CHAPTER 4

Climate Variability and Change

CHAPTER CONTENTS

Climate variability and change profoundly influence social and natural environments throughout the world, with consequent impacts on natural resources and industry that can be large and far-reaching. For example, seasonal-to-interannual climate fluctuations strongly affect the success of agriculture, the abundance of water resources, and the demand for energy, while long-term climate change may alter agricultural productivity, land and marine ecosystems, and the resources that these 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 will serve the nation by providing improved knowledge to enable more scientifically informed decisions across a broad array of climate-sensitive sectors.

Climate research has indicated that, globally, it is very likely that the 1990s were the warmest decade in the instrumental record, which extends back to the 1860s (see Figure 4-1); large climate changes can occur within decades or less, yet last for centuries or longer; and the increase in Northern Hemisphere surface temperatures during the 20th century likely exceeds the natural variability of the past 1,000 years (IPCC, 2001a,d). Placing instrumental records in the context of longer term variability through paleoclimate analyses has played a key role in these findings. Moreover, observational evidence together with model simulations incorporating a comprehensive suite of natural and anthropogenic forcings indicate that "…the changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability" (see Figure 4-2) (NRC, 2001a). All climate models used in the most recent Intergovernmental Panel on Climate Change (IPCC) assessment project that global mean temperatures will continue to increase in the 21st century and will be accompanied by other important environmental changes, such as sea-level rise, although the magnitudes of the projected changes vary significantly depending on the specific models and emissions scenarios (IPCC, 2001a,d).

Climate 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

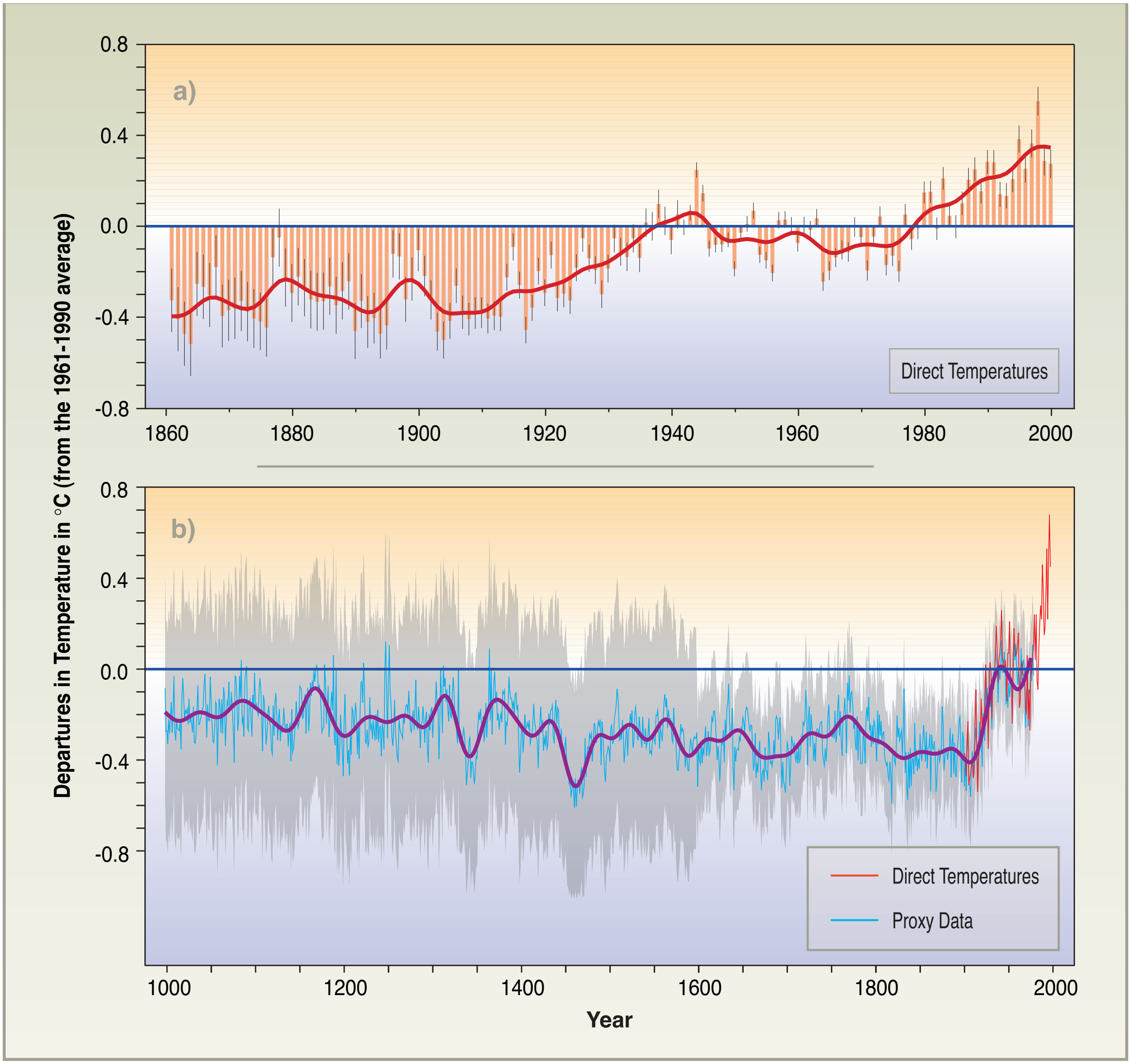

Figure 4-1: *Top Panel*: Changes in the Earth's surface temperature over the period of direct temperature measurements (1860–2000). The departures from global mean surface temperature are shown each year by the red bars (with *very likely* ranges as thin black lines) and approximately decade-by-decade by the continuous red line. *Bottom Panel*: Proxy data (year-by-year blue line with *very likely* ranges as gray band, 50-year-average purple line) merged with the direct temperature measurements (red line) for the Northern Hemisphere. The proxy data consist of tree rings, corals, ice cores, and historical records that have been calibrated against thermometer data. Source: IPCC (2001d). For more information, see Annex C.

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 an increased understanding of the mechanisms that produce ENSO, has led to useful climate forecasts at lead times of up to several months. This developing capability has given the world an unprecedented opportunity to prepare for and reduce vulnerabilities to the impacts of ENSO, and thereby provided direct social and economic benefits as returns on climate science investments.

Research supported by the U.S. Global Change Research Program (USGCRP) has played a leading role in these scientific advances, which have provided new climate information to help society better anticipate and prepare for potential effects of climate variability and change. While progress in this area has been impressive, there still remain many unresolved questions about key aspects of the climate system, including some that have enormous societal and environmental implications. For example, we are just beginning to understand how climate variability and change influence the local and regional occurrence and severity of extreme events such as hurricanes, floods, droughts, and wildfires. In many parts of the world, including the United States, such events are tied to ENSO variability, which has undergone significant changes in the past, perhaps in response to relatively subtle changes in forcing. A better

