics?					
Q 7.2. What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?					
Q 7.3. What are the effects on carbon sources and sinks of past, present, and future land use change and resource management practices at local, regional, and global scales?					
Q 7.4. How do global terrestrial, oceanic, and atmospheric carbon sources and sinks change on seasonal-to-centennial time scales, and how can this knowledge be integrated to quantify and explain annual global carbon budgets?					
Q 7.5. What will be the future atmospheric concentrations of carbon dioxide, methane, and other carbon-containing greenhouse gases, and how will terrestrial and marine carbon sources and sinks change in the future?					

Q 7.6. How will the Earth system, and its different components, respond to various options for managing carbon in the environment, and what scientific information is needed for evaluating these options?					
Ecosystems					
Q 8.1. What are the most important feedbacks between ecological systems and global change (especially climate), and what are their quantitative relationships?					
Q 8.2. What are the potential consequences of global change for ecological systems?					
Q 8.3. What are the options for sustaining and improving ecological systems and related goods and services, given projected global changes?					
Human Contributions and Responses					
Q 9.1. What are the magnitudes, interrelationships, and significance of primary human drivers of and their potential impact on global environmental change?					
Q 9.2. 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?					
Q 9.3. How can the methods and capabilities for societal decision making under conditions of complexity and uncertainty about global environmental variability and change be enhanced?					
Q 9.4. What are the potential human health effects of global environmental change, and what climate, socioeconomic, and environmental information is needed to assess the cumulative risk to health from these effects?					

Appendix D
Workshop Participants

Ana Barros, Duke University
William Brennan, National Oceanic and Atmospheric Administration
Dan Brown, University of Michigan
Antonio Busalacchi, University of Maryland
John Carberry, E.I. du Pont de Nemours & Company
Keya Chatterjee, World Wildlife Fund - U.S.
Paul Crutzen, Scripps Institution of Oceanography
Thomas Delworth, NOAA Geophysical Fluid Dynamics Laboratory
J.R. DeShazo, University of California, Los Angeles
Robert Dickinson, Georgia Institute of Technology
Kirstin Dow, University of South Carolina
Manvendra Dubey, Los Alamos National Laboratory
Dara Entekhabi, Massachusetts Institute of Technology
Jay Fein, National Science Foundation
Gregg Garfin, University of Arizona
Mary Glackin, National Oceanic and Atmospheric Administration
Lisa Goddard, Columbia University
Scott Goetz, Woods Hole Research Center
Tony Haymet, Scripps Institution of Oceanography
Eileen Hofmann, Old Dominion University
James Hurrell, National Center for Atmospheric Research
Jeanine Jones, California Department of Water Resources
Christopher Justice, University of Maryland
Jack Kaye, National Aeronautics and Space Administration
Ralph Keeling, Scripps Institution of Oceanography
Charles Kennel, Scripps Institution of Oceanography
Charles Kolstad, University of California, Santa Barbara
Ian Kraucunas, The National Academies
Maria Carmen Lemos, University of Michigan
Anne Linn, The National Academies
Diana Liverman, Oxford University
James Mahoney, National Oceanic and Atmospheric Administration, retired
Paola Malanotte-Rizzoli, Massachusetts Institute of Technology
Chad McNutt, National Oceanic and Atmospheric Administration
Ellen Mosley-Thompson, Ohio State University
Richard Moss, University of Maryland and United Nations Foundation
Steve Murawski, National Oceanic and Atmospheric Administration
Veerabhadran Ramanathan, Scripps Institution of Oceanography
Chet Ropelewski, Lamont-Doherty Earth Observatory
Guido Salvucci, Boston University
Peter Schultz, Climate Change Science Program Office
Jeffrey Severinghaus, Scripps Institution of Oceanography

Steven Sherwood, Yale University
David Skole, Michigan State University
Anthony Socci, American Meteorological Society
Allen Solomon, U.S. Department of Agriculture
Paul Stern, The National Academies
Susan Trumbore, University of California, Irvine
Brad Udall, NOAA Earth System Research Laboratory
Michael Walsh, Chicago Climate Exchange, Inc.
Bruce Wielecki, NASA Langley Research Center
T. Stephen Wittrig, BP

