CHAPTER 6

CLIMATE VARIABILITY AND CHANGE

from the

Strategic Plan
for the
Climate Change Science Program

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

Review draft dated 11 November 2002

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11 November 2002

Dear Colleague,

The Climate Change Science Program will hold the U.S. Climate Change Science Program Planning Workshop for Scientists and Stakeholders at the Marriott Wardman Park Hotel in Washington, D.C., from 3-5 December 2002. The purpose of the Workshop is to provide a comprehensive review of the discussion draft of the Strategic Plan for U.S. climate change and global change research. This Workshop will offer extensive opportunities for the scientific and stakeholder communities to provide comment and input to the Climate Change Science Program Strategic Plan. When finalized by April 2003, the Strategic Plan will provide the principal guidance for U.S. climate change and global change research during the next several years, subject to revisions as appropriate to respond to newly developed information and decision support tools.

We are writing to request your comments on the discussion draft of the Climate Change Science Program Strategic Plan. Comments on all elements of the plan from all communities are essential in order to improve the plan and identify gaps. In your review, we ask you to provide a perspective on the content, implications, and challenges outlined in the plan as well as suggestions for any alternate approaches you wish to have considered, and the types of climate and global change information required by policy makers and resource managers. We also ask that you comment on any inconsistencies within or across chapters, and omissions of important topics. For any shortcomings that you note in the draft, please propose specific remedies. To participate in the review it is not necessary that you review the entire plan.

We ask that comments be submitted by E-mail to <comments@climatescience.gov>. All comments submitted by 13 January 2003 will be posted on the <http://www.climatescience.gov> website for public review. While we are unable to promised detailed responses to individual comments, we confirm that all submitted comments will be given consideration during the development of the final version of the Strategic Plan.

Attached to this letter are instructions and format guidelines for submitting review comments. Following the instructions will ensure that your comments are properly processed and given appropriate consideration. If you wish to distribute copies of the plan to colleagues to participate in the review, please provide them with a copy of this letter as well as the attached instructions and format guidelines. We have posted the plan on the workshop website at <http://www.climatescience.gov>. PDF files for individual chapters of the plan can be downloaded from this site. If you have any questions, please contact: Sandy MacCracken at 1-202-419-3483 (voice), 1-202-223-3065 (fax), or via the address in the footer below.

We appreciate your contribution of time and expertise to this review, and look forward to your response.

Sincerely,

James R. Mahoney, Ph.D.
Assistant Secretary of Commerce for Oceans and Atmosphere, and
Director, U.S. Climate Change Science Program

Instructions For Submission of Strategic Plan Review Comments

Thank you for participating in the review process. Please follow the instructions for preparing and submitting your review. Using the format guidance described below will facilitate our processing of reviewer comments and assure that your comments are given appropriate consideration. An example of the format is also provided. Comments are due by **13 January, 2003**.

- Select the chapter(s) or sections of chapters which you wish to review. It is not necessary that you review the entire plan. In your comments, please consider the following issues:
    - **Overview**: overview on the content, implications, and challenges outlined in the plan;
    - **Agreement/Disagreement**: areas of agreement and disagreement, as appropriate;
    - **Suggestions**: suggestions for alternative approaches, if appropriate;
    - **Inconsistencies**: inconsistencies within or across chapters;
    - **Omissions**: omissions of important topics;
    - **Remedies**: specific remedies for identified shortcomings of the draft plan;
    - **Stakeholder climate information**: type of climate and global change information required by representative groups;
    - **Other:** other comments not covered above.
- Please do not comment on grammar, spelling, or punctuation. Professional copy editing will correct deficiencies in these areas for the final draft.
- Use the format guidance that follows for organizing your comments.
- Submit your comments by email to <comments@climatescience.gov> by 13 January, 2003.

Format Guidance for Comments

Please provide background information about yourself on the first page of your comments: your name(s), organization(s), area of expertise(s), mailing address(es), telephone and fax numbers, and email address(es).

- Overview comments on the chapter should follow your background information and should be numbered.
- Comments that are specific to particular pages, paragraphs or lines of the chapter should follow your overview comments and should <u>identify the page and line number</u>s to which they apply.
- Comments that refer to a table or figure should identify the table or figure number. In the case of tables, please also identify the row and column to which the comment refers.
- Order your comments sequentially by page and line number.
- At the end of each comment, please insert your name and affiliation.

Format Example for Comments

I. Background Information

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II. Overview Comments on Chapter 5: Atmospheric Composition

First Overview Comment: (Comment)
Reviewer's name, affiliation: John Doe, University College

Second Overview Comment: (Comment)
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III. Specific Comments on Chapter 5: Atmospheric Composition

Page 57, Line 5: (Comment)
John Doe, University College

Page 58, Line 32 - Page 59, Line 5: (Comment)
John Doe, University College

Table 1-4, Row 3, Column 6: (Comment)
John Doe, University College

Please send comments by email to <comments@climatescience.gov>

Foreword

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

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

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

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

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

James R. Mahoney, Ph.D.
Assistant Secretary of Commerce for Oceans and Atmosphere, and
Director, Climate Change Science Program

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of the
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CHAPTER 6

CLIMATE VARIABILITY AND CHANGE

This chapter's contents…

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

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

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

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

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

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

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

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

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

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

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

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

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

STATE OF KNOWLEDGE

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

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

High priority research will focus on several sub-questions:

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

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

RESEARCH NEEDS

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

PRODUCTS AND PAYOFFS

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

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

STATE OF KNOWLEDGE

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

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

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

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

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

RESEARCH NEEDS

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

PRODUCTS AND PAYOFFS

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

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

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

STATE OF KNOWLEDGE

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

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

RESEARCH NEEDS

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

PRODUCTS AND PAYOFFS

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

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

STATE OF KNOWLEDGE

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

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

RESEARCH NEEDS

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

PRODUCTS AND PAYOFFS

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

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

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

STATE OF KNOWLEDGE

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

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

RESEARCH NEEDS

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

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

PRODUCTS AND PAYOFFS

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

Key Linkages

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

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

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