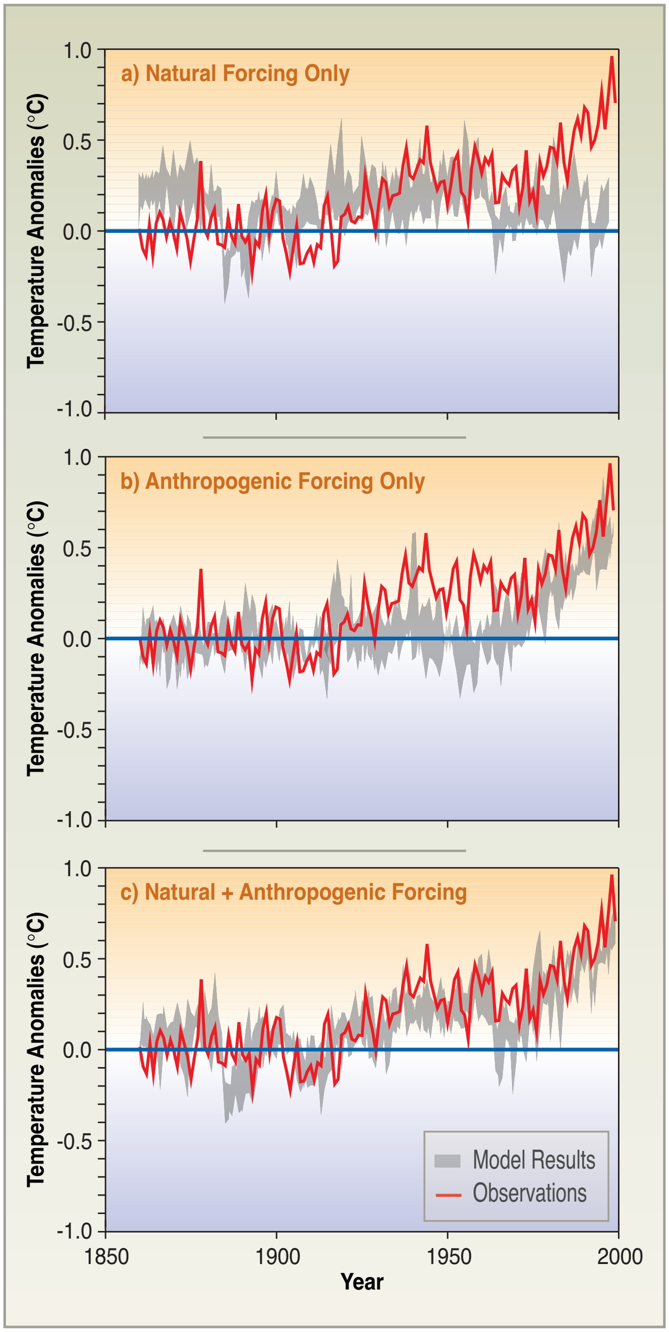

Figure 4-2: Climate model simulations of the Earth's temperature variations compared with observed changes for (a) natural forcing due to solar variations and volcanic activity; (b) anthropogenic forcing from greenhouse gases and an estimate of sulfate aerosols; and (c) both natural and anthropogenic forcing included. The model results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed. Source: IPCC (2001d). For more information, see Annex C.

understanding of ENSO behavior under different climate states is therefore needed.

We have also 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 in many instances are still quite poor. We have yet to obtain confident estimates of the likelihood of abrupt climate transitions, although such events have occurred in the past (NRC, 2002). 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 human and natural systems (see, e.g., Figure 4-3).

The transformation of knowledge gained from climate research into information that is useful for societal decisions presents many challenges, as well as significant new opportunities. The process of understanding climate impacts and using climate information requires a detailed understanding of the interactions of climate, natural systems, and human institutions. Thus, to obtain maximum benefits from advances in knowledge of climate variability and change, it will be essential to forge new relationships between the climate research community, social scientists, 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 climate variables that are important to human and natural systems affected by changes in the Earth system resulting from natural processes and human activities?
- How can emerging scientific findings on climate variability and change be further developed and communicated in order to better serve societal needs?

Providing decision-relevant answers to these questions will require a research infrastructure that includes: a sustained, long-term observing system of a quality necessary for climate research and assessments (Chapter 12); a highly focused and adequately funded modeling activity to analyze and integrate climate observations and support climate predictions and projections (Chapter 10); and a research-based infrastructure to develop partnerships among climate scientists, other natural scientists (e.g., biologists), social scientists, and public/private-sector decisionmakers to accelerate the production and applications of climate knowledge (Chapter 11). In addition,

Figure 4-3: Wind-blown dust buried farms and equipment, killed livestock, and caused human death and misery during the Dust Bowl drought of the 1930s. Source: *Monthly Weather Review*, June 1936 (courtesy NOAA).

coordinated research management will be required to ensure a broad-based and collaborative research program spanning academic institutions, government and private laboratories, and public and private sector expertise, to sustain research into climate variability and change and to provide advanced graduate and post-doctoral training for the next generation of scientists (Chapter 16).

In developing a research strategy, it is vital to recognize that the problems of climate variability and change are intrinsically connected: for example, regional impacts of climate change will depend directly on the variability of the global climate system. Moreover, future climate variability (e.g., frequency of ENSO events) will depend in part on changes in the mean climate. Therefore, problems of climate variability and change cannot be cleanly separated, and the success of understanding each will require improved understanding of both. The overall scientific strategy described in this chapter includes:

- Carefully designed, implemented, and managed observing system elements that will directly improve our knowledge of the climate system and will drive improvements in climate models
- Systematic, ongoing programs of climate data collection, integration, and analysis
- Process studies to elucidate critical processes that govern the climate system, but which in many cases are poorly understood and modeled
- Building a research infrastructure, such as the Earth System Modeling Framework, that supports collaborations among climate scientists and climate modeling centers
- Improving capabilities to assess climate information needs and to provide needed information to decisionmakers at local, regional, and national levels.

Advances will require improvements in paleoclimatic data 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 or longer time scales. For example, in the Arctic, few climate stations have records extending back beyond 50 years, but paleoenvironmental analyses indicate that both the magnitude and spatial extent of 20th century Arctic warming may be unprecedented over the past 400 years. Paleoclimatic analyses also reveal the occurrence of decades-long mega-droughts at lower latitudes, including large portions of the United States (NRC, 2002).

The Climate Variability and Change research element will play a central integrating role in the Climate Change Science Program (CCSP). As indicated by the numerous linkages, the Climate Variability and Change research element will provide the array of advanced climate prediction and projection products that the other CCSP elements will utilize. This can be achieved only through the continued development of core climate system models that integrate the observational, analytical, and specialized modeling capabilities planned within the other CCSP elements, in order to provide improved information necessary to respond to the scientific and decisionmaking needs of the overall program. The overarching questions in the areas of climate variability and change can be addressed most effectively by focusing attention on five key science questions and their associated research objectives, as described below.

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

State of Knowledge

Climate system feedbacks, such as from clouds, water vapor, atmospheric convection, ocean circulation, ice albedo, and vegetation, produce large uncertainties in climate change projections by modulating the direct response to radiative perturbations that result from changing greenhouse gas concentrations, solar variability, or land-cover changes. State-of-the-art climate models exhibit a large range in the cumulative strengths of these feedbacks, with major U.S. models used in recent IPCC assessments lying at nearly the opposite ends of this range (IPCC, 2001a). A key issue for climate science is the extent to which the range in model projections resulting from the differences in climate system feedbacks can be quantified and reduced. Important feedbacks include relatively fast processes on time scales of minutes to months (e.g., clouds and turbulent ocean mixing). Such rapid processes also affect models used for seasonal-to-interannual climate predictions, which can be used as effective test beds for research in this area.

All major U.S. climate models fail to accurately simulate certain climate system processes and their associated feedbacks in response to natural or anthropogenic perturbations. The oceans store and transport energy, carbon, nutrients, salt, and freshwater on multiple time scales and help to regulate and determine climate changes on a continuum of time scales. Yet some critical ocean phenomena, including ocean mixing and large-scale circulation features that determine the rate of storage and transport, remain as key challenges to understand, assess, and model. Other critical processes that are inadequately represented in climate models include atmospheric convection, the hydrological cycle, and cloud radiative forcing processses. Although observed changes in incoming solar radiation, a natural climate forcing, are small relative to changes in net radiative forcing by greenhouse gases (IPCC, 2001a,b), there is some evidence that feedbacks within the climate system may magnify otherwise weak solar variability. In spite of many research efforts over the past several decades and longer, the physical processes responsible for such feedbacks remain uncertain.