Appendix E
Biographical Sketches of Committee Members

Veerabhadran Ramanathan, *chair*, is distinguished professor of atmospheric and climate sciences and the Victor C. Alderson Professor of Applied Ocean Sciences at the Scripps Institution of Oceanography. He also directs two research centers at Scripps: the Center for Clouds, Chemistry, and Climate; and the Center for Atmospheric Sciences. Dr. Ramanathan earned his Ph.D. in planetary atmospheres at the State University of New York at Stony Brook. His research focuses on understanding how atmospheric gases, clouds, and aerosols regulate the planetary greenhouse effect, solar radiative heating, and climate. In the mid-1970s he identified the strong greenhouse effect of chlorofluorocarbons and other man-made trace gases. His recently completed Indian Ocean Experiment led to the discovery of the South Asian brown cloud and its impact on regional climate, and to the initiation of a United Nations-sponsored research program to study the impact of brown clouds worldwide. His current research focuses on the use of miniaturized instruments on unmanned aircraft to understand how the planet regulates its albedo. Dr. Ramanathan is the recipient of many awards for his research and international leadership, including the American Meteorological Society Rossby Medal, the Royal Netherlands Academy of Sciences Buys Ballot Medal, and the Volvo environment prize. He is an active participant in national and international advisory committees concerned with climate and air pollution, and has served on the National Research Council (NRC) Committee on Radiative Forcing Effects of Climate, the Climate Research Committee, and the Board on Global Change. He is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, the Pontifical Academy of Sciences, the Academia Europaea, and the Third World Academy of Sciences.

John B. Carberry is director of environmental technology at the DuPont Company. He holds an M.E. in chemical engineering from Cornell University and an M.B.A. from the University of Delaware. He is also a registered professional chemical engineer in Delaware. Although his early career focused on developing chemical processes or new products, he is currently analyzing environmental issues to help set policy or develop business programs for his company. In that capacity, he has participated in environmental assessments and formulated performance metrics for sustainability. He has also participated in a number of climate change-related activities, including the mid-Atlantic assessment of the environment. Mr. Carberry has served on a number of committees dealing with performance metrics and the environment, most notably the NRC Committee on Metrics for Global Change Research, the Committee on Novel Approaches to the Management of Greenhouse Gas (GHG) Emissions from Energy Systems, and the Committee on the Industrial Environment Performance Metrics: Opportunities and Challenges. He is a fellow of the American Institute for Chemical Engineering.

Robert E. Dickinson is a professor in the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. He received his Ph.D. in meteorology from the Massachusetts Institute of Technology (MIT). Dr. Dickinson's research interests are in climate modeling, global change research, natural and anthropogenic forcing of climate variations, and land-atmosphere interactions in large-scale models. Dr. Dickinson has received a number of awards for his work in these areas, including the American Geophysical Union's Roger Revelle Medal and the

American Meteorological Society's Rossby Award, Jule G. Charney Award, and Meisinger Award. He has also participated in a number of climate-related committees, including the Climate Variability and Predictability Programme, the International Global Carbon Project (of the International Geosphere-Biosphere Programme, International Human Dimensions Programme, and World Climate Research Programme), and the NRC Committee on the Science of Climate Change. Dr. Dickinson is past president of the American Geophysical Union (AGU), and a member of the National Academy of Engineering and the National Academy of Sciences.

Eileen E. Hofmann is a professor in the Department of Ocean, Earth and Atmospheric Sciences and a member of the Center for Coastal Physical Oceanography at Old Dominion University. She received her Ph.D. in marine sciences and engineering from North Carolina State University in 1980. Her research interests are in physical-biological interactions in marine ecosystems, climate control of diseases of marine shellfish populations, descriptive physical oceanography, and mathematical modeling of marine ecosystems. Dr. Hofmann has worked in a variety of marine environments, the most recent being the continental shelf region off the west Antarctic Peninsula. She currently chairs the Southern Ocean Global Ocean Ecosystem Dynamics (SO GLOBEC) Planning Group and is an ex-officio member of the U.S. and International GLOBEC science steering committees. Dr. Hoffman has served on a number of NRC committees concerned with oceanography and ecology, including the Ocean Studies Board, the Committee on Ecosystem Management for Sustainable Marine Fisheries, and the Ecology Panel. She also brings expertise in evaluating research progress, having recently served on the NRC Committee on Metrics for Global Change Research.

James W. Hurrell is director of the Climate and Global Dynamics Division at the National Center for Atmospheric Research (NCAR). Although most of his professional career has been at NCAR, he spent a year as a visiting scientist at the U.K. Hadley Centre for Climate Prediction and Research in 1999. Dr. Hurrell received his Ph.D. in atmospheric science from Purdue University. His research interests focus on climate variability and anthropogenic climate change. Dr. Hurrell has contributed to national and international efforts on climate variability and change, including the Intergovernmental Panel on Climate Change (IPCC), and U.S. Climate Variability and Predictability committees and panels. He also testified to the U.S. Senate Committee on Energy and Natural Resources on climate change science and economics. He is a fellow of the Royal Meteorological Society, a fellow of the American Meteorological Society, and a recipient of its Clarence Leroy Meisinger Award.