The cumulative effect of these processes influences the magnitude, rate, and spatial distributions of the climate response to natural or anthropogenic forcing. Modeling deficiencies are related both to limits in understanding the physics of the climate system and insufficient fine-scale treatment of the key processes. They contribute to uncertainties in projections of climate change, and thereby hinder the development of adequate response strategies and formulation of environmental and energy policies. High-priority research will focus on several sub-questions:

- *4.1.1*—What are the key climate system feedbacks that determine the transient and equilibrium responses for a specified radiative forcing?
- *4.1.2*—How and to what extent can uncertainties in these feedbacks be quantified?
- *4.1.3*—How sensitive are climate change projections to various

strategies for limiting changes in anthropogenic forcing, such as by enhancing biogeochemical sequestration or changing land use and cover?
- *4.1.4*—How can satellite, instrumental, and paleoclimatic observations of the Earth's past variations in climate be used to quantify and reduce uncertainties in feedbacks and provide bounds for the major elements of climate change projections for the next century?
- *4.1.5*—To what extent are climate changes as observed in instrumental and paleoclimate records related to volcanic and solar variability, and what mechanisms are involved in producing climate responses to these natural forcings?
- *4.1.6*—How may information about climate sensitivity and feedbacks be used to develop effective strategies for the design and deployment of observational systems?

Research Needs

U.S. research into climate forcing, feedbacks, and sensitivity is conducted at a few major modeling centers, federal and private laboratories, and universities. The intellectual quality of the research is outstanding, with many new and innovative ideas for model development and applications. However, the infrastructure and the observational data are currently inadequate to implement and evaluate these ideas cooperatively among the various modeling groups. Steps are being taken to address these deficiencies, but more must be done.

In order to optimize modeling resources and enable meaningful collaborations among modelers, it is necessary to develop and maintain a common and flexible infrastructure at the major modeling centers. By adopting common coding standards and system software, researchers will be able to test ideas at any of the major modeling centers, and the centers themselves will be able to easily exchange parameterizations as well as entire modules so that all groups benefit. The CCSP-supported Earth System Modeling Framework is an important start in this direction.

Additional infrastructure needs include: continuing enhancements of computational resources to keep pace with increasing model complexity (e.g., chemistry, biology); higher resolution, multi-century climate model simulations run from many different initial states (i.e., as ensembles) to help understand climate variability and change of the 18th, 19th, and 20th centuries and quantify probabilities of future climate events; additional software engineers for developing and managing model codes and building common and flexible infrastructure; and modeling center outreach scientists to aid and enable collaborations with external researchers. Benefits will include more efficient and rapid transfer of research results into applications, thereby achieving savings in human resource and dollar costs (Chapter 10).

Climate research also requires sustained, high-quality environmental observations. Long-term climate observing systems (e.g., ARGO floats and ocean profilers, aerosol-radiation-cloud observatories), satellite data, retrospective data (instrumental and paleoclimatic), field observations, and increased fidelity of current operational data streams and improved reanalyses of historical data will all be needed to produce data sets designed for climate change detection studies, trend analyses, process research, and model development and testing (see also Question 4.2 and Chapter 12). Moreover, incorporation of observational data into modeling through improved data assimilation methods and more advanced models will address the reliability and uncertainties of these frameworks as well as facilitate the design of observing networks.

Further modeling research is required to improve simulations of seasonal-to-interannual variability in global models used for climate projections and to apply these models to improve seasonal-to-interannual climate predictions. Because many of the most important effects of global change will be felt at regional to local scales, improved capabilities of the global models to simulate and predict seasonal-to-interannual variability at these scales will be important both for validating the credibility of the models and building confidence among decisionmakers regarding the use of these models in global change projections.

A new research mode for accelerating improvements in climate models will be tested and evaluated with Climate Process and Modeling Teams (CPTs, see Box 4-1). CPTs are intended to complement rather than replace single investigators or other collaborative research on climate sensitivity and feedbacks. Pilot CPTs will begin in FY2003-2004.

Milestones, Products, and Payoffs

Products

- 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 (Questions 4.1.1 and 4.1.2) [2-4 years and beyond].
  - For cloud and water vapor feedbacks, the Water Cycle research element will provide theoretically based cloud-resolving models, mesoscale models of cloud processes, cloud/precipitation process research, cloud energy budgets, and satellite data sets (e.g., CloudSat). The Climate Variability and Change research element will be responsible for cloud/water vapor feedback processes in the context of the coupled climate system models (e.g., the use of cloud-resolving models to test cloud parameterizations in climate models).
- Improved estimates of the climate response to different emissions [e.g., carbon dioxide (CO_2), aerosols, black soot] and land-use scenarios (Question 4.1.3) [2-4 years and beyond].
  - The capabilities of current climate models to link emissions to global atmospheric distributions of concentrations of pollution, including the chemical and heating and cooling properties of embedded atmospheric aerosols, will be addressed in cooperation with the Atmospheric Composition research element, as will assessments of the ability of the models to simulate observed radiative forcing of chemically active greenhouse gases, including improved uncertainty ranges. Aspects of this research will also be conducted cooperatively with the Land-Use/Land-Cover Change research element.
- New and improved climate data products, including: assimilated data from satellite retrievals and other remotely sensed and *in*

BOX 4-1

CLIMATE VARIABILITY AND CHANGE

FY04 CCRI Priority - Cloud and Water Vapor Feedbacks and Ocean Circulation and Mixing Processes
The Climate Change Science Program will address targeted climate processes known to be responsible for large uncertainties in climate predictions and projections. A new paradigm for conducting the research—Climate Process and Modeling Teams—will be used and evaluated.

Important processes that are inadequately represented in climate models include atmospheric convection, the hydrological cycle, and clouds and their net radiative forcing. Water vapor is the most important of the greenhouse gases, and clouds affect both vertical heating profiles and geographic heating patterns. Results from climate models suggest that there will be an overall increase in water vapor as the climate warms. However, scientists know neither how the amounts and distributions of water vapor and clouds will change as the total water vapor in the atmosphere changes, nor how the associated changes in radiative forcing and precipitation will affect climate. Improved representation of the distribution of and processes involving water vapor in climate models is therefore critical to improving climate change projections.

Ocean mixing plays a pivotal role in climate variability and change, and is a primary source of uncertainty in ocean climate models. The highly energetic eddies of the ocean circulation are not well resolved and cannot be sustained for the multiple thousands of years of simulations required to assess coupled climate sensitivity. This leaves the problem of parameterization of eddy fluxes as a key issue for improving coupled model simulations.

Accelerating improvements in climate models requires coordinated observational, process, and modeling programs by teams of scientists—that is, CPTs, an approach first proposed by U.S. CLIVAR (a complete description of CPTs can be found on its website, <http://www.usclivar.org>). CPTs will rapidly identify, characterize, and ultimately reduce uncertainties in climate model projections as well as determine observational requirements for critical processes. For problems that are generic to all climate models (e.g., cloud processes and ocean mixing), the CPTs will consist of teams of climate process researchers, observing system specialists, and modelers working in partnership with designated modeling centers.

situ data for model development and testing; consistent and regularly updated reanalysis data sets suitable for climate studies; centuries-long retrospective and projected climate system model data sets; high-resolution data sets for regional studies [e.g., Atmospheric Radiation Measurement (ARM) site data to initialize and evaluate cloud-resolving models]; and assimilated aerosol, radiation, and cloud microphysical data for areas with high air pollution, such as urban centers throughout the world (Question 4.1.4) [2-4 years and beyond].
  - Some of these data will be collected, quality-controlled, and integrated in cooperation with the Atmospheric Composition and Water Cycle research elements, and will support these and the Carbon Cycle research element.
- Increased understanding and confidence in attribution of the causes of recent and historical changes in the climate (Questions 4.1.4 and 4.1.5) [2-4 years and beyond].
  - The Atmospheric Composition research element will provide emission and atmospheric concentration data and the Land-Use/Land-Cover Change research element will provide historical land-use change time series and land-use scenarios. Selected Climate Variability and Change data and analyses will be provided for the Atmospheric Composition research element's assessment of the impacts of tropospheric ozone on radiative forcing brought about by clean air regulations enacted during the last decade.
- Targeted paleoclimatic time series as needed, for example, to establish key time series of observations and natural forcing mechanisms as benchmarks of climate variability and change (Question 4.1.5) [2-4 years and beyond].
- Improved effectiveness of global and regional observing systems, including deployment of new systems and re-deployment of existing systems, based on guidance provided by modeled climate sensitivities and feedbacks (Question 4.1.6) [2-4 years and beyond].
- Policy-relevant information on climate sensitivities and the uncertainties in climate model projections due to climate system feedbacks, in support of the IPCC and other national and international assessments (all 4.1 questions) [2-4 years and beyond].

Payoffs

- More efficient and rapid transfer of research results into applications [2-4 years and beyond].
- Increased confidence in estimates of the global and regional manifestations of future changes in climate [beyond 4 years].

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

State of Knowledge

One of the major advances in climate science over the past decade has been the recognition that much of climate variability is associated with a relatively small number of recurrent spatial patterns, or climate modes. These include, in addition to ENSO, the North Atlantic Oscillation (NAO), the northern and southern hemisphere annular modes (NAM, SAM), Pacific Decadal Variability (PDV), Tropical Atlantic Variability (TAV), the Tropical Intra-Seasonal Oscillation (TISO), and monsoon systems. At present, there is limited understanding of the physical mechanisms that produce and maintain natural climate modes, the extent to which these modes interact, and how they may be modified in the future by human-induced climate changes. These limitations in knowledge introduce major uncertainties in climate predictions, climate change projections, and estimates of the limits of climate predictability, especially for regional climate (see also Question 4.1). They directly hinder our capabilities to address many of the "If…, then…" questions posed by decisionmakers.

Simulations of past climate conditions for which forcing estimates have been obtained provide an effective and practical means for assessing the scientific credibility of climate models. They enable detailed investigations of whether climate models realistically reproduce past climate states and responses in key environmental variables, such as sea level. They may also be used to evaluate how well the models simulate the various naturally recurring modes of climate variability. Process research that includes enhanced and extended observations—such as over the Pacific, Atlantic, and Indian Oceans basins and adjacent land and ice regions—provides a critical means for evaluating physical mechanisms and feedbacks, validating models, and assessing the corresponding effects on regional climate.

The extent to which skillful regionally specific climate predictions and climate change projections can be provided is an issue of fundamental practical importance. Various approaches have been proposed, including high-resolution global models, nested global-regional models, probabilistic information derived from ensembles with either individual or multiple climate models, and statistical downscaling. Much additional work is required to determine optimal methods and the feasibility of downscaling climate information to regional-to-local levels. Here, research on short-term climate variability (e.g., due to ENSO) can provide valuable insights. Developing capabilities to reproduce regional manifestations of interannual climate variability in climate models will also be crucial for establishing credibility with scientists and decisionmakers regarding longer term climate change scenarios (see, e.g., Figure 4-4).

High priority research will seek to answer the following questions:

- *4.2.1*—How can advances in observations, understanding, and modeling of ocean-atmosphere-land interactions be used to further improve climate predictions on seasonal to decadal time scales?
- *4.2.2*—What are the time scales for changes in climate variability following major changes in the land surface, oceans, or sea ice, and how does this "memory" contribute to climate predictability on multi-year to decadal time scales?
- *4.2.3*—What are the projected contributions from different components of the climate system to future sea-level changes,

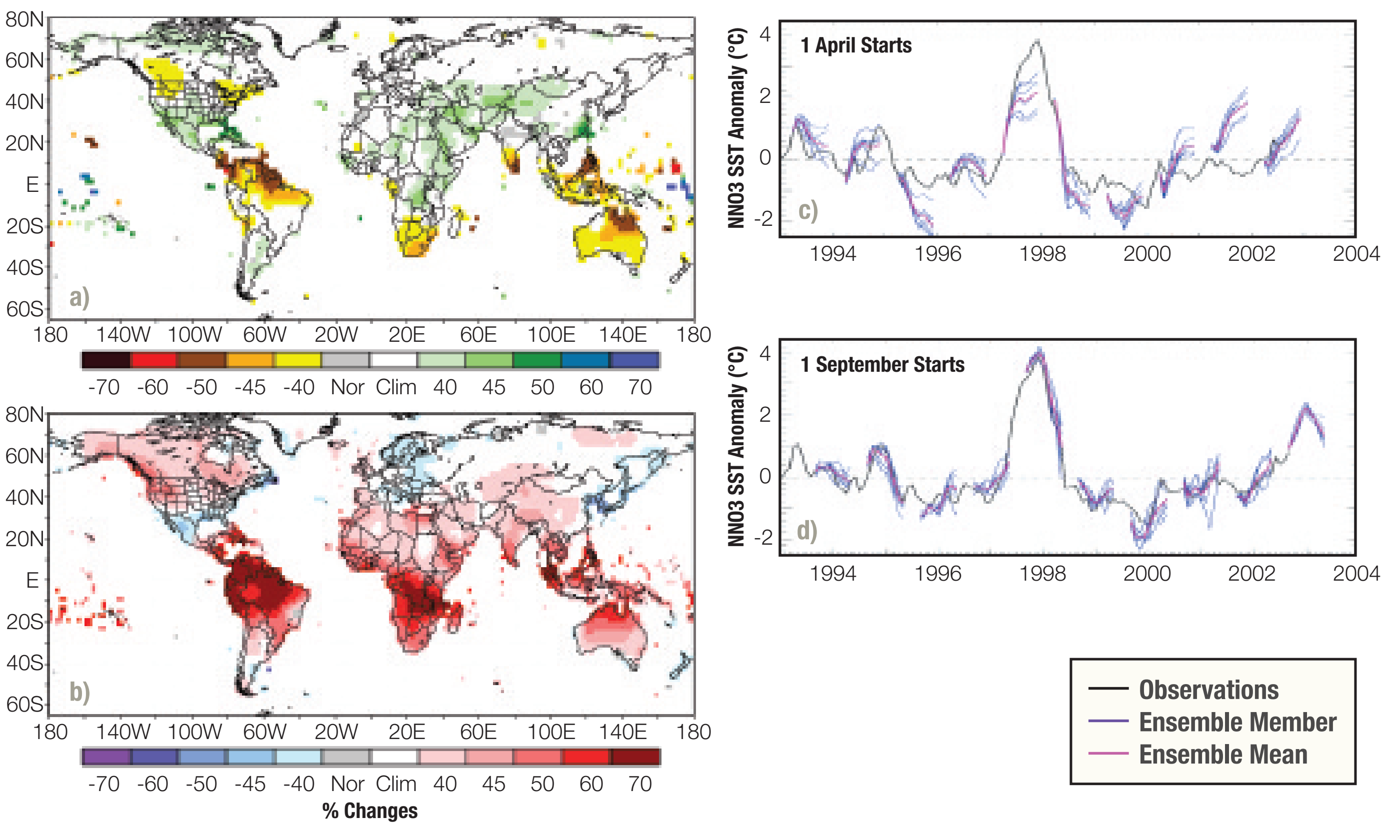

Figure 4-4: *Left Panel*: Multi-model derived probability forecasts of the most likely category for (a) precipitation and (b) temperature for January-March 2003 (models run December 2002). Positive values indicate forecast probabilities in the above normal category (upper one-third of climatological temperature or precipitation distributions, respectively) while negative values indicate probabilities in the below normal category (lower one-third of the distributions). *Right Panel*: Ensemble predictions with a coupled model system of eastern Pacific sea surface temperature (SST) anomalies 9 months in advance, with predictions starting in April (top) and September (bottom) of each year. The spread of the six-member ensembles, which is particularly evident in the 1 April starts, indicates the relatively large uncertainties in predicting SST anomalies so far in advance. Sources: (a) International Research Institute for Climate Prediction, and (b) NASA Seasonal-to-Interannual Prediction Project.

what are the uncertainties in the projections, and how can they be reduced?