Jeanine A. Jones is a principal engineer and interstate resources manager at the California Department of Water Resources. She received her M.S. in civil engineering from the California State University, Sacramento, and is a registered civil engineer in California and Nevada. Ms. Jones was responsible for preparation of the 1998 update of the California Water Plan and the 2000 Governor's Advisory Drought Planning Panel report. She also participated in negotiations for the 2003 Colorado River Quantification Settlement Agreement and related agreements with relevant states and local agencies, and currently participates in the Colorado River Basin States negotiations over drought and shortage management. Her statewide planning and drought management responsibilities included actions to inform the public about California drought vulnerability and to mitigate its effects. Such actions require the collection and analysis of regional data on parameters of interest to the Climate Change Science Program, including land use, water use, water supply, and surface and groundwater hydrology. Ms. Jones has served on the Colorado River Board of California and on a variety of committees of the Western States Water Council. She was also a governor's liaison to the Western Water Policy Review Advisory Commission.

Christopher O. Justice is director of research and a professor in the Department of Geography at the University of Maryland. He holds a Ph.D. in geography from Reading University (U.K.). Dr. Justice has research interests in land use and land cover change, global change, remote sensing, satellite-based fire monitoring, and terrestrial observing systems. He is the project scientist for NASA's Land Cover and Land Use Change Program and the Fire Implementation Team leader for the Global Observation of Forest Cover project, which is part of the Global Terrestrial Observing System. He is also responsible for developing the Moderate Resolution Imaging Spectroradiometer (MODIS) fire product and rapid response system, a decision-making tool for resource managers. Dr. Justice is a former member of the scientific steering committee for the International Geosphere-Biosphere Programme Data and Information System and the NRC Committee on Earth Studies. He is a current member of the Integrated Global Observation of Land theme, which is part of the Integrated Global Observing Strategy.

Roger E. Kasperson is a research professor and distinguished scientist at Clark University. While at Clark University, he also directed the Stockholm Research Institute from 1999 to 2002. He holds a Ph.D. in geography from the University of Chicago. He has written widely on issues connected with risk analysis and communication, global environmental change, and environmental policy. Dr. Kasperson has served as a consultant or adviser to federal agencies and private entities on energy and environmental issues. Notable committee appointments include the Potsdam Institute of Climate Change Research Science Advisory Board, the U.K. Tyndall Institute for Climate Change Scientific Advisory Committee, and the NRC Committee on the Human Dimension of Global Change. He has been honored for his hazards research by the Association of American Geographers and was made a fellow of the American Association for the Advancement of Science and the Society for Risk Analysis for his contributions to the field of risk analysis. He is a member of the National Academy of Sciences.

Charles D. Kolstad is the Donald Bren Professor of Environmental Economics and Policy at the University of California, Santa Barbara, where he holds joint appointments in the Bren School of Environmental Science and Management and the Department of Economics. He received his Ph.D. in economics and operations research from Stanford in 1982. Dr. Kolstad's research interests are in environmental and natural resource economics, with a focus on environmental regulation and valuation. He is actively engaged in the economics of climate change and has a long-standing interest in energy markets. He was a participant in the U.S.-EU High-Level Transatlantic Dialogue on Climate Change in 2005 and is a lead author in the current assessment of the IPCC. Dr. Kolstad has been a member of several NRC committees concerned with climate, energy, and measuring program performance, including the Committee for Review of the U.S. Climate Change Science Program Strategic Plan, the Committee on Building a Long-Term Environmental Quality Research and Development Program in the U.S. Department of Energy, and the Board on Energy and Environmental Systems.

Maria Carmen Lemos is an assistant professor of natural resources and environment at the University of Michigan and a senior policy analyst at the Udall Center for Studies of Public Policy at the University of Arizona. She holds a Ph.D. in political science from the Massachusetts Institute of Technology. Her research interests focus on the use of technical and scientific knowledge in environmental policy making, especially in less developed countries, the impact of technocratic decision making on democracy and equity, public participation in policy making, and the human dimensions of global change. Dr. Lemos has contributed to a number of national and international efforts related to climate change, including the Intergovernmental Panel on Climate Change fourth assessment (chapter on industry, settlement, and society) and CCSP decision support systems on seasonal-to-interannual forecasts and the carbon cycle.

Paola Malanotte-Rizzoli is a professor in the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology. She is also director of the Joint Program in Oceanography and Ocean Engineering at MIT and the Woods Hole Oceanographic Institution. Dr. Malanotte-Rizzoli received her first Ph.D. in theoretical physics from the University of Padua (Italy) and her second Ph.D. in physical oceanography from the Scripps Institution of Oceanography. Her research interests are in modeling ocean circulation with application to specific basins, constraining ocean models with observations, modeling Black Sea ecosystems, and studying tropical-subtropical interactions in the tropical Atlantic, with emphasis on coupled ocean-atmosphere modes of variability from seasonal-to-decadal time scales. She also has practical interests in mitigating the impact of sea level rise and has been involved in a project to build tidal gates in Venice since 1995. She is a former president of the International Association for the Physical Sciences of the Ocean, a former member of the NSF Advisory Committee for the Geosciences, and a current member of the NRC Panel on Climate Variability and Change. She is a fellow of the American Geophysical Union and the American Meteorological Society.