- *4.2.4*—What is the potential for improved representation of natural modes of climate variability, such as ENSO, PDV, NAO, TAV, TISO, monsoons, and the annular modes, and how might this knowledge be used to extend and improve climate predictions?
- *4.2.5*—How might human-induced changes that affect the climate system, such as changes in atmospheric composition, aerosols, ground cover and land use, and natural forcing from solar variability and volcanic activity, alter climate forcing and hence climate variability and predictability on global and regional scales?
- *4.2.6*—How do current and projected climate changes compare with past changes and variations in 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 research needs include the development and support for long-term, sustained climate modeling and observing capabilities (see also Question 4.1 and Chapters 10 and 12). These include remote-sensing data sets, global and regional reanalyses, and retrospective data including new high-resolution paleoclimate data sets. Field observations and process studies are necessary for improving understanding and modeling of the physical mechanisms responsible for climate feedbacks, evaluating the extent to which climate models successfully replicate these mechanisms, and determining observational requirements for critical processes. Additional research is required to develop improved methodologies to determine from global model projections changes in regional climate and seasonal-to-interannual variability. Vital constraints that must be considered include the water cycle (Chapter 5) and global energy balance.

Focused research efforts, such as the CPTs described earlier in this chapter, can play an important role in accelerating improvements in global climate models. Sea-level observations, geodetic reference frame measurements, ice sheet and glacier volume estimates, as well as advances in modeling are required to further refine sea-level change projections. Other research needs include producing data sets from ensembles of extended model simulations, and an updated, consistent reanalysis suitable for climate diagnostic analysis, attribution, and detection, including, if feasible, all of the 20th century. Moreover, access to model products, predictions, and tailored value-added products/information must be provided to the decisionmaking community to foster progress in utilizing prediction capabilities (see Question 4.5 and Chapter 11).

Milestones, Products, and Payoffs

Products

- Dynamically consistent global time series of observations (e.g., regularly updated and extended global climate reanalyses; 50-year long, 1° ocean data assimilation products) (Question 4.2.1.) [2-4 years].
  - Some aspects of this work will be conducted in collaboration with the Water Cycle research element. Selected data products will provide the Carbon Cycle research element information required for carbon cycle model development. Climate model simulations of the 18th, 19th, and 20th centuries, and projections for the next couple of centuries that contain gridded values of all climate (ocean, atmosphere, sea ice, etc.) variables, also will be available for use by several other science elements.
- Extended model-based data sets to assess predictability and develop new approaches to improving seasonal-to-interannual climate predictions (Question 4.2.1) [2-4 years and beyond].
- Improved predictions of El Niño-La Niña, particularly the onset and decay phases (Question 4.2.1) [2-4 years and beyond].
- Improved probability forecasts of regional manifestations of seasonal climate anomalies resulting from ENSO (Questions 4.2.1 and 4.2.4) [less than 2 years and beyond].
- A paleoclimatic database designed to evaluate the ability of state-of-the-art climate models to simulate observed decadal- to century-scale climate change, responses to large changes in climate forcing, and abrupt climate change (Questions 4.2.2, 4.2.5, and 4.2.6) [2-4 years].
  - The Carbon Cycle research element will provide information on feedbacks to the climate from large changes in carbon storage and fluxes.
- Development and extension of critical data sets to improve analyses of climate variability and attribution of causes of climate change (Questions 4.2.2 and 4.2.6) [2-4 years and beyond].
- Improved high-resolution, three-dimensional ocean circulation models (Questions 4.2.1–4.2.4) [2-4 years and beyond].
  - The Climate Variability and Change research element will lead in development of suitable ocean models for climate purposes, but will rely on other elements for model subcomponents (e.g., Carbon Cycle for biogeochemistry, Ecosystems for biological, Water Cycle for important forcings such as continental freshwater runoff).
- Improved estimates of global air-sea-land fluxes of heat, moisture, and momentum needed to discern characteristics of ocean-atmosphere-land coupling and to assess the global energy balance (Questions 4.2.1–4.2.4) [2-4 years].
  - The Water Cycle research element (providing precipitation products and land-surface fluxes) will work jointly with Climate Variability and Change on this product. Climate Variability and Change, working with the Water Cycle research element, will coordinate selected field measurements with those of the Carbon Cycle research element to derive more complete three-dimensional time series for flux and transport studies of carbon and ocean nutrients.
- Improved representation of processes (e.g., thermal expansion, ice sheets, water storage, coastal subsidence) in climate models that are required for simulating and projecting sea-level changes (Question 4.2.3) [2-4 years and beyond].
  - In addition to the above factors, local to regional changes in sea level will be affected by movements in land due to natural processes or human influences (e.g., the removal of groundwater), which will require Climate Variability and Change to coordinate in this area with the Water Cycle and Land-Use/Land-Cover Change research elements.
- Improved understanding and parameterizations of key mechanisms for seasonal-to-decadal variability, based on process studies together with modeling research and analyses (Question 4.2.4) [2-4 years and beyond].
- Improvements in the representation of major modes of climate

variability in climate change projection models and predictions of regional patterns of different modes of climate variability (Question 4.2.4) [beyond 4 years].

- An assessment of potential predictability beyond ENSO (e.g., associated with PDV, NAO, annular modes, tropical Atlantic and Indian Ocean variability and trends, and the monsoons) (Question 4.2.4) [beyond 4 years].
- Estimates of the spatial and temporal limits of predictability of climate variability and change forced by human activities (Question 4.2.5) [beyond 4 years].
- Policy-relevant information on natural climate variability and the potential predictability of climate variability and change in support of national and international science assessments [2-4 years and beyond].

Payoffs

- 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 "If…, then…" policy-related questions [beyond 4 years].
- Increased understanding of changes in natural variability and potential impacts on predictability that may result from anthropogenic forcing [beyond 4 years].
- Research to address Questions 4.1 and 4.2 will provide more reliable and useful climate prediction products and other essential support to U.S. 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 10) [2-4 years and beyond].

Question 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?

State of Knowledge

Analyses of the paleoclimate record—the record of the Earth's environmental history derived from sources such as ice cores, tree rings, and lake and ocean sediments—provide compelling evidence for past abrupt climate changes. In some locations, changes of up to 16°C in temperature and a factor of two in precipitation have occurred within decades to years, yet lasted for centuries and longer (NRC, 2002). Paleoclimate data indicate that these changes have been manifested by significant shifts in the baseline climate and in the character and patterns of variations about average conditions. The rapidity of such changes poses major challenges to the vulnerability and adaptability of societies and ecosystems.

Previous paleoclimate research has provided significant advances in our understanding of the general structure and geographic extent of past abrupt climate changes. Much past research has focused on colder climate conditions, and a challenge for the future will be to understand the potential for abrupt change in the context of an overall warming climate. Abrupt climate changes may be associated with the crossing of a climatic threshold, the onset of nonlinear responses, or feedbacks in the climate system. To date, however, the causes of past abrupt changes are not fully explained or understood. In addition, present climate models fail to adequately capture the magnitude, rapidity, and geographical extent of past abrupt changes. Consequently, at this time climate models cannot be used with confidence to estimate the potential for future abrupt changes (NRC, 2002). Improved knowledge of the causes for abrupt changes, and the ability to project their future probabilities, will provide policymakers with an improved scientific basis to evaluate risks of future abrupt changes and, as needed, to develop strategies to reduce vulnerabilities. Major questions include:

- *4.3.1*—How common are abrupt changes, based on paleoclimate records?
- *4.3.2*—What are the observational requirements needed to resolve the spatial and temporal patterns of past abrupt changes, and to answer questions about differences in timing of the changes in different parts of the globe?
- *4.3.3*—What are the primary natural mechanisms for producing abrupt climate changes?
- *4.3.4*—When might future abrupt changes be expected to occur, and what would be the expected global and regional manifestations of such changes?

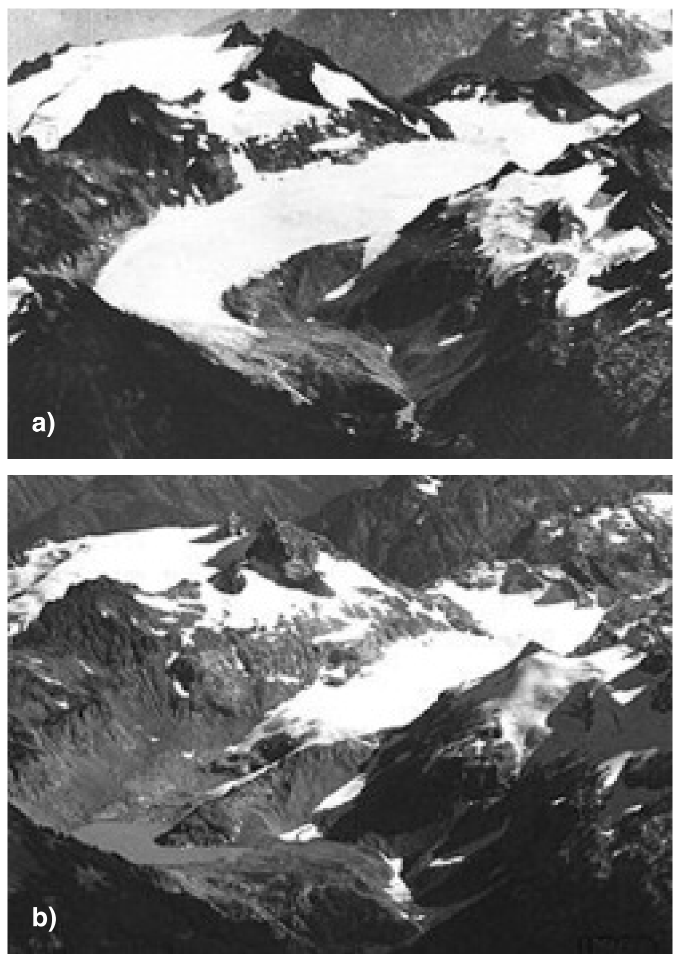

Figure 4-5: The retreat of the South Cascade Glacier in Washington's Cascade Mountains shown in photographs from (a) 1928 and (b) 2000. Since 1957, the glacier has retreated about 700 meters, losing about one-fifth of its length and one-third of its volume. Source: USGS.

- *4.3.5*—What is the nature and extent of abrupt climate change in the Holocene? Are these stochastic events or the result of periodic forcing?
- *4.3.6*—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?
- *4.3.7*—What would be the environmental consequences of extreme warming in the Arctic, and what would be the expected feedbacks on global climate?

Research Needs

Improved paleoclimatic data sets, expanded observing and monitoring systems and rigorous paleoclimate modeling studies will be required to identify the causes and mechanisms of past abrupt changes. Efforts should be focused on key regions or phenomena that may be especially vulnerable or contribute most strongly to abrupt climate change, such as the tropics, the Arctic and Antarctic regions, and the ocean thermohaline circulation. Significant research into how to numerically model the full three-dimensional circulation of the ocean will be required in order to accurately project impacts and time scales for abrupt changes, which range from interannual ENSO variability to centennial-millennial fluctuations in the ocean circulation. Key research needs include better understanding of the relationships between abrupt change and:

- Oceanic circulation, especially related to deepwater formation
- Sea-ice transport and processes, particularly where they interact with deepwater formation
- Land-ice behavior, including conditions beneath ice sheets
- Modes of atmospheric variability and how they are altered by changes in mean climate conditions
- The hydrological cycle, including storage, runoff, and permafrost changes. The Water Cycle research element will provide studies and modeling of cryosphere hydrological processes to complement the efforts of Climate Variability and Change to address cryosphere-atmosphere-ocean coupling and feedbacks.

Milestones, Products, and Payoffs

Products

- Databases of drought and mega-drought occurrences in North America (Questions 4.3.1 and 4.3.6) [2-4 years].
- Online database of annual-to-decadal resolution paleoclimatic time series and maps of Arctic climate variability over the past 2,000 years (Questions 4.3.2, 4.3.6, and 4.3.7) [2-4 years].
- Improved understanding of thresholds and nonlinearities in the climate system, especially for coupled atmosphere-ocean, ocean thermocline and deepwater, hydrology, land surface, biogeochemical cycle, and ice processes (Questions 4.3.3 and 4.3.5) [beyond 4 years]. Advances require cooperation with the Water Cycle and Carbon Cycle research elements.
- Improvements in the accuracy, management, and synthesis of paleoclimatic data that can be combined with instrumental observations and climate models to address the nature and likelihood of future abrupt climate changes (Questions 4.3.2 and 4.3.4) [beyond 4 years].
- Policy-relevant information of the state of understanding on the causes of abrupt changes, and probabilistic estimates of future risks of abrupt global and regional climate-induced changes, including the collapse of the thermohaline circulation, persistent ENSO conditions, and abrupt sea-level rises, in support of national and international assessments (Questions 4.3.4 and 4.3.6) [2-4 years and beyond].

Payoff

- Increased use and effectiveness of paleoclimate data and analyses of abrupt change to better inform environmental decisions and adaptation strategies [4 years and beyond].

BOX 4-2

CLIMATE VARIABILITY AND CHANGE

FY04 CCRI Priority - Polar Feedbacks

The Climate Change Research Initiative (CCRI) will leverage existing USGCRP research to address major gaps in understanding climate change. Polar systems may be especially sensitive to climate change and might provide early indications of climate change as well as interact with climate variability and change through several important feedback processes.

The CCRI will support research to improve understanding of processes that determine the behavior of slowly varying elements of the physical climate system, especially the oceanic and cryospheric portions. Particular foci include the processes by which ice-covered regions of the high-latitude Earth behave, the processes by which the distribution of sea ice varies, and the way in which knowledge of ocean circulation can be enhanced through use of global observations of ocean state and forcing parameters. The development and testing of new capabilities for measuring climatic properties, such as ocean surface salinity, mixed layer depth, and ice sheet thickness will also be carried out.

The CCRI will support the obtaining of systematic data sets for a limited number of Earth system parameters such as ice thickness, extent, and concentration in the case of sea ice, and mass balance and surface temperatures in the case of land ice and snow cover. It will shortly enable the initiation of regular observations of ice-sheet thickness. Data assimilation systems using satellite data that provide for accurate, geophysically consistent data sets will also be carried out through this program. The polar feedbacks research will also contribute to decision support through cryospheric observations and associated models that enable the initialization and verification of climate models, and the reduction in uncertainty of model output. The models will also provide real-time information for use by the U.S. Navy and commercial maritime interests in high-latitude regions.