Ellen S. Mosley-Thompson is a professor of climatology in the Department of Geography, and a research scientist at the Byrd Polar Research Center at the Ohio State University. She holds a Ph.D. in atmospheric science (geography) from Ohio State University. Her research focuses on paleoclimate reconstructions from chemical and physical properties preserved in ice cores collected from Antarctica, Greenland, China, Africa, and Peru. Dr. Mosley-Thompson has served on a number of NRC committees concerned with climate and polar regions, including the Committee on Glaciology, the Polar Research Board, and the Board on Global Change. She is a fellow of the American Association for the Advancement of Science and a member of that association's steering group for geology and geography.

Guido D. Salvucci is a professor and chair of the department of Earth Sciences at Boston University. He received his Ph.D. in hydrology from the Massachusetts Institute of Technology. His research focuses on coupled atmospheric water and energy balance processes, vadose zone hydrology, stochastic hydrology, and estimation of evapotranspiration and the water budget at large spatial scales through remote sensing. Dr. Salvucci has been active on hydrology committees and workshops, including the Consortium of Universities for the Advancement of Hydrologic Science's Standing Committee on Hydrologic Science, the NRC Committee to Review the GAPP Science and Implementation Plan, the Science Steering Group for the NASA Water Cycle Initiative, and the NRC workshop on Groundwater Fluxes Across Interfaces. He is a recipient of the American Geophysical Union's James B. Macelwane Medal and is also a fellow of that society.

Susan E. Trumbore is a professor in the Department of Earth System Science and director of the Institute for Geophysics and Planetary Physics, Irvine Branch, at the University of California, Irvine. She received her Ph.D. in geochemistry from Columbia University. Her research interests are in the application of isotopes and tracers to problems in ecology, soil biogeochemistry, and terrestrial carbon cycling. Dr. Trumbore was an author of the IPCC report on land use, land use change, and forestry. In addition to her teaching and scientific pursuits, she is interested in the evaluation of research programs and served on the NRC Committee on Metrics for Global Change Research. She is a fellow of the American Association for the Advancement of Science and of the American Geophysical Union and a former president of AGU's biogeochemistry section.

T. Stephen Wittrig is director of advanced technologies at BP. He received his Ph.D. in chemical engineering from the California Institute of Technology. Dr. Wittrig is responsible for BP's academic and external technology programs in Russia and China. His current work focuses on developing a long-term technology strategy for BP, emphasizing clean energy technologies (solar, wind, hydrogen, and combined-cycle-gas-turbine power generation) and techniques for sequestering CO_2 in depleted oil reserves. In previous positions at Amoco, he helped develop strategies for converting gas to liquids and oxygenates and for implementing chemical technologies, managed the engineering and process evaluation group for new chemical products development, and led a team to develop new reactor technology for converting methane to syngas. Dr. Wittrig was a member of the NRC committee that reviewed the CCSP strategic plan in 2004.

Appendix F
Acronyms and Abbreviations

CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CCRI	Climate Change Research Initiative
CCSP	Climate Change Science Program
CERES	Clouds and the Earth's Radiant Energy System
CFCs	chlorofluorocarbons
CHDGC	Committee on Human Dimensions of Global Change
CLIVAR	Climate Variability and Predictability
CMEP	Climate Model Evaluation Project
CPT	climate process team
DMUU	Decision Making Under Uncertainty
DOE	Department of Energy
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System
GCOS	Global Climate Observing System
GEOSS	Global Earth Observing System of Systems
GOES-R	Geostationary Operational Environmental Satellite Series R
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
Hydros	Hydrosphere State
IPCC	Intergovernmental Panel on Climate Change
IRI	International Research Institute for Climate and Society
IWG	interagency working group
LTER	Long-Term Ecological Research
MIT	Massachusetts Institute of Technology
MODIS	Moderate-Resolution Imaging Spectroradiometer
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NSF	National Science Foundation
OCCP	Ocean Carbon and Climate Change Program
PCMDI	Program for Climate Model Diagnosis and Intercomparison
RISA	Regional Integrated Sciences and Assessments
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SNOTEL	Snowpack Telemetry
SORCE	Solar Radiation and Climate Experiment
TAO	Tropical Atmosphere Ocean
TRMM	Tropical Rainfall Measuring Mission
USDA	U.S. Department of Agriculture

USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
UV	ultraviolet
VIIRS	Visible Infrared Imager/Radiometer Suite