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

State of Knowledge

One of the highest priorities for decisionmakers is to determine how climate variations, whether natural or human-induced, alter the frequencies, intensities, and locations of extreme events (NRC, 1999a). There is now compelling evidence that some natural climate variations, such as ENSO, PDV, and the NAO/NAM, can significantly alter the behavior of extreme events, including floods, droughts, hurricanes, and cold waves (IPCC, 2001a,b). Studies of long-term trends in extreme events show that in many regions where average rainfall has been increasing, these trends are evident in extreme precipitation events (there continues to be debate on how to define an extreme precipitation event). For other high-impact phenomena, such as tropical storms/hurricanes, no compelling evidence yet exists for significant trends in frequency of occurrence (IPCC, 2001a,b).

A question central to both short-term climate predictions and longer term climate change is how climate variability and change will alter the probability distributions of various quantities, such as of temperature and precipitation, as well as related temporal characteristics (e.g., persistence), and hence the likelihood of extreme events (see Figure 4-6). A key challenge is to develop improved methods for modeling or downscaling climate information to the scales required for extreme event analysis (IPCC, 2001a). Further, understanding of the processes by which climate variability and change modulate extreme event behavior is incomplete. Major research questions include:

- *4.4.1*—What is the range of natural variability in extreme events, by phenomena and region?
- *4.4.2*—How do frequencies and intensities of extreme events vary across time scales?
- *4.4.3*—What are observed and modeled trends in extreme events and how do they compare?

Figure 4-6: Heavy rains and high surf from storms associated with the 1998 El Niño event produced severe erosion along the California coast, leading to major property losses. Source: Paul Neiman, Environmental Technology Laboratory, NOAA.

- *4.4.4*—How are the characteristics of extreme events changed by natural climate variations, for example, by ENSO, PDV, NAO/NAM and SAM?
- *4.4.5*—To what extent are changes in the statistics of extreme events predictable?
- *4.4.6*—How are behaviors of extreme events likely to change over this century, and what are the mechanisms that would be expected to produce these changes?
- *4.4.7*—How can the emerging findings on climate-extreme event links be best developed and communicated to evaluate societal and environmental vulnerability and opportunities?

Research Needs

Progress in this area will require two key steps. First, it will be necessary to advance scientific understanding and quantitative estimates of how natural climate variations such as ENSO, NAO/NAM, SAM, or PDV alter the probabilities of extreme events (e.g., floods, droughts, hurricanes, or storm surges). Second, it will be essential to improve understanding of how human-induced climate change may alter natural variations of the atmosphere, ocean, land surface, and cryosphere, and hence the behavior of extreme events in different regions.

Key data requirements include the development of improved climate-quality data and reference data sets and higher resolution model reanalyses to support analyses of extreme event variability and trends. High-resolution observations together with focused process studies will be essential for scientific evaluation of regional model simulations, especially in regions with significant topographic variations, such as mountainous and coastal regions. Higher resolution paleoclimatic data will also be necessary to improve descriptions and understanding of how natural climate variations have in the past altered drought, mega-drought, flood, and tropical storm variability (see Question 4.3). Improving hydrological extreme event risk estimates will require improved hydrological data sets and advances in coupled climate-land surface-hydrology models (see Chapters 5, 6, 11, and 12).

Empirical and diagnostic research will be required to ascertain relationships between natural climate modes, boundary forcing mechanisms (e.g., SST variations, land surface and cryospheric changes), and extreme events; to clarify the physical bases for these relationships; and to evaluate the veracity of model simulations and projections. Model sensitivity experiments will significantly advance understanding of how natural climate modes, boundary variations, and human-induced climate trends alter the probabilities of extreme events. Further development of regional climate modeling and improved downscaling techniques will be necessary to provide information at the scales needed by resource managers and decisionmakers.

Continuing development of ensemble-based approaches, and the capabilities to produce large ensembles from climate models, will be essential in order to improve probability estimates of extreme events for either short-term climate predictions or longer term climate projections. Because extreme events can have societal and environmental impacts, it will be essential to identify key climate information needed to better anticipate and plan for such events (see Question 4.5 and Chapters 9 and 11).

Milestones, Products, and Payoffs

Products

- Improved observational databases, including paleoclimate and historical data records, and model simulations of past climate to detect and analyze regional trends in extreme events and to assess whether changes in the frequencies of extreme events lie within or outside the range of natural variability (Questions 4.4.1-4.4.3) [2-4 years and beyond].
- Observational and statistical analyses to assess the relationships between extreme events and natural climate variations, such as ENSO, PDV, NAO/NAM, and SAM (Question 4.4.4) [2-4 years and beyond].
- Improved diagnostic capabilities to better interpret the causes of high-impact climate events, such as droughts or unusually cold or warm seasons (Question 4.4.4) [2-4 years and beyond].
  – Aspects of this research require data, information, and analyses of regional hydrological processes related to floods and droughts, to be provided by the Water Cycle research element.
- Assessments of potential predictability and forecasts of probabilities of extreme events associated with natural climate variations (Questions 4.4.4 and 4.4.5) [2-4 years and beyond].
  – For floods and droughts, the Water Cycle research element will focus on the role of hydrological feedbacks and the predictability of extreme events on weather time scales. The Climate Variability and Change research element will focus on variations and changes that generate conditions favorable for extreme events, assess the predictability of these events, and develop products useful for applications (e.g., extreme event outlooks) on seasonal and longer time scales.
- Documented impacts of climate extremes on regions and sectors, and evaluations of the implications should climate change in the future (Question 4.4.6) [2-4 years and beyond].
- Policy-relevant information on past variability and trends in extreme events, and probabilistic estimates of possible future changes in frequencies, intensities, and geographical distributions of extreme events in support of national and international assessments (Question 4.4.1 and 4.4.6) [2-4 years and beyond].

Payoffs

- Improved anticipation of and response to extreme climate events (e.g., to reduce regional impacts of ENSO or more rapidly respond to emerging droughts) [2-4 years and beyond].
- Increased understanding of and capabilities to project the regional manifestations of extreme climate events, to provide a sounder scientific basis for policymakers to develop strategies to minimize potential vulnerabilities [beyond 4 years].

Question 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?

State of Knowledge

Research in this area focuses on making climate knowledge more useful and responsive to the needs of decisionmakers, policymakers, and the public. Climate information, when integrated together with knowledge of non-climatic factors, can reduce costs and risks related to climate variability and change while increasing management and decisionmaking opportunities across a broad range of sectors, from local and regional to global scales (NRC, 1999a; IPCC, 2001b).

For example, pilot efforts in sustained regional integrated science research, such as the NOAA-supported Regional Integrated Science and Assessments (RISA) projects, NASA Regional Earth Science Application Centers (RESACs), and NOAA-supported International Research Institute for Climate Prediction (IRI) for areas outside of the United States, have provided opportunities to apply climate information in decision processes in climate-sensitive sectors, including agriculture, water, energy (e.g., hydropower), and forest (wildfire) management. USEPA also sponsors regional science and assessment projects. Finally, specialized entities outside the research domain, such as state climatologists, regional climate centers, and agricultural cooperative networks, have served as partners and liaisons by identifying and communicating climate information needs and requirements between the climate research and service communities and a broad array of users.

With continuing population growth and increasing demands on environmental resources, the need to more effectively identify, develop, and provide climate information useful for society will become ever more vital. Even in the absence of human-induced climate changes, further research in this area provides new opportunities for resource managers and policymakers to develop strategies to reduce vulnerabilities to natural climate variability. Major questions include:

- *4.5.1*—What new climate information would provide the greatest potential for benefits, for different regions and sectors?
- *4.5.2*—How can climate information be best developed for use in adaptive management strategies?
- *4.5.3*—Can new climate indicators be developed to better assess climate vulnerability and resilience in climate-sensitive sectors such as agriculture, water, marine fisheries and other environmental resources, transportation, and the built environment, as well as other potential societal impacts (positive and negative), including on human health?
- *4.5.4*—What are potential entry points and barriers to uses of climate information?
- *4.5.5*—How can access to and communication of climate data and forecasts be improved in order to better serve the needs of the public, scientific community, decisionmakers, and policymakers?

Research Needs

In recent reports the National Research Council (NRC) identifies the "region" as a key scale for decisionmaking, and stresses the critical need to improve regional scientific capabilities and user interactions to better inform such decisions (NRC, 1999a, 2001e). As these reports emphasize, the impacts of climate variability and change will continue to be felt most directly at regional to local scales—for example, within natural boundaries associated with coastlines, mountains, or watersheds, within the context of demographics, ecosystems, and land use, and within the context of its economic and technological wherewithal. A central goal of research over the next decade will be to improve capabilities to identify, develop, and deliver climate information at regional to local scales in order to better meet societal needs.

A key challenge in this area is to continue developing the observational, diagnostic, and modeling expertise required to determine the impacts of climate variability and change at global and regional scales. The required basic science research must be complemented by a strong applied research component to ensure identification of key regional issues and impacts of multiple stresses on resource management, determine responsiveness to user needs, and develop objective means for measuring success. To be developed most effectively, these research efforts should be conducted as sustained, two-way partnerships that directly involve decisionmakers and other regional stakeholders. This will help to ensure that results of climate research are made most useful for applications. Further, user needs can provide important guidance for developing future research directions. Regional "test beds" or "enterprises" can serve as important foci for developing such partnerships, evaluating potential uses of climate information at regional scales, and performing analyses of regional climate impacts, vulnerabilities, adaptation, and mitigation options related to climate variability and change. They can also be used as demonstration projects for providing end-to-end delivery of climate information and evaluations of its uses, and for establishing an improved national decision support capability.

Because of the difficulties in evaluating the effectiveness of decisions with long lead times, important initial steps toward building confidence in the use of climate information can be made through focused research on shorter term decisions, such as those that occur on monthly and seasonal-to-interannual time scales (e.g., agriculture, water management, energy distribution, wildfire management). Improved information for supporting climate-sensitive decisions on these time frames will be critical for building credibility on the uses of climate data and projections to better inform difficult, long-term decisions. A focus on shorter term climate variability also provides opportunities to try various decision options.(e.g., through adaptive management strategies). Evaluating the effectiveness of strategies on shorter time scales will be useful for developing longer term policy options and decisions.

As climate knowledge improves, evaluation can be extended to multi-year and decadal time scales, which will provide an important bridge to policy and decision options related to longer term changes. In this regard, the decadal time scale offers a valuable bridge for research on climate-sensitive adaptive strategies across time scales. It links the management of the impacts of individual extreme events and interannual variations to longer term variations and can provide tangible observational regional analogs for climatic change.

To ensure that these efforts are efficient and cost-effective, it will be crucial to involve existing regional experts in climate information, applications, and user needs, such as state climatologists, regional climate centers, university extension agents, local weather service offices, and members of the private sector. These regional efforts must ultimately be coordinated effectively in order to provide information that will serve the needs of policymakers and decisionmakers at the national level (see Chapter 11).

Milestones, Products, and Payoffs

Milestones and Products

- Establishment of research teams involving climate and social scientists and stakeholders in climate-sensitive regions to create focused, user-responsive partnerships (Questions 4.5.1–4.5.5) [less than 2 years and beyond].
- Increased partnerships with existing stakeholder support institutions, such as state climatologists, regional climate centers, agricultural extension services, resource management agencies, and state governments to accelerate uses of climate information (Questions 4.5.1–4.5.5) [less than 2 years and beyond].
- Assessments 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, such as drought planning and response (Questions 4.5.1 and 4.5.2) [2-4 years].
- Development of high-resolution climate products for climate-sensitive regions, based on monthly instrumental data, annual paleoclimatic data, and climate forecasts (Questions 4.5.1 and 4.5.3) [2-4 years and beyond].
- Documented regional impacts of climate variability, and development of reports on the potential implications of projected climate changes (Questions 4.5.1 and 4.5.5) [beyond 4 years].
- Development of a framework for assessing the effectiveness of current regional-scale climate science and services (Question 4.5.5) [2-4 years].
- Development of first-generation "test bed" integrated climate science and assessment decision support systems for subsets of user groups (e.g., farmers, ranchers, water managers, forest managers, fisheries managers, coastal zone managers, urban planners, and public health officials) in regions where user demand is already demonstrated (Question 4.5.5) [2-4 years and beyond].
- Policy-relevant information on uses and needs for climate information, and potential impacts of future climate variability and change at regional to local levels, in support of national and international assessments (Question 4.5.1-4.5.5) [2-4 years and beyond].

Payoffs

- Expanded decision support resources and the capacity to effectively apply climate knowledge [2-4 years and beyond].
- Increased public and decisionmaker use of research-based information on climate variations, forecasts, and impacts [2-4 years and beyond].
- Knowledge to develop and sustain effective climate services for all parts of the nation and to support national decisionmaking capabilities [2-4 years and beyond].

National and International Partnerships

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 (IGBP) 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 in a coordinated manner.

In particular, CLIVAR—the broadest of the WCRP programs (WCRP, 1995)—has a suite of vigorous activities that address numerous facets of the climate problem. For example, its Working Group on Seasonal-to-Interannual Prediction leads worldwide development and assessment of prediction approaches and forecast systems while the CLIVAR-WCRP Working Group on Coupled Modeling is fostering advancements in coupled modeling. In the Atlantic region, CLIVAR is actively coordinating and encouraging international (e.g., U.S., European, and South American) observational, analysis, and modeling activities that will advance understanding and predictions of the puzzling climate changes that impact this region. These research activities are identifying how the regional climate changes are manifested through features such as TAV and NAO/NAM. Furthermore, CLIVAR investigations are elucidating critical ocean-atmosphere-land-cryosphere (and with WCRP-SPARC, stratosphere-troposphere) coupled processes as well as critical inherent features such as the Atlantic Ocean thermohaline circulation that must be correctly modeled to project future climate changes. CLIVAR and WCRP are fostering numerous activities in the Americas that are addressing global issues (e.g., process studies focusing on the evolution and dynamics of the monsoons) as well as regional issues (e.g., extreme events, paleoenvironmental variability) and their implications for the global climate system.

Within the United States there are a number of partners that will coordinate implementation of the Climate Variability and Change strategic vision. U.S. CLIVAR has in place a nucleus of scientific and programmatic elements, but will need to strengthen ties with additional WCRP groups (e.g., U.S. CliC) as well as with focused model and assimilation system development (e.g., at the National Center for Atmospheric Research, Geophysical Fluid Dynamics Laboratory, and the Goddard Space Flight Center). The deep-ocean observation program—a joint U.S. CLIVAR-Carbon Cycle Study Program effort—is fostering a complementary international component that is providing an example of the benefits of program coordination. Additionally, NOAA's International Research Institute of Climate Prediction is leading international development of climate predictions and their applications. Finally, NOAA's National Centers for Environmental Prediction (NCEP) will also contribute in many key areas including climate monitoring and diagnostics, forecasting, reanalyses, and high-resolution weather modeling. Stronger linkages with NCEP and other members of the weather modeling community will be most helpful in advancing capabilities to address issues of high societal relevance, such as downscaling information to regional and local scales and improving predictions and projections of extreme events. Finally, involving the cadre of regional climate centers and state climatologists will help ensure that regional and user expertise is represented in the development of effective frameworks for developing useful information.

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